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Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Approaches for their Adaptation

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Foreword

The Agreement negotiated at the 2015 Conference of the Parties of the United Nations Framework Convention on Climate Change Conference (UNFCCC) in Paris, France, gathers today 188 parties out of the 197 UNFCCC members. This shows global concern and shared belief that actions need to be taken to limit greenhouse gas emissions. However, as stressed by recent reports such as the International Energy Agency (IEA) *World Energy Outlook 2021*, current policies are insufficient to curb emissions at the level required by the Paris Agreement. In those circumstances, according to global climate projections such as those published by the Intergovernmental Panel on Climate Change (IPCC), global warming accompanied by an increase in extreme weather events is likely to affect many regions of the world. Extended droughts, intense heat waves, forest fires, storms, and floods are expected to impact populations, economies and infrastructures. Resilience to climate change for energy infrastructures that ensure the security of energy supply is therefore becoming a key issue. This project, entitled "Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Approaches for their Adaptation" aims precisely at evaluating the resilience of nuclear power plants to climate change and related extreme weather events, as well as approaches to improving their resilience. The study draws from case studies of past extreme weather events that are characteristic of likely future weather patterns, and their impacts on nuclear power plant operation and safety. The conclusion of the study is that nuclear power plants are generally very resilient infrastructures and become key assets in extreme weather situations, provided associated infrastructures such as grids that transport the electricity produced by the nuclear power plants are themselves resilient. The main risks that climate change poses to the operation and safety of nuclear power plants relate to water: excessive amounts due to intense flooding or a lack of water for cooling. The report documents such cases, as well as the adaptation measures and safety upgrades that were developed to improve the resilience against these types of events.

Acknowledgements

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The Secretariat also thanks the members of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC) for their comments during the review of the report. A full list of those who contributed to the study or provided input is given in Appendix 1.

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AOGCM	Atmosphere-Ocean General Circulation multi-model (IPCC)
ASN	Autorité de sûreté nucléaire (French Nuclear Safety Authority)
BWR	Boiling water reactor
CCGT	Combined-cycle gas turbines
CCREM	Canadian Council of Resource and Environmental Ministers
CMIP5	Coupled Model Inter-comparison Project Phase 5
CMIP3	Coupled Model Inter-comparison Project Phase 3
ConEd	Consolidated Edison
CSA	Canadian Standards Association
CSN	Consejo de Seguridad Nuclear (Spanish Nuclear Safety Council)
DMP	Drought management plans
EDF	Électricité de France
EEA	European Environment Agency
ESWS	Essential service water system
EU	European Union
FDR	Franklin D. Roosevelt East River Drive (United States)
GHG	greenhouse gases
GtG	gigatonnes of carbon
HI	Hourly
HIS	Hydrological indicators system
I&C	Information and communication
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MTA	Metropolitan Transit Authority
MWAT	Maximum weekly average temperature
NDC	NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NEA)
NEA	Nuclear Energy Agency (
NOAA	National Oceanic and Atmospheric Administration (US Dept. of Commerce)
NPPD	Nebraska Public Power District (United States)
OECD	Organisation of Economic Co-operation and Development

OPG	Ontario Power Generation
OPPD	Omaha Public Power District
OTC	Once-through cooling
PRIS	Power Reactor Information Systems (IAEA)
PSR	Periodic safety review
PWR	Pressurised water reactor
R&D	Research and development
RCP	Representative concentration pathway
SRES	Special Report on Emissions Scenarios (IPCC)
STDM	Short-term daily maximum
TVO	Teollisuuden Voima Oyj (Finland)
USACE	US Army Corps of Engineers

Executive summary

For several decades the international community has voiced concern over the growing emissions of greenhouse gases (GHG), identified as a primary factor responsible for global warming and, more generally, climate change. The 2015 Paris Agreement sets out a global action plan to put the world on track to limit global warming to well below 2°C. Climate scientists believe that failure to reduce anthropogenic emissions of GHG substantially may lead to disastrous impacts on the climate. According to the Intergovernmental Panel on Climate Change (IPCC, 2007, 2013 and 2014), the frequency and amplitude of heat waves and droughts are likely to increase in many parts of the world in the future, as are the frequency and intensity of storms, floods and cold spells. Concern over the possible consequences of this projected climate change has prompted calls to reduce the use of fossil fuels and to promote low-carbon energy sources.

Climate conditions directly impact our energy systems. Thermal power plants such as fossil fuel and nuclear power plants will be affected by the reduction of water availability and the increased likelihood of heat waves, impacting the cooling capabilities of the plants and thus their power output. In the case of coal, its shipping transport can be disrupted by low levels in the waterways. Also, the increased use of variable renewable technologies (wind and solar photovoltaics), while desirable to reduce GHG emissions from the power sector, is likely to make electricity production and distribution systems more dependent on climatic conditions (IEA, 2020a).

Regions and countries will not be affected by climate change in the same way. Some countries may benefit from it while others will see their energy supply security and reliability undermined. According to the IPCC (2014), the world remains ill-prepared for risks from a changing climate because of a lack of forethought and the high exposure to climatic hazards. The IPCC makes the case that these risks can be partly mitigated through adaptation measures.

Nuclear energy is the largest source of low-carbon electricity in OECD countries, and the second-largest (behind hydro) at the world level, and plays an important role in future decarbonisation scenarios. This role has been recognised for a number of years, and was discussed in previous NEA publications (NEA, 2012, 2015, 2021) and in the International Energy Agency's 2°C scenario (IEA, 2021) in a context of growing concern that GHG emissions cannot be reduced quickly enough (IEA, 2020b).

Given the long operating period of nuclear reactors, with an initial design licence of 60 years for generation III designs, the possible impact of climate change on the safety and operation of nuclear power plants needs to be studied and addressed at design and siting stages to limit costly adaptation measures during operation. The availability of water for cooling will certainly become one of the major criteria for siting new large nuclear power plants. Existing reactors, on the other hand, may face more severe environmental and regulatory standards (e.g. post-Fukushima safety measures) requiring plant retrofits, especially if long-term operation is considered. In some cases, additional investments may be needed to cope with local variations in climatic and hydrological conditions exceeding initial design assumptions.

In this context, this NEA study assesses the level of adaptation to climate change and environment protection regulations that will be necessary to improve the resilience of nuclear power, and to ensure that it remains a reliable, secure, and cost-effective technology. Two key issues are assessed:

- the level of vulnerability of nuclear power to future climatic challenges, on the basis of national, regional and international studies;
- the level of adaptation to possible extreme weather conditions, the technologies and preparedness measures involved, and whenever possible the associated cost.

Impact of climate change and other environmental considerations

The IPCC has outlined projected changes in climate from a range of scenarios characterised by different assumptions on population growth, economic development and energy use. Although climate predictions depend on the scenario assumptions, the general trend of projections is consistent and includes the following possible effects (IPCC, 2007 and 2013):

- increase in global mean surface air temperature over the 21st century;
- greatest temperature increases over land and at high northern latitudes;
- likely occurrence of intense heat waves, which will be more frequent and longer-lasting;
- likely increase of peak wind intensities and precipitation in future tropical cyclones, etc.

The OECD (2012) warns that, according to current emission trends (baseline scenario), the global average temperature increase is projected to be 3°C to 6°C higher by the end of the century, exceeding the internationally agreed goal of limiting it to well below 2°C above pre-industrial levels. This would alter precipitation patterns, increase glacier and permafrost melt, increase sea levels, and worsen the intensity and frequency of extreme weather events such as heat waves, floods and hurricanes.

This report considers the question of whether nuclear generation will be vulnerable to these extreme climatic events and measures that could be implemented to improve its resilience. Climatic events that can affect the availability (and quality) of cooling water for nuclear power plants and the reliability of components obviously require particular attention. But events that affect the transmission grid (e.g. storms that bring down power lines) can also affect the operation of the plants. In addition, the study addresses the impact of climate change on the front end of the nuclear fuel cycle, and in particular on the uranium mining sector.

Beside the possible impact of climate change on power plants generation, its consequences on energy consumption needs to be assessed as well. Extreme weather events leading to strong temperature variations could drive energy demand beyond historical levels putting the overall energy infrastructure under stress. Thus, it is clear that a thorough assessment of the power sector resilience will consider a system point of view, encompassing the supply side and the different generation technologies, the demand side as well as the grid infrastructure.

Finally, more stringent environmental and regulatory requirements will also have an impact on the operation and competitiveness of nuclear power generation. For instance, regulations concerning the threshold temperatures for thermal releases or the cooling approach (i.e. once-through cooling vs. closed cycle cooling) may pose operational limitations and add costs to power plant retrofits.

Water usage in nuclear power plants: Impact of droughts and heat waves

One of the most critical effects of climate change for power generation systems is its impact on cooling water availability and quality. Nuclear power plants have in general greater cooling needs than other thermoelectric generating technologies. This results from the lower efficiency of the power conversion cycle, as well as from the latent safety function cooling water plays, for instance to evacuate residual heat during planned or unplanned shutdowns.

Cooling is part of the power transformation cycle (usually the Rankine steam cycle) by which thermal plants, including nuclear power plants, generate electricity and heat for other applications. In a steam cycle, a closed loop of water is transformed into steam in a boiler, with heat provided by concentrated solar radiation, combustion of a fossil fuel, or nuclear fission. The steam then expands through a turbine, which in turn drives a generator to produce electricity. Before returning to the boiler to restart the cycle, the steam is condensed to liquid state. This is accomplished by the action of the condenser, through the tubes of which cooling water passes and removes heat from the steam. This process therefore relies on two distinct flows of water, one in a closed loop for electricity generation and another connected to the heat sink, e.g. a source of cold, for cooling.

In the cooling process, withdrawal constitutes all water extracted from the environment, whereas consumption refers to the portion of withdrawal that is not returned to the source, for instance because it is evaporated in a cooling tower. As a result, four types of cooling systems for thermoelectric plants can be envisioned directly affecting water withdrawal and consumption patterns: once-through cooling; wet closed-cycle cooling; hybrid systems employing some subset of the two previous technologies; and dry cooling.

Due to the lower efficiency of heat transfer to air, dry cooling has never been used for nuclear power plants, with the exception of the Bilibino nuclear power plant (4 x 12 MW units) in the north-eastern region of Russia. A particular form of hybrid system consists of once-through cooling with a so-called "helper" tower, which can be used on a seasonal basis, to cool discharges below regulatory thresholds.

Droughts affect water river levels and have a direct impact on the performance of the cooling water intakes. High water temperatures also reduce the thermal efficiency of the power plant, increasing the cooling needs. The impact of the 2003 and 2020 heat waves on European nuclear power plants can be measured by the loss of output due to outages related to cooling water constraints.

Nuclear power plants in the United States have also been affected by droughts and heat waves in recent years, with several cases of plant outages or output reductions to conform to environmental legislation concerning thermal releases, or because cooling water temperatures exceeded design thresholds. An increase in water temperature can also affect the operation of so-called "essential service water systems" (ESWS) which are designed to operate below a specified maximum temperature. Exceeding this limit may constitute a risk in the sense that the efficiency of the decay heat removal processes can be compromised, and this can force the shutdown of the plant. Finally, high air temperatures can also have a detrimental effect on the safety and availability of nuclear power plants. Regulations limit the maximum allowable temperatures in rooms containing safety-classified equipment, particularly in the reactor building itself. However, these aspects are not generic and the extent of climatic impacts needs to be analysed on a case-by-case basis.

Other climatic issues

Besides the impact of heat waves and droughts on the water quality and availability, climate change can also lead to extreme weather events, such as floods, frazil ice, and forest fires, that can undermine the operation of nuclear plants. Events such as tropical and ice storms (e.g. Sandy hurricane in the United States in 2012, ice storms in 1998 in Canada or more recently in 2021 in Texas) have underscored the vulnerability of the transmission network which can lead to the shutdown of large generation stations such as nuclear power plants in case of grid failure. These types of weather events can also undermine the reliability of nuclear facilities by transporting debris and affecting cooling systems.

According to the IPCC, floods are expected to occur with greater frequency and severity as a result of increased intensity of precipitation events, greater storm wind speeds and rising sea levels. Reactors located on shorelines of oceans and large lakes are more vulnerable to these types of events. Examples of flooding events that had an impact on the operation of nuclear plants include the 2002 floods of the Oder and Elbe rivers in Central Europe, or the 1999 event at Blayais in France, where a high tide coupled with a storm surge resulted in a Level 2[1] event on the International Nuclear Event Scale (INES).

Overall, outages related to environmental conditions have remained limited compared to those caused by other factors and the lessons drawn from these events have been properly integrated in existing emergency plans. However, in the long term, their rate will likely increase unless adaptation measures are developed and implemented.

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[1] Incident without severe consequences for people and the environment.

Adaptation to climate change

There are different ways in which the resilience of nuclear power plants can be improved in the face of climate change.

Technological improvements can be made to existing plants, through minor engineering changes or retrofits of cooling systems. For instance, lowering water intake at the source can decrease the temperature sensitivity of the cooling water in case of heat waves. However, the merit of building a new water intake needs to be assessed in the light of the benefits (lower water temperatures at a greater depth in summer, which means higher thermal efficiency) and the costs (the design and construction, but also lower thermal efficiency in winter, when near-surface temperatures tend to be colder than temperatures at greater depth). The cost of the loss of output and the ability to recover the necessary investments of course have to be evaluated in the context of the electricity market conditions in which each nuclear power plant is operating.

Another possible improvement includes changing the cooling system from a once-through cooling system to a closed-cycle or hybrid system in order to limit water withdrawal and the associated thermal releases. It represents a more ambitious retrofit effort, however. Besides the cost of such a retrofit, it may in some cases be difficult to find the space needed to build a cooling tower. If water withdrawal is not an issue but thermal releases are, then an increase in the pumping capacity, i.e. a higher cooling flow rate, would result in lower discharge temperatures, but this may require the redesign of the power plant's cooling systems, including the condenser.

To guarantee the safety functions of the nuclear plants' cooling systems and to ensure the design threshold temperatures are not exceeded, more efficient heat exchangers can be installed, as well as equipment able to operate at higher temperatures than the initial design or more powerful air-conditioning units.

Constructing a new nuclear power plant offers more possibilities, at the stage of design and siting, to effectively address the issue of water resources. Because nuclear power plants situated along coasts are less vulnerable to temperature-related phenomena and offer lower water withdrawal constraints (though they can be more vulnerable to flooding), coastal sites may be preferred over river sites, if the country has access to the sea. Otherwise, the use of closed-cycle cooling reduces significantly the water intake compared to once-through systems (though most of the water is evaporated in the process) and there are even alternatives to withdrawals from rivers. For instance, the use of non-traditional water resources such as municipal water, reclaimed water, brackish water or mine water can be considered for cooling thermoelectric plants. The Palo Verde plant in Arizona, which is the largest nuclear generation plant in the United States, uses treated waste water from the city of Phoenix and other municipalities for cooling through evaporation in the plant's nine mechanical draft cooling towers.

Operation of a nuclear power plant in which the cooling water itself is considered "warm" because of climatic and geographic conditions is not a major technical issue. The Barakah nuclear power plant in the United Arab Emirates, for instance, pumps cooling water from the gulf at temperatures above 30°C. In such conditions, the use of larger heat exchangers, in particular condensers, can compensate for the less optimal temperature of the cooling water to achieve the required efficiency (Byung and Yong, 2007).

Fresh water, which is required by all existing nuclear power plants and is often taken from rivers or aquifers, can also be produced by using desalination units. In the future, desalination on a much larger scale can also be combined with nuclear power plants to provide fresh water to countries that are seriously lacking such resources. Some nuclear-powered desalination projects operated in the past (in Kazakhstan) and are operating today (in Pakistan).

Besides technological adaptation means, organisational levers such as planning and plant management can be used to improve plants' operation, especially for utilities that manage a fleet of reactors or a portfolio of different generating technologies. Furthermore, the governing framework of nuclear power enables continuous improvement of potential adaptation measures thanks to periodic safety reviews and international operating experience sharing. Finally, since air temperature is an important parameter in determining electricity demand (heating in winter in countries that use electric space heating, and cooling in summer), enhanced forecasting capabilities can help utilities optimise their refuelling and maintenance outages plans in order to adapt to the effects of climate change on water temperature and availability in a cost-effective manner.

Summary of key findings

This NEA study assesses the level of adaptation to climate change and environmental protection regulations that will be necessary to improve the resilience of nuclear power, and to ensure that it remains a reliable, secure, and cost-effective technology. It is based on an extensive review of the vulnerability of nuclear power to climate change and the level of possible adaptation to extreme weather conditions from both a technological and organisational standpoint.

Climate change will create specific risks and challenges for the electricity system as a whole, including nuclear power plants. The key factors that can influence nuclear power plants are:

- higher air and water temperatures;
- seawater rise that can impact the location of nuclear power plants on coastlines;
- greater variability and more extreme weather events (such as droughts, floods, storms, hurricanes, tornadoes, tsunamis and electric storms).

These factors can affect existing nuclear power plants as well as new designs. A range of solutions can be implemented for nuclear power plants to effectively adapt to climate change. Technological improvements can be made to existing plants through minor engineering changes or retrofits of cooling systems. Similarly, equipment can be designed or retrofitted to ensure the design threshold temperatures are not exceeded. New nuclear reactors offer additional possibilities to integrate the issue of water resources at the design and siting stages. Lastly, operational practices can help adapt to climate change, in particular for utilities that manage a fleet of reactors or a portfolio of generating technologies and can plan outages during summer periods.

From an economic standpoint, the cost of adaptation can vary significantly depending on the type of reactor, the climate change issues at stake, and the applicable regulations and standards. The required measures typically mean investments worth several million euros to several hundred million euros. However, while these adaptation costs can, in some cases, be significant, so can the costs of inaction – both directly at the plant level (e.g. loss of efficiency, unplanned outages) and indirectly for the utility (e.g. electricity procurement on the spot market, compensation for certain customers such as energy-intensive industries).

Overall, the range of solutions means that nuclear power should remain in the long run a technology that can effectively adapt to climate change. However, beyond adaptation at the plant level, the analysis of the vulnerability and resilience of a given technology needs to be made at the system level – including the electricity grid and the environment (water in particular). Nuclear power plants, with their robust designs, long-lasting fuel, and a high availability factor that is to a large extent independent of weather conditions, can significantly enhance the security of energy supply and the resilience of energy systems.

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Chapter 1. **Introduction**

For several decades, the international community has voiced concern over the growing emissions of greenhouse gases (GHGs), which are believed to be the primary factor responsible for global warming, and more generally climate change. According to the Intergovernmental Panel on Climate Change (IPCC, 2007 and 2014), the frequency of heatwaves and droughts is likely to increase in many parts of the world, as are the frequency and amplitudes of storms, floods and cold snaps. Concern over the possible consequences of this projected climate change has prompted calls to reduce the use of fossil fuels, unless combined with carbon capture and storage, and to promote low-carbon energy sources. The potential of nuclear energy to play an important role in decarbonisation has been recognised for many years, and was discussed in the *Nuclear Technology Roadmap* of the International Energy Agency and the OECD Nuclear Energy Agency (IEA/NEA, 2015). The 2°C Scenario (2DS) in this publication provides the long-term vision for this technology roadmap and projects that a wide basket of low-carbon technologies will be needed to decarbonise the power sector. Nuclear energy plays a major role, with over 900 GW (gross) of nuclear capacity projected to be required by 2050, up from 393 GW today, and the share of nuclear electricity production projected to increase from 10% today to 15% by 2060 (IEA, 2017a), one of the largest shares of any low-carbon power-generating technology.

At the same time, there is also growing concern that if GHG emissions cannot be reduced quickly enough (the IEA having warned many times that the “door was closing” on the possibility of maintaining global warming well-below 2°C [IEA, 2021]), climate change will occur on a scale such that many industrial sectors, and power generation in particular, will be significantly affected. Increased use of renewable energy technologies (wind, solar and hydro), which is desirable to reduce the GHG emissions from the power sector, is at the same time likely to make electricity production and distribution systems more dependent on climate conditions. Thermal power plants, such as fossil fuel and nuclear power plants, will also be affected by the reduction of water availability and the increased likelihood of heatwaves, which have an impact on the cooling capabilities of the plants and their power output. Over the last 20 years, there have been various reports of thermo-electric power plants having to reduce output or even temporarily shut down during severe droughts and heatwaves because of environmental constraints related to thresholds for thermal releases or concerns over water intake, especially for inland plants located on rivers. This has been the case again in 2018 and in 2019, when heat waves in various regions of the world affected power generation from thermal power plants, including nuclear power plants. This report provides studies illustrating the impact of some extreme weather events, whether these can be related to climate change or not, on the operation and safety of nuclear power plants and adaptation measures taken afterwards to improve the resilience of these plants.

Given the long operating life of nuclear reactors, typically 60 years for generation III designs, the possible impact of climate change on the operation and safety of nuclear power plants needs to be studied, and addressed at the design and siting stages, to limit costly adaptation measures. The availability of water for cooling will certainly become a major criterion for siting new nuclear plants. Existing reactors, on the other hand, may require more significant investments to deal with variations in climatic and hydrological conditions that exceed initial design values, especially if long-term operation is considered.

In addition, environmental and regulatory constraints to protect the quality of bodies of water can lead to the limitation of thermal releases or water intake to preserve aquatic wildlife, a topic that has been known for a long time (UNESCO, 1979). This, in turn, may pose operational limitations to the use of water-cooled thermoelectric plants, and add considerable costs to power plant retrofits.

The mutual dependence of energy and water is called the "energy-water nexus", and is being debated in many circles, such as the OECD (OECD, 2010 and 2017), the World Energy Forum (WEF, 2009), the World Energy Council (WEC, 2010 and 2016) or the World Bank (WB, 2011). This nexus was also discussed in two special reports from the IEA, *Redrawing the Energy Climate Map* published in 2013 (IEA, 2013) and *Water-Energy Nexus* published in 2017 (EIA, 2017b). But climate change manifestations are not limited to heatwaves and droughts: harsher winters, ice storms and floods are also expected, and these phenomena may similarly represent challenges to power generation, whatever the technology, as well as the electricity grid.

Furthermore, building on reports that underlined the vulnerability of thermoelectric plants and nuclear power plants in particular (e.g. Kopytko and Perkins, 2011; van Vliet et al., 2012), this study provides with updated information on nuclear power plants vulnerability levels and highlights existing solutions. Technical measures that improve thermal efficiency, reduce water use and ensure safe operation even under extreme climatic conditions, are being implemented where necessary. In the future, nuclear power may even offer countries with limited freshwater resources the possibility to produce freshwater through desalination processes – as envisaged for instance in the project developed jointly by Korea and Saudi Arabia to build in the latter country a small modular reactor coupled to a desalination plant. Certainly, the ability to produce electricity to meet demand while maintaining precious freshwater resources is an important criterion of sustainable development.

The purpose of this study is to assess the level of adaptation to climate change and environmental protection regulations that will be necessary to improve the resilience of nuclear power, and to ensure that it remains a reliable, secure and cost-effective technology. Such a study by the NEA is the first of its kind. It addresses in particular:

- the level of vulnerability of nuclear power plants to future climate challenges, on the basis of national, regional and international studies;
- the level of adaptation to possible extreme weather conditions, the technologies involved and their associated costs.

This report has been carried out by an ad hoc expert group of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC), whose members are listed in Appendix 1. Additional experts also contributed a number of case studies. The NEA Secretariat also provided further analysis and input to the report.

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Chapter 2. **Climate change, extreme weather events, uncertainties and regional projections to 2080-2100**

Introduction

Climate science is an empirical science. Any interpretation of observations is a hypothesis first, but can evolve into a theory if sufficiently backed by successful predictions. The present mainstream climate theory explains more of the observed changes in the climate than any other interpretation so far. Its predictions over the last 30 years have been consistent and successful.

Nevertheless, large uncertainties remain. Data coverage is often insufficient, atmospheric processes are not fully understood, computing facilities pose limits and only assumptions can be made about the development of external factors.

While climate science is rather clear and robust on temperature change issues, scenario results for other parameters and extreme events are less robust. In general, large-scale climate features and their expected changes are better understood than small-scale features; thus, globally averaged or regional effects are more reliable than local ones.

From an ethical point of view, not all possible or likely consequences of climate change are equally important. When strategies to adapt to or cope with climate change are discussed, risks that endanger human lives are of special relevance. The safety principle may also demand that in case of doubt the "worst case scenario" be assessed. It follows that climate science must depict the full range of possible effects, including best and worst cases, to enable stakeholders and the public to take informed decisions. In this sense, the inclusion of worst-case scenarios in this chapter is not intended to suggest that those are most likely to occur, or that they are at all likely, but it does mean that they are considered possible by scientific researchers, in many cases by the large international teams of the Intergovernmental Panel on Climate Change (IPCC).

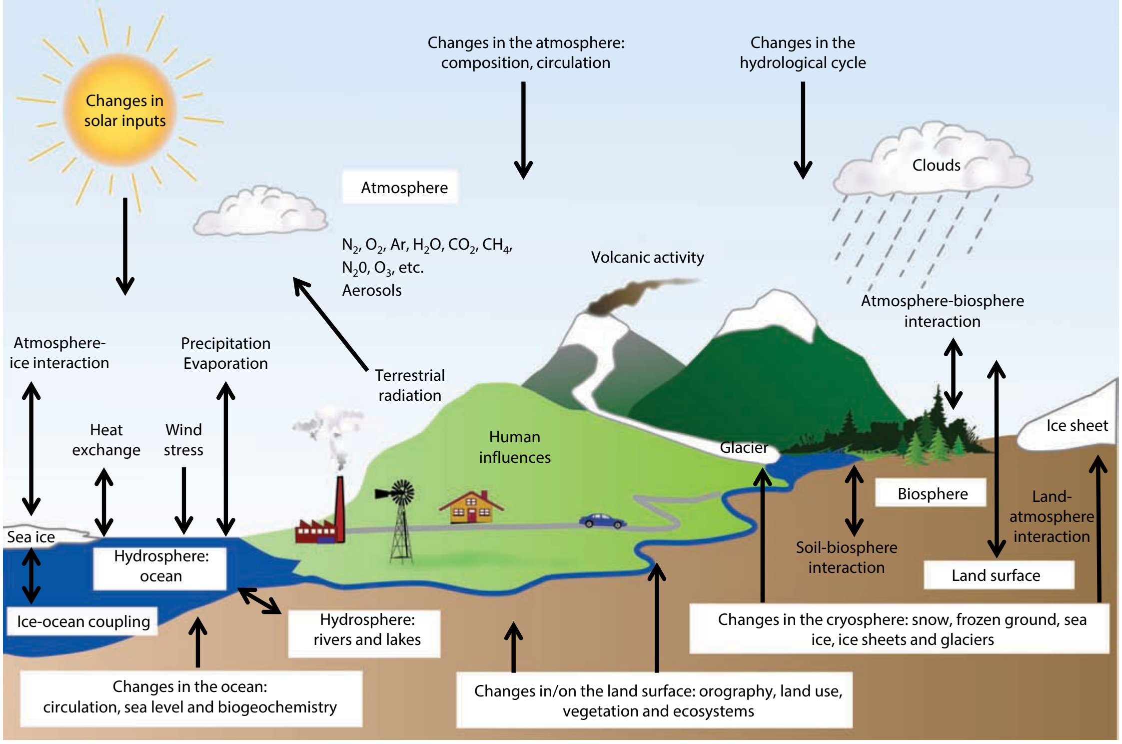
Information given here is only an indication of possible changes that may affect nuclear power plants and other energy infrastructures. Before embarking on any adaptation measure at any specific site, whether efficiency- or safety-oriented, a much more specific study of local climate change is strongly recommended.

The climate system

Driving forces

The climate system encompasses several interacting sub-systems: atmosphere, hydrosphere, cryosphere, biosphere and lithosphere (see Figure 2.1). It is driven by variable boundary conditions, internal dynamics, feedbacks and changes in external dynamics ("forcings"), including natural phenomena (such as volcanic eruptions, solar variations) and human-induced phenomena, e.g. enhanced greenhouse gas concentrations. Even with unchanging external conditions, variations in climate would occur because of non-linear interactions leading to internal oscillations. Thus, change over varying time scales is an intrinsic characteristic of climate and the climate system.

Figure 2.1. **The climate system and sub-systems, their interactions and processes**



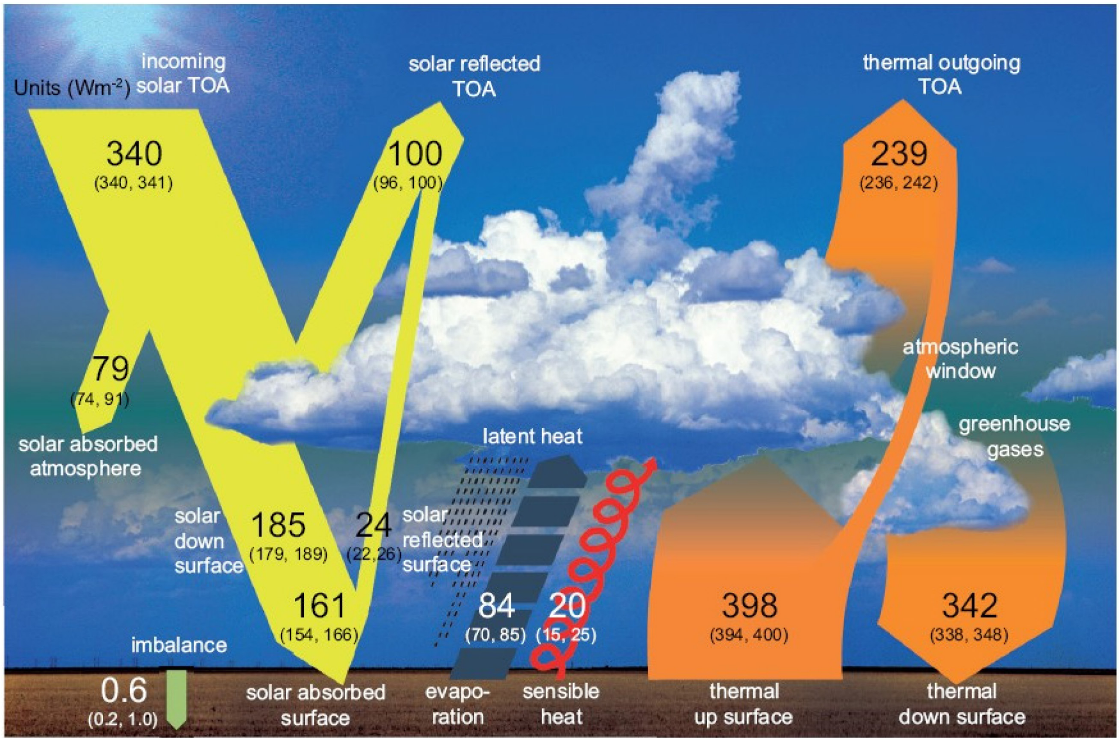
Source: IPCC, 2007.

The global energy budget of the earth (Figure 2.2) describes how the energy received from the sun is distributed within the climate system. About one-third of solar energy is reflected and scattered back to space without energy impact on the atmosphere or the earth's surface. A considerable part of solar energy is absorbed at the earth's surface and converted to latent heat, sensible heat and kinetic energy, and distributed within the atmosphere-ocean system. Another part is absorbed within the atmosphere and radiated in all directions (see below the greenhouse effect). Over the past 10 000 years the outgoing terrestrial radiation and the incoming solar radiation were roughly in balance on a multi-year average.

Externally forced changes in the climate system can be related to, for example, continental drift, changes in the earth's orbit and the rotational parameters, volcanic activities or changes in solar irradiation. They affect the energy balance of the earth through a change in the radiation balance, by either:

- changing the amount of incoming solar radiation through e.g. a change in the sun's radiation intensity or the earth's orbit (eccentricity, axial tilt, precession);
- changing the fraction of the reflected solar radiation, thus the albedo, by e.g. changing ice cover, vegetation, clouds, atmospheric particles;
- modifying the outgoing long-wave radiation e.g. by changing the greenhouse gas concentrations. Responses of the climate system can be either direct or indirect, e.g. through feedback mechanisms.
- Boundary conditions causing changes within the climate system may be due to changing plate tectonics influencing the position of the continents, the character of ocean basins, or the heaving of mountains, especially high-altitude mountains; their location and shape can alter climate and weather, depending on their orientation relative to dominant flow directions. Continental drift, e.g. of Antarctica, and the heave of the Tibetan plateau improved the conditions for glaciation and thereby changed the surface albedo. Such changes in boundary conditions dominated climate until about two million years ago.

Figure 2.2. **Global annual mean energy budget of the earth**



Note: Global mean energy budget under present-day climate conditions. Numbers state magnitudes of the individual energy fluxes in W m–2, adjusted within their uncertainty ranges to close the energy budgets. Numbers in parentheses attached to the energy fluxes cover the range of values in line with observational constraints.

Source: IPCC, 2013.

During the past 600 000 years, a sequence of glacial and interglacial periods, the so-called Milankovich cycles, has dominated the climate, triggered by the oscillation of the earth's orbit and its parameters, the eccentricity, the axial tilt (obliquity) and the precession. Important though these cycles are in triggering and timing climate changes, they cannot explain the observed amplitude of temperature change. Positive feedback mechanisms enhance external forcing, especially the ice-albedo and the greenhouse gases (GHG) feedback. The first refers to the fact that in a warming world, ice and snow covers shrink and reduce the reflectivity of the earth's surface, thus increasing absorption and warming that in turn leads to more melting. The GHG feedback describes the increase of water vapour, carbon dioxide (CO_2) and methane (CH_4) concentrations in the atmosphere with rising temperatures due to releases from the warming ocean or thawing permafrost regions.

Solar variability is also influenced – on a much shorter time scale – by the sun spot cycle. The intensity of solar radiation at the earth's surface varies by about ±0.08% over the course of the 11-year sun spot cycle.

Volcanic eruptions that are energetic enough to transport particulate matter into the stratosphere influence climate in the short term. Sulphate and other volcanic particles reflect incoming solar radiation and therefore have a cooling effect, as demonstrated by the Mount Pinatubo eruption in 1991 and the Krakatau eruption in 1883. The combined effect of multiple volcanic eruptions within four years – Mount Soufrière Saint Vincent in 1812, Mount Mayon in 1814 and Mount Tamora in 1815 – caused the well-known "year-without-summer" in 1816. Monthly summer temperatures in Central Europe were 2.3-4.6°C below average (Fagan, 2000).

Greenhouse effect

Life on earth would not be possible without the so-called *greenhouse effect*. The earth receives energy from the sun through radiation (Figure 2.2), mostly as visible light and nearby wavelengths (UV, near infrared) and, owing to its lower temperature, emits infrared radiation. Greenhouse gases (mainly water vapour [H_2O], carbon dioxide [CO_2], methane [CH_4] and ozone [O_3]) and aerosols in the atmosphere absorb infrared radiation and re-emit it towards space and the earth (back radiation) (Figure 2.2). Back radiation increases the energy within the lower layers of the atmosphere and the surface, and raises the equilibrium temperature by about 33°C. Any change in concentration of GHGs and aerosols within the atmosphere changes absorption and therefore also the equilibrium temperature.

The effect of aerosols on the energy balance of the earth is twofold. On the one hand, light scattering aerosols, such as sulphates, cool the earth, whereas aerosols containing black carbon absorb the incoming shortwave radiation and thus warm the atmosphere.

Attributing recent temperature change

Over roughly the last 2 000 years, the global average temperature was rather constant and only modified by shorter-term fluctuations attributed essentially to internal variabilities of the climate system, volcanic eruptions and the sun spot cycle. A rapid temperature increase occurred within the last ~150 years that significantly exceeded the former variations.

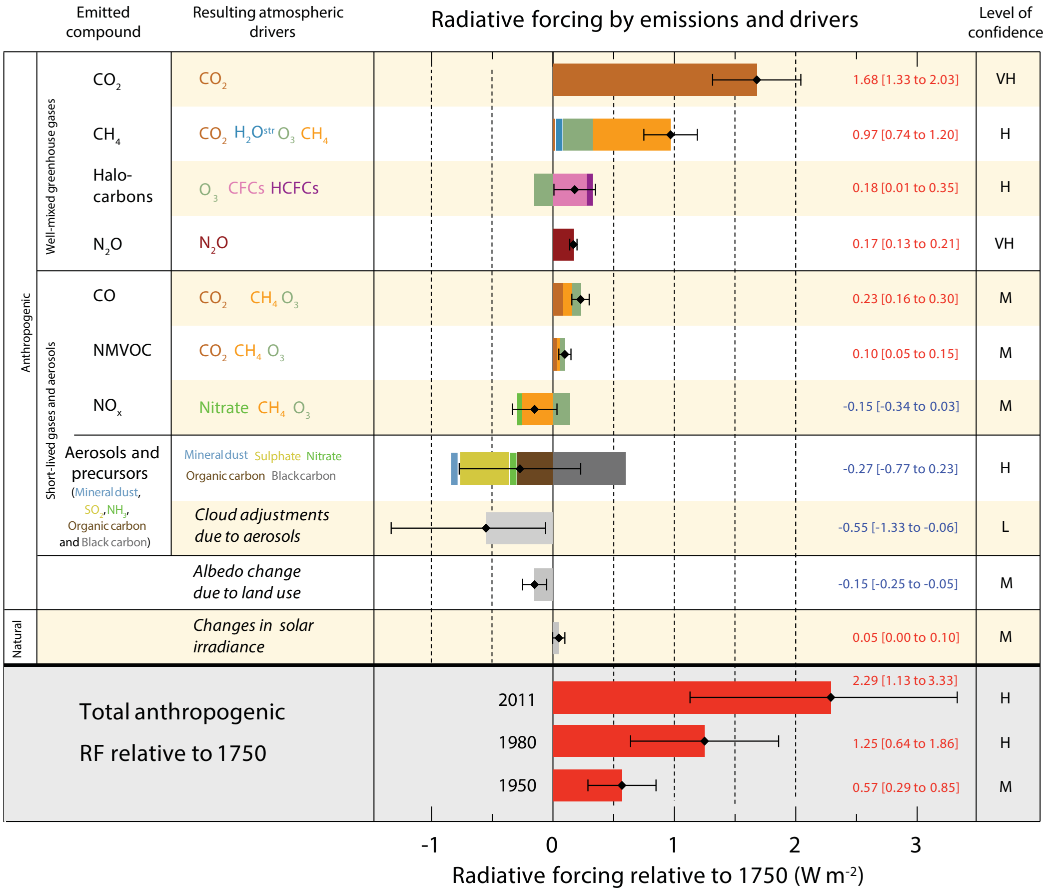
The rapid temperature increase over the last decades is attributed largely to a human-induced rise in GHG concentrations in the atmosphere. Human influence on the climate system is highly complex but can be traced back to the release of GHGs into the atmosphere, particle emissions, and land-use and land-cover changes that can result either in gaseous or particulate emissions or changes in surface albedo. Together, these activities release approximately 10 gigatonnes of carbon (GtC) per year worldwide (Le Quéré et al., 2009; Peters, 2011), less than half of which remains in the atmosphere. The ocean and the land-biosphere systems act as carbon sinks, but cannot compensate the anthropogenic emissions (IPCC, 2013). In balance, only 2.4 ± 0.5 Gt/year and 2.6 ± 1 Gt/year are absorbed by the ocean and the biosphere, respectively. This has led to a systematic increase of CO_2 in the atmosphere.

The ongoing increase in GHG concentrations in the atmosphere leads to a decrease of outgoing radiation and an increase of energy in the climate system. According to Fasullo and Trenberth (2008) this increase is near 0.9 Wm^{-2}, which agrees with the 0.5 ± 0.43 Wm^{-2} since the beginning of the industrial period calculated by Loeb et al. (2012). This extra energy is partly stored in deeper layers of the ocean and cryosphere, but mainly it heats the surface. Once GHG concentrations stabilise, a new radiative equilibrium corresponding to the higher surface temperature will evolve.

The effect of the increase in GHG concentrations on the radiation budget, temperature and other climate parameters is calculated by using climate models based on established physical laws, e.g. the conservation of mass, energy, and momentum. They reproduce well the basic features of the observed temperature developments during the 20th century on a continental scale, despite model uncertainties and limitations. Multi-model ensembles, such as the PRUDENCE project (Christensen et al., 2007), the ENSEMBLES project (Hewitt and Griggs, 2004), or the latest Coupled Model Inter-comparison Project Phase 5 (CMIP5) (Taylor et al., 2012) account for model spread (Meehl et al., 2007a; Tebaldi and Knutti, 2007). Models are also able to simulate important aspects of past climate (near past and holocene and last glacial maximum) and the current climate and climate system (e.g. monsoon, storm tracks). The capacities of the models are continuously increasing.

Validated global climate models also serve to analyse the relative importance of different human interventions. Each atmospheric component altered by human activities contributes to anthropogenic radiative forcing; thus, anthropogenic radiative forcing is a measure for the perturbance of the radiation balance by human activity. The numbers in Figure 2.3 clearly indicate that GHG concentration changes are by far the most important component of anthropogenic radiative forcing, even taking uncertainties into account. Since 1950, radiative forcing has almost doubled every 30 years.

Figure 2.3. **Global radiative forcing change distributed into the components for the year 2005 difference from the pre-industrial radiative forcing in 1750**



Notes: NMVOC = non-metallic volatile organic compounds. Warming at the earth's surface is not considered.

Source: IPCC, 2013.

Climate change scenarios for the 21st century

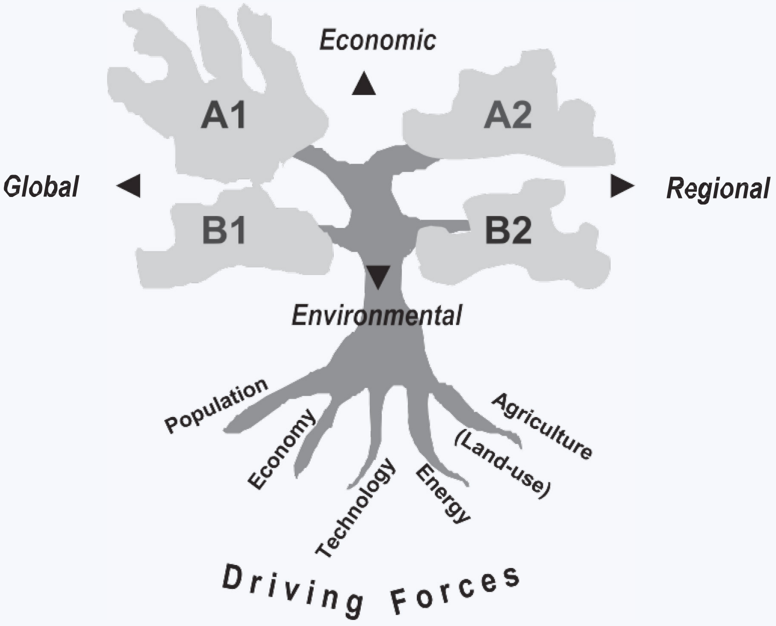
Scenario methodology

Climate models, when used to assess future developments of the climate and the possible impacts of future climate change, need input regarding the driving forces. Thus, assumptions must be made regarding GHG and aerosol concentrations. These, however, depend on natural and anthropogenic forcing and cannot be predicted in a reliable manner. Therefore, climate research analyses several climate scenarios spanning the field of possible developments. The most widely used climate scenarios were based on the *IPCC Special Report on Emissions Scenarios* (SRES) since 1995 (IPCC, 2000). With the recent IPCC report (IPCC, 2013), a transition to so-called representative concentration pathways (RCPs) approach has been made (Van Vuuren et al., 2011). As both scenario families are currently in use, both are briefly described in Box 2.1.

Box 2.1. **IPCC SRES Scenarios 1995**

The SRES contains in total 40 different scenarios, grouped into 4 major families, called the A1, A2, B1, and B2 families (Figure 2.4).

Figure 2.4. **The four SRES scenario families***



* These scenarios are grouped according to their relative orientation (economy, environmental concerns) and their development patterns (global and regional).

Source: IPCC, 2000.

The A1 storyline describes a future world with rapid introduction of new and efficient technologies, rapid economic growth and a global population that peaks in the mid-century and declines afterwards. Increasing mobility, the convergence between regions and increased cultural and social interactions ("rich" and "poor") are major themes in this scenario family. Three sub-families describing alternative directions of future technologies exist: a fossil-intensive (A1F1), a non-fossil energy sources (A1T), and a balanced (A1B) scenario.

The A2 family describes a heterogeneous world based on self-reliance and preservation of local and regional identities. Regional economic growth, more fragmented and slower technological change, and continuously increasing global population define this scenario.

The B1 storyline represents a convergent world. Growth of the global population resembles the A1 scenario family but economic structures change more rapidly towards a reduction in material intensity and cleaner and more efficient technologies. Global solutions are the major underlying theme of this family but no additional climate initiatives are introduced.

The B2 storyline is similar to the A2 family, but the global population growth rate is lower than in A2. Its emphasis lies on local economic, social and environmental solutions with intermediate levels of economic development and diverse technological changes. Activities at local and regional levels are preferred.

Box 2.2. **IPCC representative concentration pathways 2013**

The RCPs used in the fifth IPCC assessment report (IPCC, 2013) mark a new approach no longer based on story lines. Pathways of radiative forcings are normatively determined; every pathway can result from a diverse range of socio-economic and technological development scenarios. The pathways for the year 2100 span the range of radiative forcing values from 2.6 to 8.5 W/m^2 and are closely related to GHG concentrations rather than emissions trajectories.

The four scenarios were developed independently by four modelling teams (see Van Vuuren et al., 2011, for more details). They are not forecasts and they do not represent boundaries for land-use changes or climate change. The four RCPs are:

- RCP2.6: a peak of the radiative forcing of 2.6 W/m^2 and decline before 2100.
- RCP4.5: a peak of 4.5 W/m^2 without overshoot and stabilisation after 2100.
- RCP6: a peak of 6 W/m^2 without overshoot and stabilisation after 2100.
- RCP8.5: a continuously rising pathway with 8.5 W/m^2 in 2100.

Dufresne et al. (2013) summarised the differences in radiative forcing until 2100 and van Vuuren et al. (2011) estimated the CO_2 emissions and concentrations which lead to the radiative forcing. As can be seen, RCP4.5 is close to the SRES B1, RCP6.0 lies between SRES B1 and SRES A1B, and RCP8.5 is higher than the SRES A2 scenario. The lowest RCP scenario, RCP2.6, is lower than any of the SRES scenarios and satisfies the 2°C target.

Changes in average climate conditions

All climate model scenarios indicate warming within this century. Expected global surface warming for RCP scenarios covers a wider range than for SRES scenarios. RCP2.6 aims for stabilisation of the global mean surface temperature at +2°C and RCP8.5 scenario leads to stronger warming than the SRES-A2 scenario, indicating a more extreme future.

The global mean temperature is comparable between the newest General Circulation Models (GCM) generation and former model runs. Also, the spatial pattern of the mean temperature and pattern of annual precipitation for a multi-model mean of two time slices, and two seasons for the RCP8.5 and the SRES-A2 scenario also show clear similarities. Warming will be more pronounced in high northern latitudes and on continents and less in the tropics and over the sea. This indicates the robustness of the large-scale features and consistency with the results of the fourth IPCC assessment report.

Precipitation projections indicate that for the next few decades, the mean precipitation will increase especially in regions where it is already relatively high (e.g. tropics) and decrease in regions where mean precipitation is low (e.g. subtropics). For the higher latitudes, including the polar region, precipitation is expected to increase with increased transport of water vapour into the atmosphere. Arid and semi-arid regions will have less precipitation, and moist mid-latitudes more precipitation. Seasonal shifts with more precipitation in winter are expected in northern Eurasia and North America. In the People’s Republic of China, increases over most areas except the south-west are projected. Changes are also expected in the frequency distribution of precipitation events.

For run-off, decreases are likely in the regions with less precipitation, while increases are expected for the high latitudes. However, snow-cover related run-off is not yet well represented.

An increase of frequency and intensity of heavy precipitation events is expected at the global scale (Chou et al., 2009). There are considerable regional differences, however. Evaluation of extreme precipitation indices (Sillmann et al., 2013a and 2013b) shows an increase in wet days (95th percentile) in most of the regions considered, except for the Mediterranean region, Central America, South America, and Australia, where decreases are projected. The Mediterranean region shows increased drought conditions, captured also by the consecutive dry day index. According to projections of the Palmer Drought Severity Index (PDSI), an increase of drought conditions is also to be expected in the People's Republic of China (see also section below on extreme events). Projections for droughts and soil moisture are still considered rather uncertain. However, according to the latest IPCC study on the impact of global warming of 1.5°C above pre-industrial levels, there is medium confidence that droughts and precipitation deficits will occur in some regions, even if the 2°C is achieved (IPCC, 2018).

Relative humidity is projected to remain constant or decrease as temperature and evaporation rise, whereas specific humidity will increase, especially in the warmer climates. Evaporation projections are in accordance with the global temperature increase of the oceans and are expected to change over land in similar patterns as precipitation changes.

Mean sea level pressure is projected to decrease in high latitudes and increase in mid-latitudes. Thus, a poleward shift of the mid-latitude jet of up to two degrees under the RCP8.5 scenario is expected. Similar effects are expected for the southern hemisphere storm tracks. Projections for vertical circulations, such as the Hadley and Walker circulations, show a slow-down linked to changes in moisture transport from within the boundary layer to the free atmosphere and precipitation changes.

Changes in the cryosphere and sea level rise

Sea level rise, as a result of warming of surface ocean waters and of melting land-bound polar and alpine glaciers, is likely to range between a minimum of 26 cm for RCP2.6 and a maximum of 81 cm for RCP8.5 by 2100 with respect to 1986-2005 (IPCC, 2013). In a study commissioned by the World Bank (WB, 2013), sea level rise stays below 70 cm in all parts of the world until the end of the 21st century for the RCP2.6 scenario, while it exceeds 1 m in most tropical regions and reaches 1.25 m in some for the RCP8.5 scenario (WB, 2013). Local values can differ considerably from global averages, mainly due to superimposed coastal rising or sinking.

The Arctic sea ice cover is expected to continue to shrink and thin as global temperature rises. The average reduction of the extent ranges between 43% to 94% (RCP2.6 and RCP8.5, respectively) in September and 8% to 34% in February by 2100 (also according to RCP2.6 and RCP8.5, respectively). With the high projection, it is very likely that the sea ice cover will nearly vanish during summer before the end of the century. An occasionally seasonally ice-free Arctic ocean is possible within 50 years.

Snow cover changes result from precipitation and ablation changes. In the northern hemisphere, snow cover is expected to be reduced by 7% to 25% (RCP2.6 and RCP8.5, respectively). This does not exclude local increases due to regionally increased precipitation.

Changes for permafrost regions are caused by changes in temperature and snow cover. Under the RCP8.5 scenario, permafrost will most probably only be sustained in such regions as the Russian Arctic coast, east Siberia, and the Canadian Archipelago (Slater and Lawrence, 2013). Overall decreases of permafrost range from 37% to 81% (RCP2.6 and RCP8.5, respectively).

Specific features: Anomalies during El Niño/La Niña

One of the most prominent features of internal variability in the climate system is the El Niño-Southern Oscillation. El Niño is defined as anomalously warm ocean water temperatures developing off the western coast of South America and influencing the weather across the Pacific Ocean and beyond. Signs of El Niño are a rise of surface pressure over the Indian Ocean, falling pressure over Tahiti and central and eastern Pacific, weakening trade winds in the south Pacific, and rising warm air near Peru resulting in rain in the north Peruvian deserts. Moist air and rain are displaced along with the pressure system causing droughts in the western Pacific basin and rainfall in the eastern Pacific. In the Northern, Midwest and Mideast United States, winters are usually warmer and drier during El Niño, whereas in the south winters are wetter. Teleconnections of El Niño can be found almost globally, including the high southern latitudes around Antarctica.

The corresponding cold phase is called La Niña. During La Niña, conditions are wetter than normal in South Africa and drier than normal in equatorial East Africa. In Asia, the formation of tropical cyclones is shifted westwards with increased landfall threats to China and increased heavy rains over the Philippines, Indonesia and Malaysia. In North America, the effects of La Niña are opposite to those of El Niño.

These anomalies occur at intervals of between two and seven years, lasting between nine months and two years. Both phases cause extreme weather such as floods and droughts in many regions of the world.

The 2013 IPCC assessment report states that El Niño-Southern Oscillation very likely will remain a dominant mode of inter-annual variability in the future and the regional rainfall variability it induces will likely intensify. Over the North Pacific and North America, patterns of temperature and precipitation anomalies related to El Niño and La Niña (teleconnections) are likely to move eastwards in the future, while confidence is low regarding changes in climate impacts on other regions, including Central and South America, the Caribbean, Africa, most of Asia, Australia and most Pacific Islands (IPCC, 2013).

Specific features: monsoon

The term monsoon describes seasonal changes of the atmospheric circulation and precipitation. A monsoon is a large-scale sea breeze occurring when land temperatures are significantly warmer than the ocean surface. In the colder months, the cycle is reversed causing the air over land to flow to the ocean. The major monsoon systems are the West African and Asia-Australian monsoons. Monsoon systems also exist in North and South America. Monsoon rains are essential for agriculture in the affected areas; their non-occurrence can lead to famine. On the other hand, excessive monsoon rains can also produce devastating floods, such as those in Pakistan in 2012, in South Asia (Bangladesh, India, Nepal, Pakistan) in 2017 and in the Indian state of Kerala in 2018.

Monsoon precipitation intensity is projected to increase in the future owing to increases in the moisture content of the warmer atmosphere. The monsoon area and total precipitation are also projected to increase by the end of the century (Hsu et al., 2012; Kitoh et al., 2012). Monsoon circulation, on the other hand, is expected to weaken.

For the South Asian and East Asian monsoon, an increase in precipitation extremes is expected, as well as in the North and South African and Australian monsoon regions. The Indian monsoon precipitation is expected to increase, whereas the Australian is expected to decrease. In general, also, an increase in the inter-annual averaged season precipitation variability is expected. For other regions, such as the Sahel zone as well as Mexico and Central America, a decrease is projected.

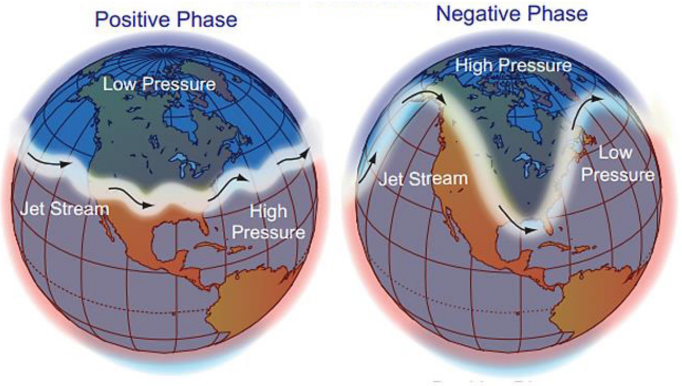
The development of monsoons in climate change is affected by aerosol forcing and induced feedback processes that can modulate the large-scale circulation and thus monsoon rainfall (Lau et al., 2008). Aerosol forcing in climate simulations is still an important source of uncertainty; thus, projections for the future development of the monsoon and the associated monsoon precipitation are still under investigation.

Extreme events

Many extreme weather events are strongly influenced by climate change, even if individual cases cannot always be attributed to climate change, and statistical analysis often does not (yet) show the connection. This is not surprising in that extreme events are by definition rare and reliable statistical analyses would therefore require databases over long periods. Besides, very small-scale extreme events such as tornadoes or some thunderstorms are not captured by the monitoring network or by global or even regional climate models. However, once the underlying physical processes are understood, expected changes in extreme events can be evaluated conceptually and also by climate models.

All present assessments on future frequencies and intensities of extreme temperature and snowfall events in the northern hemisphere could be subjected to significant modifications once the connection between rapidly warming Arctic temperatures, loss of Arctic sea ice and large-scale hemispheric flow is better understood. Some studies (e.g. Petoukhov and Semenov, 2010; Screen, 2013; Tang et al., 2013; Francis and Vavrus, 2012; Overland, 2013) expect an amplification of the Polar Oscillation, which means more pronounced or longer-lasting positive phases (Figure 2.5) that could bring more severe weather e.g. to Canada and the United States in winter, as was the case in the winter 2013/2014, but others (e.g. Screen, 2014) expect less variance as a consequence of a warming Arctic.

Figure 2.5. **Illustration of the Arctic Oscillation in its positive and negative phases**



Source: Courtesy of the National Oceanic and Atmospheric Administration.

In 2012, the IPCC published a special report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (IPCC, 2012). Key findings concerning past observations of extreme events in this report are the following:

- It is very likely that there has been an overall decrease in the number of cold days and nights and an overall increase in the number of warm days and nights at the global scale, that is, for most land areas with sufficient data.
- There have been statistically significant trends in the number of heavy precipitation events in some regions.
- There is medium confidence that some regions of the world have experienced more intense and longer droughts.
- There is limited to medium evidence available to assess climate-driven observed changes in the magnitude and frequency of floods at regional scales.

The fifth IPCC assessment report (IPCC, 2013) states that, since 1950, it is likely that the number of heavy precipitation events over land has increased in more regions than it has decreased. Regional trends vary but confidence is high for North America with very likely trends towards heavier precipitation events.

In the IPCC projections, all regions of the world show an increase in frequency of high daily maximum temperatures (Figure 2.6) for three SRES emission scenarios for the periods 2046-2065 and 2081-2100 relative to the base period 1981-2000. In Europe, 20-year events turn into 5-year events by mid-century and into 2-year events at the end of the century. In the tropics, the increase in frequency sets in earlier and is therefore even more pronounced.

Extreme precipitation is expected to increase with warming, though by how much remains uncertain. Observations and projected future changes both indicate an increase in extreme precipitation associated with warming. Analysis of observed annual maximum one-day precipitation over global land areas with sufficient data samples indicates a significant increase in extreme precipitation globally (IPCC, 2013), with a median increase, about 7% per degree Celsius, of global mean surface temperature (Westra et al., 2013).

In the IPCC study (IPCC, 2012) most regions show an increase of frequency in high daily precipitation events (Figure 2.7). Changes are larger in high latitudes and the subtropics and less pronounced in the tropics. There are indications, from comparisons of satellite-based datasets, that the majority of models underestimate the sensitivity of extreme precipitation intensity to temperature in the tropics and globally. This implies a possible underestimation of the projected future increase in extreme precipitation in the tropics (IPCC, 2013).

Relevance for nuclear power plants

Nuclear power plants are built and operated in many different climates. It is unlikely that present or future climate changes will make production of nuclear energy in power plants impossible in any region where they are currently operating. However, climate change can influence nuclear power production in several ways that can make adaptation measures necessary or at least advisable:

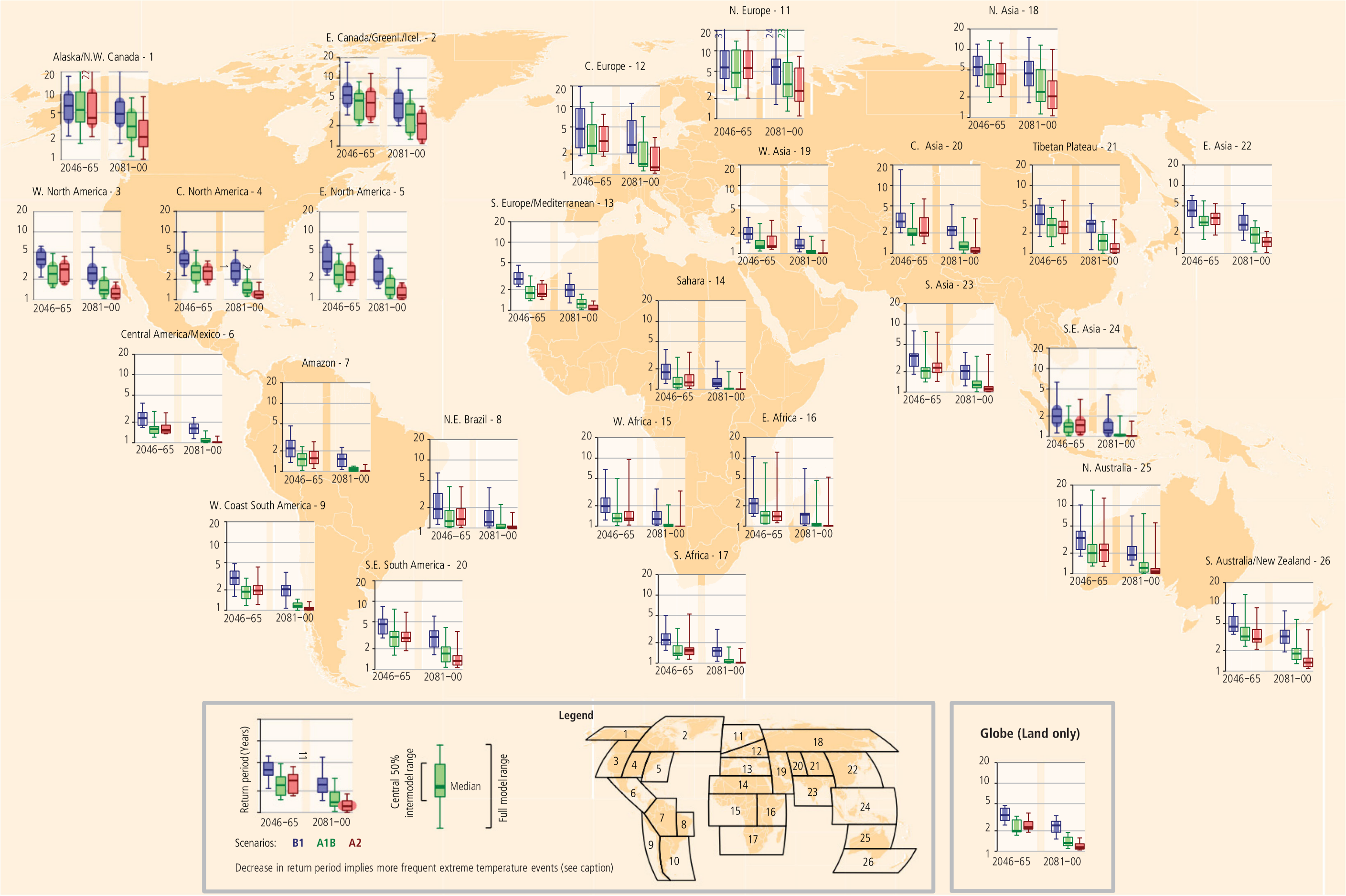
- Nuclear power production, like for all thermal power plants, will see efficiency decrease because of higher temperatures and will possibly experience outages due to the lack of sufficient cooling water (for river-based plants) or due to legal temperature limits in cooling bodies.
- Siting choices for new plants will need to account for possible sea level rise, availability of cooling media as well as risks related to more extreme weather conditions.
- Meeting safety requirements may make adaptations in existing plants necessary to cope with changes in frequency and intensity of weather- and climate-related external hazards.

Efficiency loss and siting are sensitive to gradual climate change, while other aspects are mainly related to extreme events. However, these changes are interrelated: rising sea level also entails higher extreme sea levels during storm surges. Therefore, climate issues are generally relevant for more than one aspect of nuclear power plant planning, siting and operation.

Weather and climate-related hazards may affect a nuclear plant directly, but indirect effects can be just as important because they affect the surroundings or limit accessibility to the plant (e.g. forest fires or floods), or because of cascading problems originating from some other source (e.g. a dam break upstream) or because they affect the electrical grid (e.g. disruptions through falling trees) with consequences for off-site power and/or emission of electric power generated at the plant. Small-scale weather events such as tornadoes essentially affect one power plant, while large-scale phenomena, such as the 2003 heatwave in Europe, affect all thermal plants in the region, as well as some renewable energy plants and power demand. They thus require a systemic view of the problem.

Studying past weather or climate-related incidents and events at nuclear power plants helps to constrain that list somewhat, and the events to be addressed, especially in relation to nuclear power plant safety, become more concrete. A list of relevant climate-change related events and their impacts on nuclear reactors is provided in Table 2.1. In each case, adaptation and other measures taken following the events are presented. It shows that the resilience of nuclear power plants can be improved through not only re-engineering and adaptation of plant designs, but also through organisation and planning measures. These are detailed in the different chapters of this report.

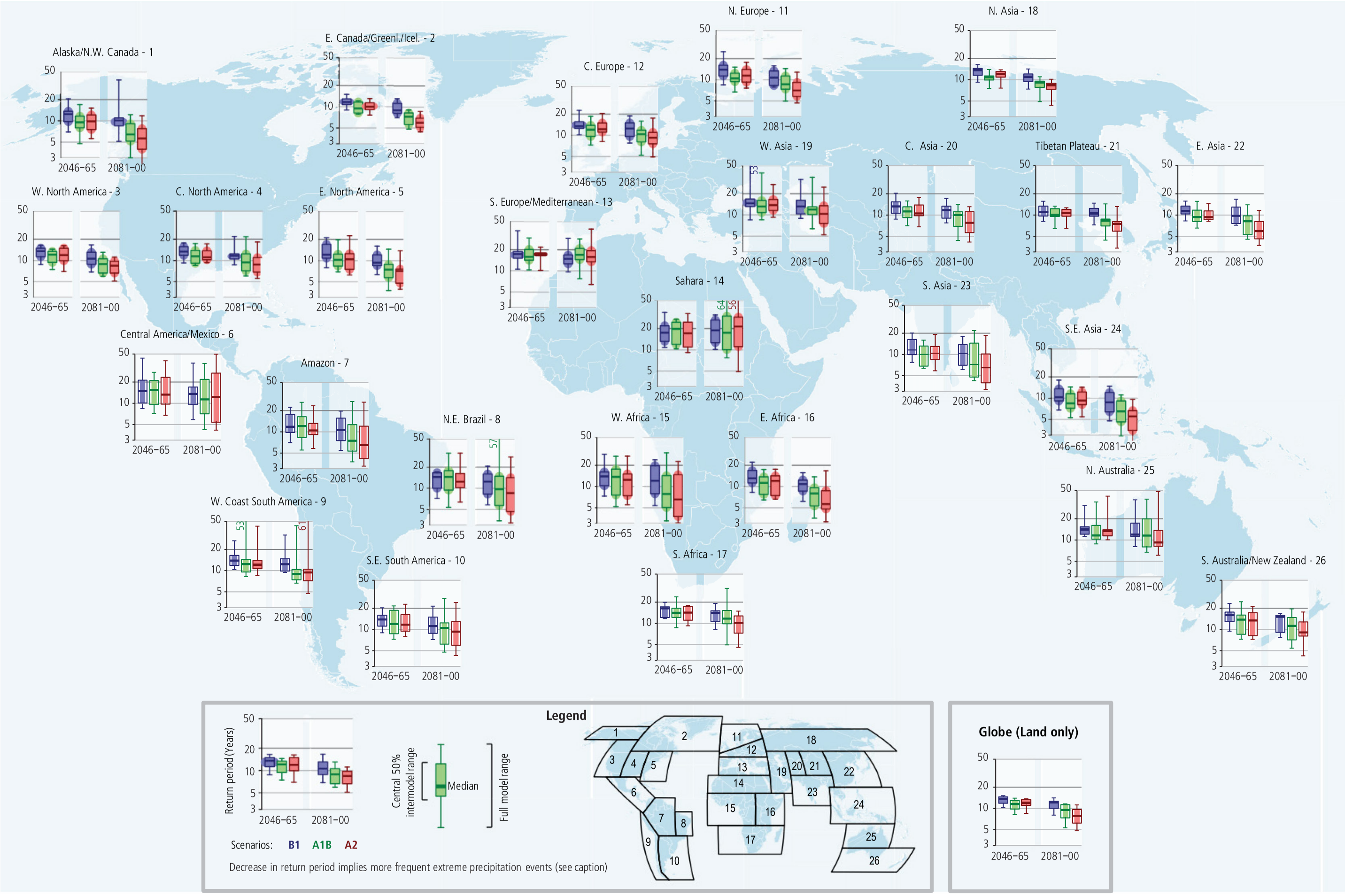
Figure 2.6. **Projected return periods for the maximum daily temperature that was exceeded on average once between 1981 and 2000**



Note: A decrease in return period implies more frequent extreme temperature events (i.e. less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late 20th century, and for three different SRES emission scenarios (B1, A1B, A2).

Source: IPCC, 2012.

Figure 2.7. **Projected return periods for a daily precipitation event that was exceeded on average once between 1981 and 2000**



Note: A decrease in return period implies more frequent extreme precipitation events (i.e. less time between events on average). The box plots show results for regionally averaged projections for two time horizons, 2046 to 2065 and 2081 to 2100, as compared to the late 20th century, and for three different SRES emission scenarios (B1, A1B, A2).

Source: IPCC, 2012.

Table 2.1. **Examples of climate-change impacts on the nuclear sector**

Event	Description	Adaptation and other measures	Chapter
1998 Ice Storm in Canada	Ice storm brings down a large part of the power grid, which impacted the generation system. No direct impact on any nuclear power plant	Reinforcement of the transmission and distribution lines. Anti-collapse towers. Looping of lines	5
Cooling impact on Great Lakes (Canada)	Study on the impact of thermal releases from nuclear power plants on the eco-system and in particular, fish populations	Multi-disciplinary analyses and simulations, considering alternatives to once through cooling systems	6
Snow storms (Finland)	Blockage of air intakes (for emergency diesel generators for example) due to snow storm	Redesign of air intake (existing plants), heated intakes and outlets (new plant)	7
Flooding (Finland)	Flooding of yards around nuclear power plant building due to intense rain	Improved draining systems	7
Frazil ice (Finland)	Blockage of water intake due to frazil ice	Recirculating water out of the condenser upstream; heating water intake rake	7
Loss of cooling for various reasons (Finland)	Main cooling system affected	Air cooling systems as back up to water cooling system	7
High sea temperatures (Finland)	Loss of efficiency of power plant	Redesigning water intake to take water at deeper level (project not carried out because not economical)	7
Heat waves 2003, 2006, 2018-2019 (France)	Loss of efficiency, limits to withdrawals and thermal releases (environmental regulations)	Improved heat exchanger equipment, mobile cooling systems, air conditioning systems, monitoring and forecasting, optimised outage planning, update of regulatory framework	8
Heat waves and drought (Spain)	Loss of efficiency, limits to withdrawal, proliferation of macrophytes in river	Updated water management and regulatory framework, planning of water releases from artificial reservoirs, cooling system improvements	9
Flooding (United States)	Flooding of Fort Calhoun and Cooper nuclear power plants	Regulatory review and requirement to shut down nuclear power plant at earlier stage of flood	10
Heat waves (United States)	Loss of efficiency of nuclear power plants	Upgrade of cooling systems	10
Hurricane Sandy/storms	Impact of storms on nuclear power plants – mostly related to electrical grid issues	Grid reinforcement	10
Le Blayais flooding (1999)	Impact of combined effect of high tide, storm surge leading to partial flooding of nuclear power plant site	Flood protection programme including revised risk assessment methodologies, engineering measures (elevated dykes, water tight doors and penetrations)	11

Changes relevant to efficiency and performance records

Temperature increase

High temperatures reduce the efficiency of power plants and extreme temperatures can reduce the lifetime of components.

Projections for future temperature and changes in surface (land) and air temperature exceed the global average by a factor of 1.5 ± 0.2. The greatest atmospheric warming is expected to occur in the high latitudes and over large continents. The areas with the highest density of nuclear power plants – the eastern United States, Europe, China and Japan – will experience 2 to 3°C warming by the middle of the century and, assuming the RCP8.5 scenario, 4 to 5°C by 2080.

The increase in average temperatures is closely linked with more frequent and higher extreme temperatures as well as a reduction of frequency of cold temperatures. Under the most extreme future scenario (RCP8.5), it is likely that in many regions, 20-year events of high temperature extremes will occur every 2 to 5 years by the middle of this century (see Figure 2.6). The cold winter extremes will continue but with reduced frequency and will become rare by the end of the 21st century.

Sillmann et al. (2013b) evaluated climate extreme indices in the IPCC CMIP5 simulations and show that indices based on daily minimum temperature are more pronounced than indices based on the maximum temperature. Consecutive dry days will increase under future scenarios, especially in regions as Australia, Central America, the Mediterranean and South Africa. Changes in the seasonal minima will be more pronounced in the northern regions with stronger increase in winter compared to summer. Changes in the maxima will be more uniformly distributed with stronger increases opposite to the minima. Especially in the Mediterranean region, the projected changes in the climate extreme indices denote an intensification of heat and water stress, in turn important for cooling of nuclear power plants. On the seasonal and regional scales, the winter minimum temperatures exceed 3°C, especially in the northern latitudes under the RCP2.6 scenario.

For China, the yearly mean temperature is expected to increase by 0.8-1.6°C, 1.5-2.7°C, and 1.9-3.3°C under the RCP4.5 scenario for three time slices 2010-2039, 2040-2069, and 2070-2099, respectively; and, 0.8-1.7°C, 2-3.7°C and 3.4-6°C under the RCP8.5 scenario for the 2010-2039, 2040-2069, 2070-2099 time slices (Wang and Chen, 2013) with increased warming in winter and reduced warming in summer. Further, for inland areas in the north-west, the increase will be larger than in the south-east.

Water temperature and water level

Water-cooled power plants depend on availability and temperature of river or seawater. Biofouling and water quality are also temperature-dependent. Sea surface temperatures may make it advisable to move cooling water intake to deeper levels.

Water temperatures generally increase with air temperature, although the extent depends on the specific conditions (glacier melt water reduces warming).

Annually averaged sea surface temperatures have risen by about 0.2°C on the global average since 1980 and are expected to continue to rise by another 0.25 to 0.65°C by the end of this century, depending on the scenario. Regional variations in sea surface temperature are caused by surface heating and ocean circulation changes. In general, tropical warming is more rapid than warming in mid-latitudes (IPCC, 2013). For power plants located on sea shores, increased surface temperatures could make it advisable to consider building water intakes at greater depth to pump cooler water into the plant's condenser and increase performance. However, as pointed out by the operator of a nuclear power plant located on the Baltic sea coast during the study, deeper intakes can make sense in summer when the surface temperatures are warm, but do not necessarily make sense in winter when surface temperatures can be much colder than water at greater depths. The design of a water intake therefore needs to be optimised in terms of cost of building it vs. the economic benefits of greater efficiency (and higher power output) in different weather and climate conditions.

The climate signal is less clear regarding river run-off than warming. On the whole, run-off increases in areas of increasing precipitation and decreases where precipitation decreases. The high northern latitude run-off increases are likely and consistent with the projected precipitation increases. Decreases in run-off are likely in southern Europe and the Middle East. During heat periods, increasing evaporation further diminishes run-off. Episodes of high temperatures and little precipitation tend to affect larger regions simultaneously.

Van Vliet et al. (2012) calculated that by 2040 water in low flows (10th percentile of run-off) would decrease in Europe by 13% to 15% and 16% to 23% for the SRES B1 and A2 scenarios, respectively. For the United States, a decrease of 4-12% and 15-19% is projected for respective scenarios. For the daily water temperatures an increase in summer of 0.8 to 1.0 and 1.4 to 2.3°C for Europe and 0.7 to 0.9 and 1.4 to 2.4°C for the United States are projected for the 2040s in those scenarios. For the 2080s, both low flows and temperatures increase even more.

Because of the combination of lower flows and higher water temperatures, cooling water problems for nuclear power plants can be expected and have to be addressed through specific adaptation measures.

Other aspects leading to increased outages, lifetime reductions of components or additional maintenance work

The *acidification of the ocean* is a slow process not directly linked to climate change, but stemming from the same cause. According to data from measuring sites in the Pacific and the Atlantic, the average surface ocean pH is assessed to have decreased by more than 0.1 units below the pre-industrial average of 8.17 so far and by 2100 is expected to change by -0.13 to -0.42 pHT units at CO_2 levels of 421 to 936 parts per million (ppm) under RCP2.6 to RCP8.5 climate scenarios, respectively (IPCC, 2013). The rate of acidification in surface waters is 50% higher in the northern North Atlantic than in the subtropical Atlantic (Olafsson et al., 2009). Salinity reduction caused by ice melt or excess precipitation exacerbates ocean acidification by diluting the concentrations of substances acting as buffers (IPCC, 2014). In the medium to long term, attention needs to be given to the corrosiveness of water intake and outlet components of seawater-cooled reactors. Other energy infrastructures such as offshore wind turbines will also likely be affected by increased corrosion risks.

Sandstorms and other materials transported by strong winds (ice, salt) can erode surfaces and damage the mechanics of moving parts. There is no clear indication of the changes in frequency or intensity of these events, but where droughts become more frequent and more intense, reducing the vegetation cover of the soil, or where desertification sets in, there is potential for more frequent dust and sand storms. Increased risk of erosion and desertification are considered likely in Mediterranean-type ecosystems, especially in very dry areas (IPCC, 2014). Increased transport of sea salt may occur as a consequence of increased storms with breaking waves and generating whitecap foam.

The ash deposited from forest fires can sully power plants and needs to be removed, especially from transformers, where it can pose a safety risk. Forest susceptibility to fire is projected to change little for the lowest emissions scenario (RCP2.6), but substantially for the high emissions scenario (RCP8.5). While there is low agreement on whether climate change will cause fires to become more or less frequent in most locations, in some, however, such as the eastern United States, the models show high agreement.

Changes relevant for siting

Sea level rise

Sea level rise endangers low-lying infrastructure and leads to increased likelihood of extreme sea level events.

The global mean sea level has risen by about 0.19 m ± 0.02 m, estimated from a linear trend over the period 1901-2010 according to tide gauge records and satellite data (since 1993). It is very likely that the mean rate of sea level rise was 1.7 ± 0.02 mm per year between 1901 and 2010, but 3.2 ± 0.04 mm per year between 1993 and 2010 (IPCC, 2013).

In addition to these variations, local rates of sea level rise can be considerably higher or lower than the global or regional mean rate for periods of a decade or more. Vertical land motion can dramatically affect local sea level change. Some extreme examples of vertical land motion are in Neah Bay, Washington, where the signal is +3.8 mm per year (uplift from tectonic activity); Galveston, Texas, where the value is -5.9 mm per year (subsidence from groundwater mining); and Nedre Gavle, Sweden, where the value is +7.1 mm per year (uplift from isostatic adjustment to deglaciation). These areas will all have long-term rates of sea level rise that are significantly higher or lower than those due to ocean volume change and therefore climate change alone (IPCC, 2013).

Permafrost

Thawing permafrost may cause soil collapse and thus can impact infrastructures.

Permafrost – soil with temperatures at or below the freezing point of water for more than two years – is located in high latitude and high altitude sites. Ground ice can form at average temperatures of -2°C or colder. A large area of the Arctic is currently covered either totally by permafrost or discontinuous permafrost with an overlying active layer where plants can grow. The thickness of the permafrost layer can reach up to 700 m, in some areas even up to 1 500 m (Siberia).

Permafrost temperatures have increased in most regions since the early 1980s (high confidence), although the rate of increase has varied regionally. The temperature increase for colder permafrost was generally greater than for warmer permafrost (high confidence). Significant permafrost degradation has occurred in the Russian European North (medium confidence). There is medium confidence that in this area, over the period 1975-2005, warm permafrost up to 15 m thick completely thawed, the southern limit of discontinuous permafrost moved north by up to 80 km, and the boundary of continuous permafrost moved north by up to 50 km. Surface subsidence associated with degradation of ice-rich permafrost and changes in depth and extent of seasonally frozen ground occurred at many locations worldwide over the past two to three decades, but in others, e.g. in northern North America, there were but few significant trends.

A future retreat of permafrost extent with rising global temperatures is virtually certain. However, the projected changes in permafrost depend also on changes in snow cover. By the end of the 21st century, diagnosed near-surface permafrost area is projected to decrease by between 37% (RCP2.6) and 81% (RCP8.5) (medium confidence) (IPCC, 2013).

Drought, desertification and other forms of water scarcity

Droughts (for a limited period) and desertification mean water scarcity, increased wind erosion, possibly sand storms, as well as reduced water quality. Water scarcity can also occur with freezing.

At present, water scarcity due to freezing potentially affects more nuclear power plant sites than drought or desertification. It is likely to happen less frequently in the course of global warming.

Drought is defined as an extended period with deficiencies in water supply, surface or underground, in a specific region that can last for months or years. It occurs when an area receives consistently less-than-average precipitation. Triggers for the non-rain cases are above-average presence of high-pressure systems, transport of air masses with reduced water content, etc. Additionally, weather cycles such as the El Niño-Southern Oscillation or the North-Atlantic Oscillation are responsible for recurring droughts in specific regions. Further triggers are related to humans who can actively create local conditions favourable for droughts, such as excessive farming, deforestation, erosion. In many parts of the world, droughts are a normal recurring feature of the local climate, as in the Horn of Africa, or the western Sahel belt.

Consequences of droughts and desertification are enhanced wind erosion and sand storms, detrimental to surface materials and any moving parts not completely encapsulated. A further impact of droughts is the diminishing water quality due to reduced dilution of pollutants with lower water flows.

Only a few of the nuclear power plants are sited in regions currently prone to desertification. Recently constructed nuclear power plants in the United Arab Emirates, and possible new nuclear power plants in the Middle East and North Africa regions, are generally in areas where fresh water is scarce. However, they rely on cooling from abundant sources of water, namely the sea, though particular issues due to the relatively high surface temperatures need to be addressed to optimise efficiency and performance.

There is as yet low confidence in observed trends in drought or dryness (lack of rainfall) at a global level and in attributing changes to climate. On the regional scale, data are more robust: e.g. the frequency and intensity of droughts have likely increased in the Mediterranean and West Africa and likely decreased in Central North America and North-West Australia since 1950 (IPCC, 2013).

Regional to global-scale projections of soil moisture and drought remain relatively uncertain compared to other aspects of the water cycle. Nonetheless, under the RCP8.5 scenario, projections by the end of the century indicate that an increased risk of drought is likely (medium confidence) in currently dry regions linked to projected decreases in soil moisture on regional to global scales. Soil moisture drying is most prominent in the Mediterranean, south-west United States, and southern Africa, consistent with projected changes in the Hadley circulation and increased surface temperatures. Surface drying in these regions is likely (high confidence) by the end of the century under the RCP8.5 scenario. There is medium confidence that the inter-annual occurrence of zonally oriented South Pacific Convergence Zone events will increase, leading possibly to more frequent droughts in the South West Pacific (IPCC, 2013).

Changes relevant for nuclear safety

Nuclear power plants are licensed on the basis of specific assumptions regarding external hazards. Many of those affecting the nuclear system are directly or indirectly weather- and climate-related. While siting and operational efficiency are strongly influenced by average conditions, and only selectively by extreme events, it is extreme events that constitute or trigger safety hazards. Changes in climate frequently were not taken into account during licensing of the older plants. It must, however, be ascertained that the safety standards can be maintained throughout the lifetime of each plant in spite of observed climate change and that expected in the near future (Kastchiev et al., 2007).

As reports on nuclear power plant incidents indicate, a large number of weather- and climate-related hazards can be identified. On the one hand, nuclear power plants or their site can be directly affected; on the other, damages can be caused to related infrastructure or in the surroundings of the plant that in turn lead to incidents at the plant. All extreme events listed in Table 2.1 are influenced by climate change, but not all can be considered here, mostly for lack of information on future changes given by climate change models. But in most cases, focused, site-specific studies could generate information necessary for informed decision making regarding the necessity for or extent of adaptation measures, even if robust quantitative data on frequencies or amplitudes could be out of the scope of present climate research capacities.

Tropical cyclones

Tropical storms mainly impact structures near the coast with strong and gusty winds, debris projectiles, heavy rain, high waves and storm surges.

Tropical storms or cyclones are characterised by a low-pressure, low wind speed centre (the “eye”), strong and gusty winds outside the centre, and a spiral arrangement of clouds accompanied by thunderstorms and heavy rain. The term “tropical” refers to the origin of such storms, usually over tropical oceans and relatively warm water. In contrast to extra-tropical storms (e.g. European windstorms), they are fed by the evaporation of water from the ocean and the energy set free when condensation takes place as the air rises. Cut off from their primary energy source, they weaken rapidly after landfall. Tropical storms and cyclones can have diameters of 100 to 4 000 km.

Coastal regions are especially vulnerable to the damages caused by tropical storms and cyclones. Their impact lies not only in the strong and gusty winds, debris projectiles and heavy rain, but also in the generation of high waves, storm surges, and occasionally tornadoes. As a side effect of strong rain, local floods up to 40 km inland can also occur. The aftermaths of tropical cyclones can include infections and mosquito-borne diseases in flooded areas, power outages due to destruction of infrastructures, and other cascading effects with implications for the onset and speed of recovery measures.

Confidence remains low for long-term past (centennial) changes in tropical cyclone activity, after accounting for past changes in observing capabilities. However, since the 1970s, it is virtually certain that the frequency and intensity of storms in the North Atlantic have increased although the reasons for this increase are debated (IPCC, 2013). Studies project near-term increases in the frequency of category 4 or 5 tropical cyclones in the North Atlantic. For other areas and on a global scale, projections of trends in tropical cyclone frequency to the mid-21st century are few and, accordingly, confidence in the results is low. However, they agree in expecting intensifications of tropical cyclones (IPCC, 2013).

Extra-tropical storms

Extra-tropical storms can cause severe weather conditions, mainly strong, gusty wind and heavy precipitation. There is low confidence of large-scale trends in storminess over the last century and there is still insufficient evidence to determine whether robust trends exist in small-scale severe weather events such as hail or thunderstorms.

Overall, uncertainties regarding extra-tropical storms are high, especially as a shift in pressure patterns and therefore storm tracks are expected. Projections for extra-tropical cyclones in the North Atlantic and European regions indicate that under the RCP4.5 scenario, winter (December-January-February) shows an increase in the number of cyclones and in the mean wind speed of strong cyclones (90th percentile) in central Europe and a decrease in the Mediterranean and Norwegian Seas (Zappa et al., 2013). In summer (June-July-August), a reduction in the North Atlantic cyclones is projected. The Western Atlantic projections (Colle et al., 2013) for the cold season show a decrease in the track density of 5% to 10% (2009-2038) and 20% to 30% (2069-2098). For tracks along the eastern North American coast, an increase of 5-20% is projected. For deep (<980 hPa) storms, a decrease of 10% is projected for the western Atlantic, and an increase of 10-40% for the East Coast.

Thunderstorms and lightning

Thunderstorms form through the rapid upward movement of warm and moist air. They can be induced by topography, fronts or by warm and moist air masses. They are characterised by the presence of lightning and thunder. Coming along with thunderstorms are often strong winds, heavy rain, snow, sleet, hail, or, depending on the conditions, no precipitation at all. Furthermore, tornadoes can form in context with thunderstorms. Damages resulting from thunderstorms can include flash floods, tornadoes, mud slides, downburst winds and large hailstones, deadly projectiles, or damages caused by lightning (power outages, wildfires).

Thunderstorms are generally of too small a scale to be resolved by global or regional climate models, but large convective available potential energy (CAPE) and deep tropospheric wind shear characterise large-scale environments in which thunderstorms form, and they can be analysed in models.

Currently, nuclear power plants, especially those located in the south-east of the United States, are prone to thunderstorms with more than 60 thunderstorms per year on average. But half of the other nuclear power plant sites also experience more than 20 thunderstorms per year.

Conditions that favour thunderstorms have increased for parts of the United States east of the Rocky Mountains as Trapp et al. (2009) reports, but future changes show statistical significance only at the end of the 21st century under high forcing scenarios. For Europe, the number of days that favour thunderstorms are expected to increase (Marsh et al., 2009). In general, results indicate a trend towards environmental conditions favouring thunderstorms of greater intensity. However, the small number of studies does not allow an assessment of the robustness of this result.

Lightning is an electrostatic discharge between electrically charged regions equalising themselves through a lightning flash. Thunderstorms frequently trigger lightning, but additional factors influencing distribution and strength are the surface elevation, latitude, wind, relative humidity, and others. Dust storms, volcanic eruptions, and forest fires can also be accompanied by lightning. Experience shows that electricity transmission infrastructures and electronic equipment are particularly vulnerable to lightning, with potentially severe consequences. Therefore, lightning is very relevant for nuclear safety.

The distribution of global lightning strikes shows that they occur most frequently in the tropics in agreement with the distribution of thunderstorms. In the absence of more data there is only low confidence in trends of small-scale weather events. In the future, the frequency of lightning could increase by 10% for each degree of global warming as a consequence of more intense thunderstorms (Price, 2009). On this basis, a global surface temperature rise of 4°C by the end of the 21st century under the RCP8.5 pathway would imply an increase in the frequency of lightning strikes by 40% on average.

Fluvial floods

A combination of all or some of the following factors can produce fluvial floods: heavy or continuous precipitation, rapid run-off and insufficient buffer areas for water. In addition, dam failure or reduced conveyance because of ice jams or landslides can cause floods. All these factors are influenced by climate change, but most of them are also significantly impacted by land use and infrastructures.

Precipitation will continue to increase significantly in some parts of the world (e.g. northern Europe), but strong showers could increase even in areas where overall precipitation trends are negative. The repeated or longer periods of precipitation may be induced by increasingly persistent flow patterns as have occurred in the last decade – possibly a consequence of the amplification of the Arctic Oscillation (see section above on extreme events). Such situations lead to high soil moisture or even saturation, an important factor causing floods due to reduced buffer capacity of the soil. In mountainous areas, global warming causes the snow line to move upward, which means that less precipitation is buffered as snow in higher elevations, causing more rapid run-off.

In northern and central Europe, the western Mediterranean region and eastern Asia, recent floods very likely did not exceed those of the last five centuries, while there is medium confidence that in the Near East, India, central North America, recent large floods are comparable or surpass historical floods in magnitude and/or frequency.

Projections of fluvial flooding under RCP8.5 show significant changes in the probability for floods by the end of the 21st century. For nuclear power plant-relevant areas in Brazil, north India and eastern China, the return period of a 100-year flooding event ranges between 5 and 25 years; for the western central United States, the projected return period lies between 25 and 75 years; for the southern European region, the return period increases to between 125 and 250 years.

Coastal floods

Extreme sea level events (i.e. coastal flooding, storm surge, high water events) are caused mostly by large storms, especially in combination with high tide, although any low-pressure system offshore with associated high winds can cause a coastal flooding. There is low confidence of any trend or long-term change in extra-tropic storm frequency or intensity (IPCC, 2007 and 2012). Nevertheless, water level extremes (as annual maximum surge, annual maximum surge at high water, monthly mean high water level, changes in number of high storm surge events, changes in 99th percentile events, etc.) tend to increase as a consequence of global or temporal local (El Niño-Southern Oscillation, North Atlantic Oscillation, etc.) sea level rise.

Global analyses are limited (see Lowe et al., 2010 for a review), but a global analysis of tide gauge records from the 1970s onwards finds that the magnitude of extreme sea level events has increased in all regions studied since then (Woodworth and Blackman, 2004; Menéndez and Woodworth, 2010; Woodworth et al., 2011). The height of a 50-year flood event has increased up to more than 10 cm per decade since 1970 – a combined effect of storms, global sea level rise and regional and local factors. The most significant storm-related increases were found in the south-east United States, the Western Pacific, Southeast Asia, and a few locations in Northern Europe (IPCC, 2013).

The susceptibility of coastal regions to inundation and erosion depends on various physical, geomorphologic and ecosystem factors. The majority of flooding events are found in low-gradient shores and low-lying coastal regions (Woodruff et al., 2013). Therefore, the analysis of exposure to coastal inundation must take into account the elevation of shorelines, impacts by tropical cyclones and extra-tropical cyclones as well as relative sea level rise. A quick assessment shows that coastal inundation threats affect the Gulf of Mexico, coastal areas in Brazil, the Chinese coast of the Yellow Sea and the Indian coast on the Bay of Bengal. In Europe, the western North Atlantic coast is affected in the long run.

Tornadoes

Tornadoes typically form as a visible condensation funnel with narrow ends towards the surface. They can stretch more than 3 km across, travel for more than 100 km with wind speeds ranging from 170 km/h to more than 480 km/h. Tornadoes occur on every continent except Antarctica. In the United States, about 1 200 tornadoes occur per year, significantly more than in any other country. This is due to a unique geographic situation that allows cold, dry air from the north to meet with warm, moist air from the Gulf of Mexico. Other areas with frequent tornadoes are Bangladesh, South Africa, parts of South America, as well as portions of Europe, Australia and New Zealand and far eastern Asia. In Europe, most tornadoes are small, less intense and cause minor damage. Tornadoes can occur any time during the year, although they are more likely in the warmer seasons. They only occur during daytime, mostly in the late afternoon. Nearly all operating and planned nuclear power plants are located in areas where tornadoes occur.

Studies on future trends are based on changes in the meteorological conditions making tornadoes possible or likely. An increase in the sea surface temperature of a source region (e.g. the Gulf of Mexico and the Mediterranean Sea) increases atmospheric moisture content and this can fuel an increase in severe weather and tornado activity, particularly in the cooler season. Some evidence also suggests that the Southern Oscillation is weakly correlated with changes in tornado activity, as well as the phase of El Niño or La Niña. Shifting of the jet stream and the larger weather patterns may affect tornado frequencies. The climate-tornado link is confounded by the forces affecting larger patterns and by the local, nuanced nature of tornadoes. Although it is reasonable to suspect that global warming may affect trends in tornado activity, any such effect is not yet clearly identifiable because of the complexity and local nature of the storms and database quality issues.

Summary of possible effects of climate change on nuclear power plants

This chapter provides insight into some of the most relevant climate change phenomena that are likely to occur depending on climate change projections. Some of these phenomena can affect the performance of nuclear power plants – for example temperature increases in the cooling water sources. For such phenomena, adaptation measures can be developed, as discussed later in this report: improved heat exchangers such as condensers to compensate for the decreased efficiency, or modified water intakes. Other phenomena – typically extreme weather events – can lead to outages, not necessarily because of direct damage to the nuclear power plants (which are very robust infrastructures) but to the surrounding environment, be it the source of cooling water, or the grid infrastructure. Consequences for the safety of the nuclear power plant have to be assessed by the regulator and the operator – and examples are given in this report where specific measures have been taken to improve the resilience and safety of nuclear power plants against extreme weather events.

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Chapter 3. **Impacts of extreme weather events on nuclear power plant operation**

Introduction

Extreme weather can cause interruptions and rare cases power outages at nuclear power plants. According to projections from the Intergovernmental Panel on Climate Change (IPCC, 2013), climate change is projected to change the duration, intensity, location and other features of extreme climate events that will involve additional weather hazards for nuclear power plant operations in the future. According to Linnerud et al. (2011), climate change can reduce the thermal efficiency of nuclear power plants through increased ambient temperatures and increased frequency of disruptions as a warmer climate will lead to higher temperatures than permissible in water bodies providing water for cooling. This problem can be further compounded for nuclear power plants by reduced availability of water due to droughts for normal operation.

Extreme weather impacts all thermal power plants and even more so nuclear power plants (Rousseau, 2013). Linnerud et al., using a panel dataset from 1995 to 2008 for seven European countries, found that a rise of mean ambient temperature by 1°C reduces the supply of nuclear power by approximately 0.5% by reducing the plant's thermal efficiency. Moreover, lack of access to cooling water during droughts and heatwaves may reduce nuclear power plant operations by 2% per degree Celsius rise in the ambient temperature.

Another study compiled by the Asian Development Bank (ADB, 2012) suggested that extreme events and climate variability such as thunderstorms, higher air temperature and sea level rise, could impact nuclear power plants' cooling systems, increase risks of power outages and lower the nuclear power plants' generation efficiency output.

In a more recent study commissioned by the European Union (EU), Zerger et al. (2013) used data from the international reporting system (IRS) for operating experience – a joint operation by the International Atomic Energy Agency (IAEA) and the OECD – and concluded that the main external phenomenon affecting nuclear power plant operations is extreme weather conditions, such as low or high ambient temperature, storms (typhoons, hurricanes) and intense rainfall.

This chapter explores the impacts of extreme weather events on the operation of nuclear power plants worldwide in recent years.

Data and method

This analysis is based on data taken from IAEA's Power Reactor Information Systems (PRIS) covering the period 2004-2018 (though for 2018 the information available is not yet complete for the whole year, it serves the purpose of observing its mayor trends). Developed over four decades, PRIS is a comprehensive database of nuclear power plants worldwide since 1970 and contains information that relates to nuclear power reactors in operation, under construction or those being commissioned. PRIS is a data collection of nuclear power plants' performance, including outages and other detailed information, since the start of their commercial operation. It is based on input from nuclear plant operators.

Two types of information are included in PRIS: plant-specific data (design) and plant performance data that include information on outages. Outage data in PRIS are classified into 19 major categories specifying the direct causes of outages (see Table 3.1). Category N encompasses all outages caused by a broad range of environmental factors.

Table 3.1. **Direct causes of outages broken down by major category**

Plant equipment failure	A
Refuelling without maintenance	B
Inspection, maintenance or repair with refuelling	C
Inspection, maintenance or repair without refuelling	D
Testing of plant systems or components	E
Major backfitting, refurbishment or upgrading activities with refuelling	F
Major backfitting refurbishment or upgrading activities without refuelling	G
Nuclear regulatory requirements	H
Grid failure or grid unavailability	J
Load following	K
Human factor-related	L
Government requirement or court decision	M
Environmental conditions	N
Fire	P
External restrictions on supply and services	R
Fuel management limitations	S
Off-site heat distribution system unavailability	T
Security and access control and other preventive shutdown due to external threats	U
Others	Z

Source: IAEA, 2005: p. 54.

In order to understand the impact of extreme weather on nuclear power plant operations, a coding system was developed and implemented in order to tally environmental outages due to different causes. Table 3.2 presents a first set of all environmental causes and a second set of weather-related causes.

Table 3.2. **PRIS data coded in two categories – environmental and weather-related causes**

All environmental causes

Warm cooling water (above environmental regulatory thresholds)	0
Cold cooling water (problems due to frazil ice or ice formation)	1
Flood	2
Low water level	3
Lightning/thunderstorm	4
Typhoon/hurricane/wind storms	5
Other weather-related causes	6
Non-weather environmental: pollution, wildlife	7
Unspecified environmental restrictions	8
Earthquake/tsunami	9
Seasonal variation of cooling water temperature (CWT)	10

Table 3.2. **PRIS data coded in two categories – environmental and weather-related causes** *(cont'd)*

Weather-related causes

Warm cooling water (issue: temperatures above environmental regulatory thresholds)	0
Cold cooling water (issue: problems due to frazil ice or ice formation)	1
Flood	2
Low water level	3
Lightning/thunderstorm	4
Typhoon/hurricane/wind storms	5
Other weather-related causes	6
Seasonal variation of cooling water temperature (CWT)	10

Source: IAEA PRIS database.

Environmental causes

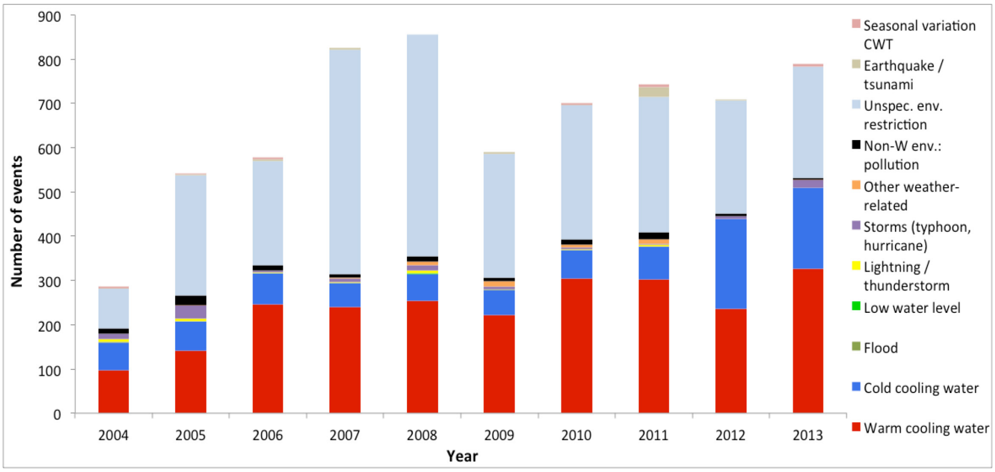
As the first step of this analysis, all N-coded events were filtered from PRIS for a more detailed analysis. The results are presented in this section.

The figures in this section clearly demonstrate the limitations of the PRIS data set for analysing nuclear power plant outages due to environmental causes in general and weather-related causes in particular. Unspecified environmental restrictions represent a significant share in all aspects of the outages examined (number of events, outage duration, energy lost), accounting for more than half of the data points in several years of the time period investigated. It is impossible to tell what fractions of such events were due to which environmental cause and how many of them were weather-related. Therefore, such events are included in the charts but not discussed.

Time series

Figures 3.1 and 3.2 show that non-weather environmental factors account for a small *number of outages* in nuclear power plants. Weather-related events, especially warm cooling water followed by cold cooling water or non-specified cooling water issues, dominate the picture. However, it is worth noting that for the 2014-2018 period, warm and generic cooling water events have been less frequent, with the unspecified environmental events explaining most of the environmental events. The number of events did not exceed 1 000 in any year in this period.

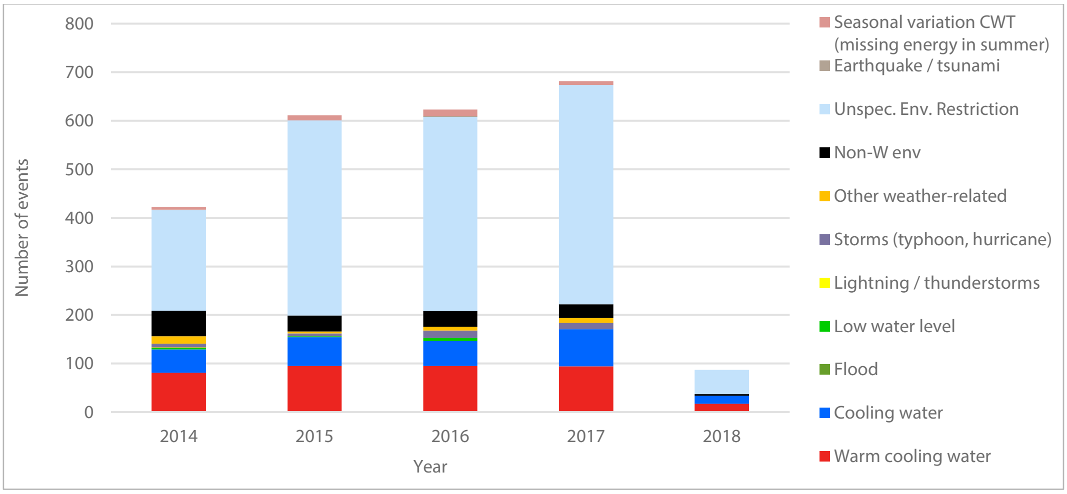
Figure 3.1. **Number of outages during 2004-2013 due to all environmental causes**



Note: CWT: cooling water temperature; Non-W: non-weather.

Source: Based on the IAEA PRIS database.

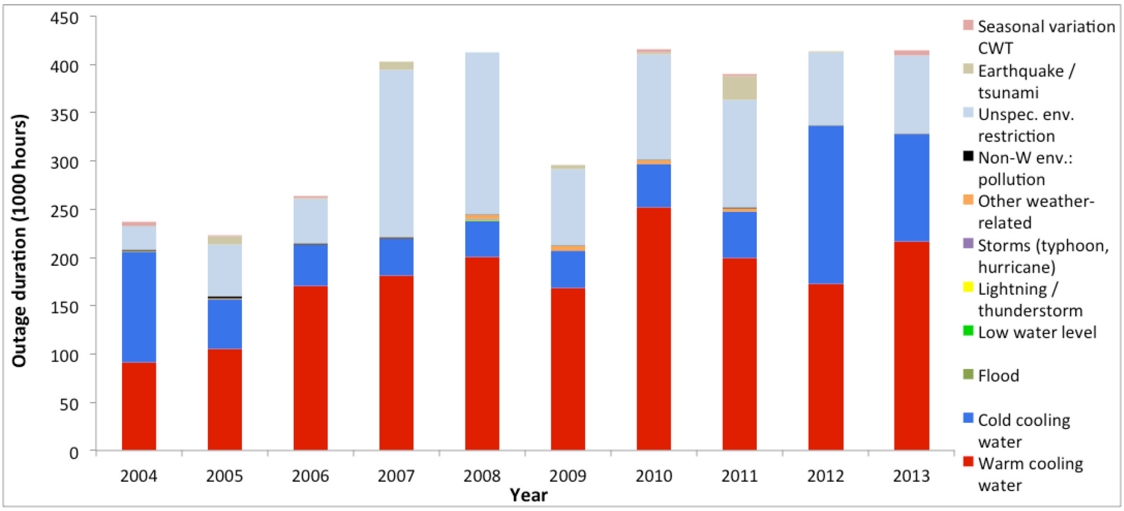
Figure 3.2. **Number of outages during 2014-2018 due to all environmental causes**



Source: Based on the IAEA PRIS database.

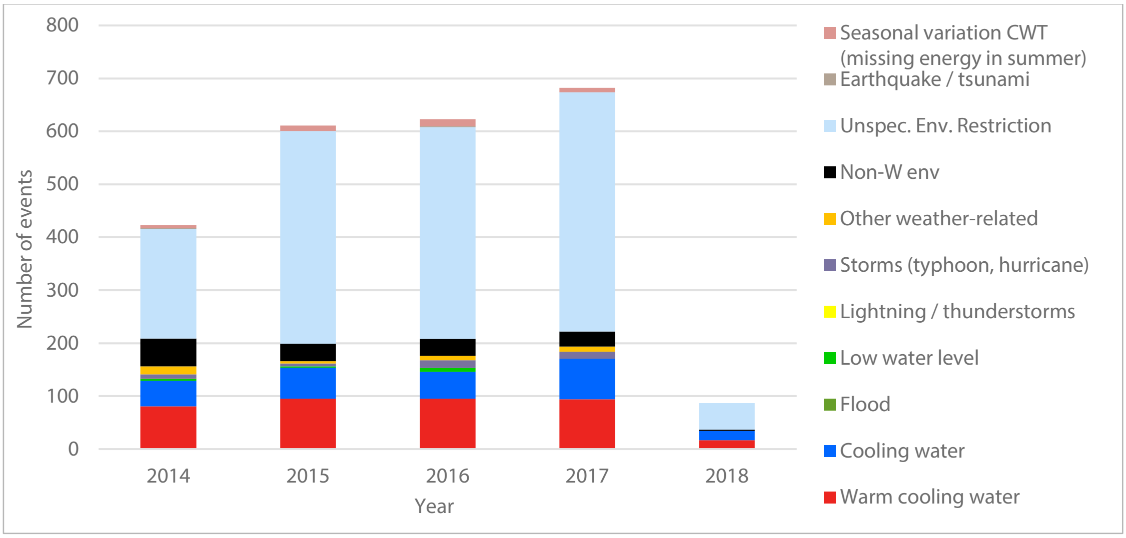
Turning to the length of the outages, Figures 3.3 and 3.4 show the annual *total duration of nuclear power plant outages* recorded during the 2004-2013 period. Non-weather environmental factors caused an almost negligible outage time. Similarly to the number of outage events, the main factors determining the total length of outages were warm cooling water, cold cooling water and unspecified cooling water issues. Warm cooling water caused 826 000 outage hours and cold cooling water caused 597 000 hours of outages during the 2003-2014 period.

Figure 3.3. **Outage durations during 2004-2013 due to all environmental causes (1 000 hours)**



Source: Based on the IAEA PRIS database.

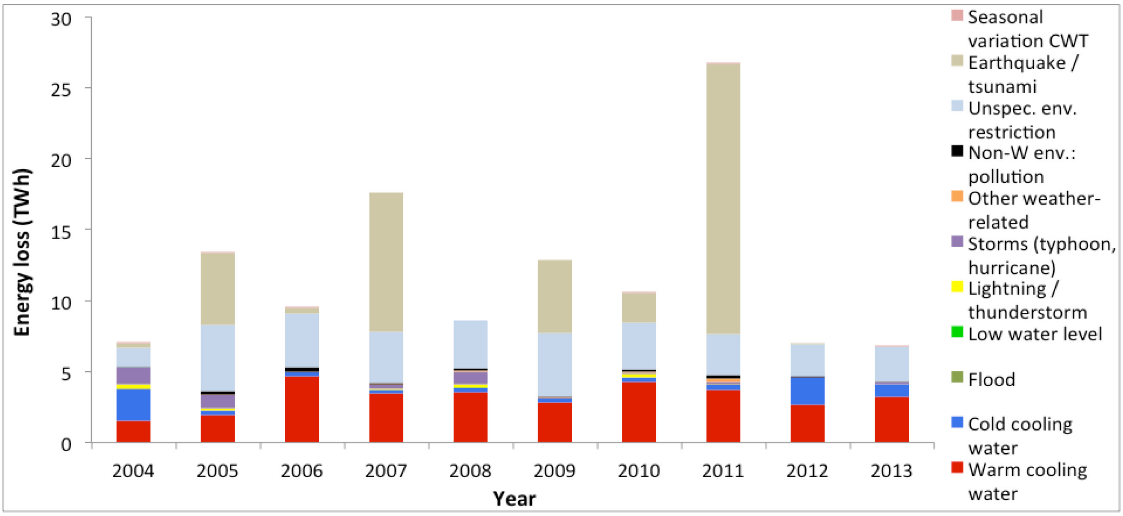
Figure 3.4. **Outage durations during 2014-2018 due to all environmental causes (1 000 hours)**



Source: Based on the IAEA PRIS database

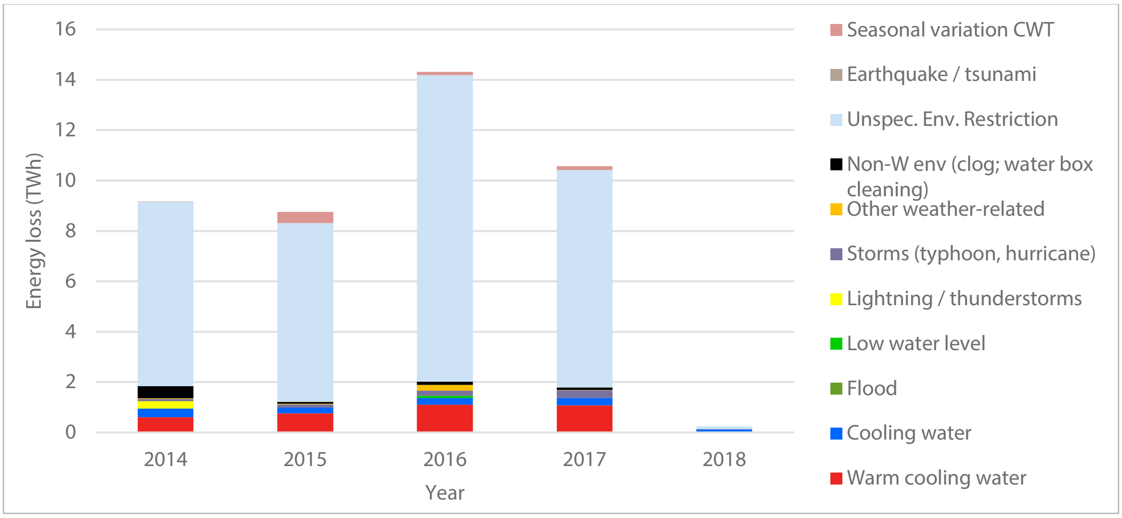
Figures 3.5 and 3.6 show the energy lost (electricity not produced) in outages due to environmental causes. The largest *energy losses* (in TWh) were caused by earthquakes and tsunamis – which are not climate-related events. In 2011, the Great East Japan Earthquake (magnitude of 9.0 M_W) and an extremely high tsunami (run-up heights up to 39 metres) hit the eastern coast of Japan and caused extensive damage to the Fukushima Daiichi nuclear power plant. The implications of this accident on the energy loss are clearly visible in Figure 3.5 (year 2011).

Figure 3.5. **Energy loss in 2004-2013 due to all environmental causes (TWh)**



Source: Based on the IAEA PRIS database.

Figure 3.6. **Energy loss in 2014-2018 due to all environmental causes (TWh)**

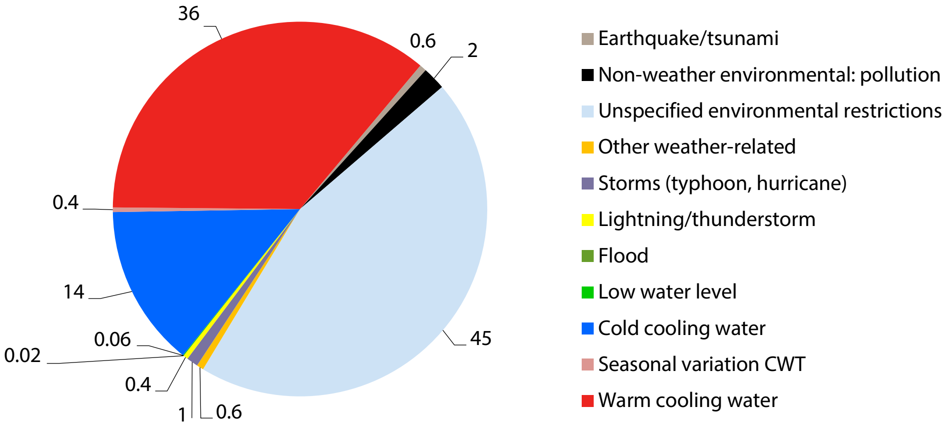


Source: Based on the IAEA PRIS database.

Share of causes in all environmental outages

Figure 3.7 provides a clear reminder of the limitations of the outage database. The causes of environmental restrictions are not specified for almost half (45%) of the outages. Non-weather related factors caused a small fraction (about 2.6%) of all outages between 2004 and 2013.

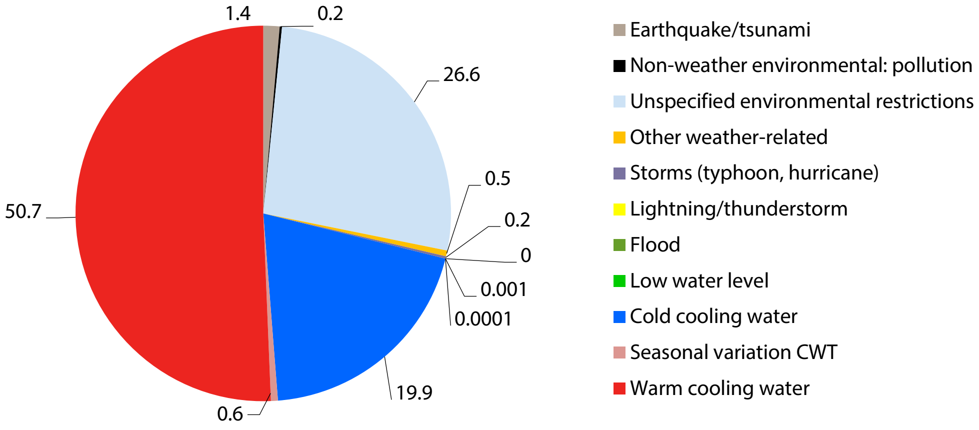
Figure 3.7. **Distribution of outages during 2004-2013 due to all environmental causes (%)**



Source: Based on the IAEA PRIS database.

The situation is somewhat different in the *distribution of outage durations*. A little more than a quarter of the total outage duration in the ten-year period was caused by unspecified environmental reasons. Earthquakes were the main non-weather reasons, accounting for about 1.4% of the aggregated outage duration globally.

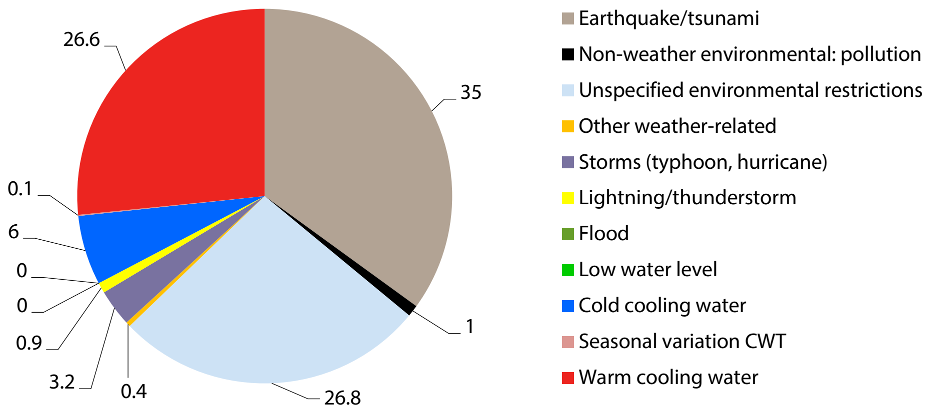
Figure 3.8. **Shares of environmental causes in total environmental outage duration in the period 2004-2013 (%)**



Source: Based on the IAEA PRIS database.

In contrast to what Figures 3.7 and 3.8 show, earthquakes and tsunamis account for 35% of the *energy loss* resulting from all outages due to environmental reasons in the period 2004-2013, as shown in Figure 3.9. This is partly due to the 2011 Fukushima Daiichi Nuclear Power Plant accident, partly due to earthquakes that affected other nuclear power plants in this period.

Figure 3.9. **Distribution of environmental causes of energy loss at nuclear power plants between 2004 and 2013**



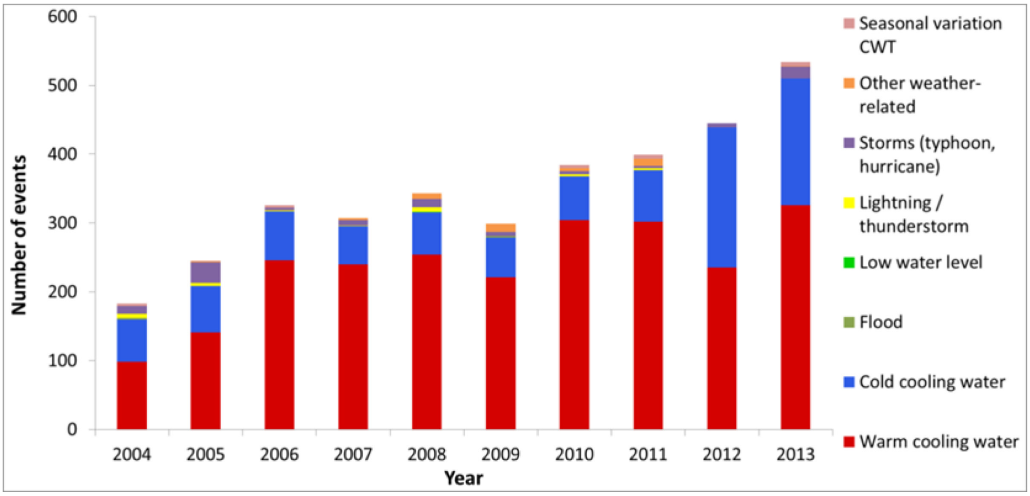
Source: Based on the IAEA PRIS database.

Weather-related causes

Time series

Reducing the scope of our assessments to *outage events* for which weather-related causes are known, temperature anomalies of cooling water (too hot or too cold) dominate the picture. It is interesting to observe that in 2013, the fourth warmest year on record globally, cold cooling water was the reason for a much larger number of events than in earlier years in the decade analysed, except 2012. The total number of outages due to weather-related causes in the 2004-2013 period was 2 690.

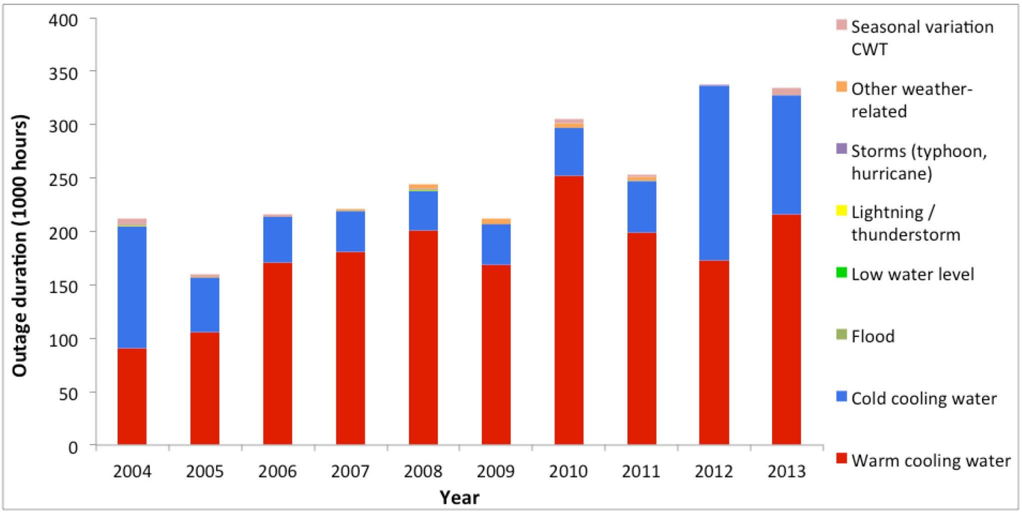
Figure 3.10. **Number of outage events in 2004-2013 due to weather-related causes**



Source: Based on the IAEA PRIS database.

The annual depiction of *outage duration* is similar (see Figure 3.11). Warm cooling water was the main factor responsible for the duration of outages each year in the 2004-2013 period while the second main factor was cold cooling water.

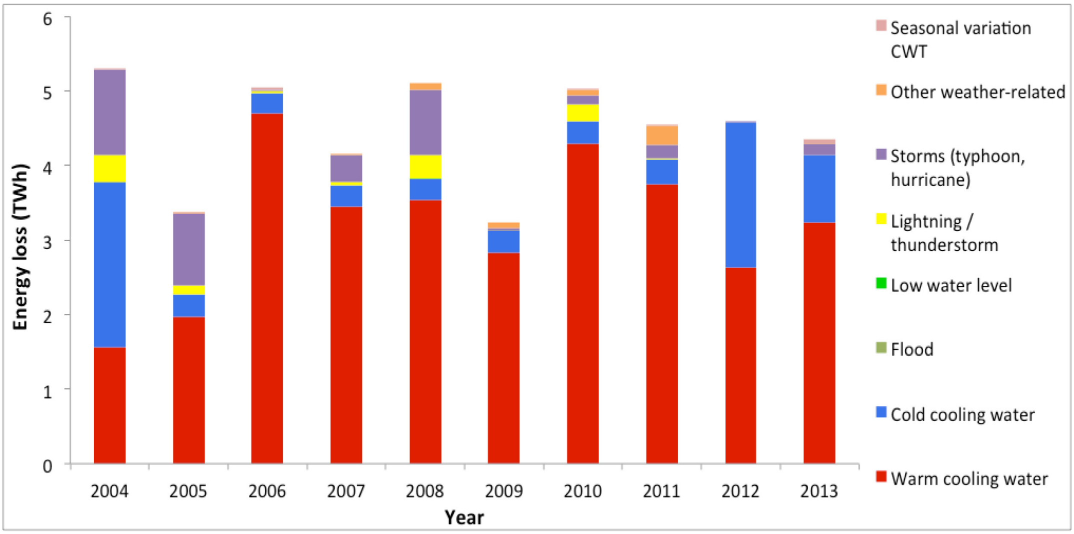
Figure 3.11. **Outage duration in 2004-2013 due to all weather-related causes (1 000 hours)**



Source: Based on the IAEA PRIS database.

Warm cooling water was also the dominant cause of *energy losses* among the weather-related causes. In the decade between 2004 and 2013, a total of 44.74 TWh of electricity was not produced by nuclear power plants because of weather-related factors. During that period, nuclear power plants produced over 25 000 TWh, so the outages from weather-related events only account for 0.17% of that overall production.

Figure 3.12. **Energy loss in 2004-2013 due to all weather-related causes (TWh)**

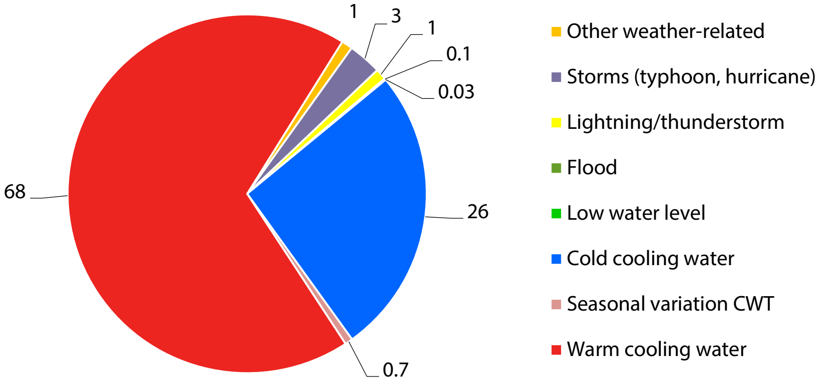


Source: Based on the IAEA PRIS database.

Share of causes in all outages

Aggregating the *number of all outages* due to weather-related causes over the ten-year period between 2004 and 2013, Figure 3.13 shows that more than two-thirds of all events were caused by warm cooling water and more than a quarter by cold cooling water. Of the remaining causes, storms (3%) and lightning (1%) were the most important causes.

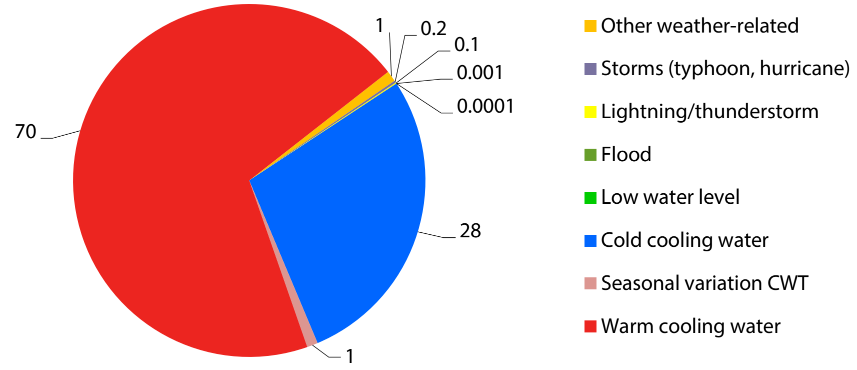
Figure 3.13. **Share of outages in 2004-2013 due to all weather-related causes**



Source: Based on the IAEA PRIS database.

The shares in *total outage time* caused by temperature anomalies (too warm or too cold cooling water) were comparable, albeit somewhat higher, to the other outage events, indicating the more persistent nature of temperature anomalies compared to the impacts of episodic events (storms and lightning) after which nuclear power plants can return to full capacity operation sooner (see Figure 3.14).

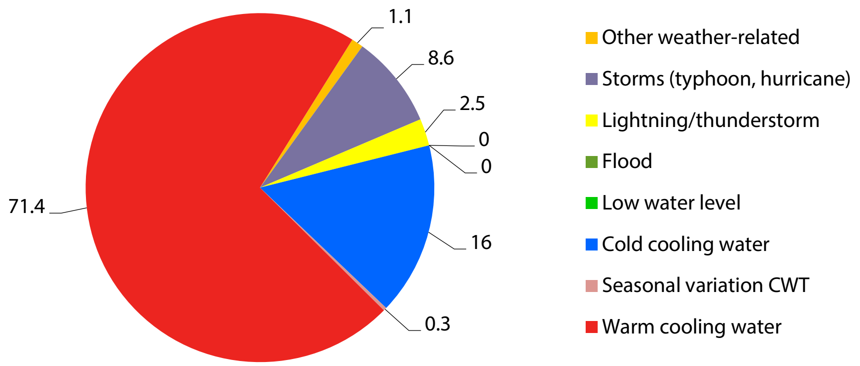
Figure 3.14. **Distribution of outage duration due to various weather-related causes during 2004-2013**



Source: Based on the IAEA PRIS database.

The distribution of causes of *energy loss* from outages triggered by weather-related events is more diverse. While warm cooling water obviously dominates the picture, the shares of energy losses due to storms and lightning are much higher than the corresponding shares of outage events or in their duration. One possible reason is that these events, and also cold cooling water, affect large reactors more often than small ones, leading to larger energy losses even in shorter outage duration.

Figure 3.15. **Shares of specific causes in all energy losses due to weather-related causes between 2004 and 2013**



Source: Based on the IAEA PRIS database.

Conclusion

Considering the whole spectrum of environmental causes for outages in nuclear power plants in the period 2004-2013, outages related to “warm cooling water” (above environmental regulatory thresholds) and “cold cooling water” (with frazil ice or ice formation) represent the largest shares of outages in all three indicators (numbers, duration and energy loss). Warm cooling water accounts for 50.7% of all outages due to environmental causes and cold cooling water accounts for 19.9%. Earthquakes and tsunamis (38%) – which are not climate related – and warm cooling water (26.6%) are the two main environmental factors for energy loss during 2004-2013.

Focusing on the duration of weather-related outages, warm cooling water and cold cooling water were the two main factors during the period 2004-2013. Warm cooling water is responsible for nearly 70% and cold cooling water for 26% of weather-related outages. Energy loss due to weather-related events during the same period was caused by several factors: warm cooling water, cold cooling water, storms and lightning. However, weather-related outages represent only a loss of 0.17% of the total electricity production during this period, so the vulnerability of nuclear power plants seems limited.

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Chapter 4. **Energy-water nexus – a focus on cooling issues (drought and heatwave events)**

Introduction

Increasing amounts of greenhouse gases in the atmosphere are predicted to result in more frequent and severe droughts, heatwaves and severe weather in the coming decades. In order to cope with these expected events, a careful and encompassing analysis of the needs for water for all uses is critically needed. As described in Gleick, P.H (1993), the earth's inventory of water (H_2O) is predominantly contained in the oceans, and only 3.5% is freshwater. That freshwater is, in turn, predominantly stored in glaciers and underground, with only 140 000 km^3 (0.4% of total H_2O) contained on the surface and in the atmosphere. The distribution of surface and atmospheric water indicates that about 30% is not available for use in cooling.

A short summary of the annual flows in the global water cycle is shown in Table 4.1. Note that the flow of rivers into the oceans is a relatively small fraction of the total cycle and that about two-thirds of the precipitation falling on land evaporates and does not flow via the rivers into the oceans.

The primary conclusion from these two tables is that, in considering the needs for water in power generation, one has to look beyond the traditional river sources, which are incidentally the sources most susceptible to drought and most widely used for other domestic and agricultural purposes.

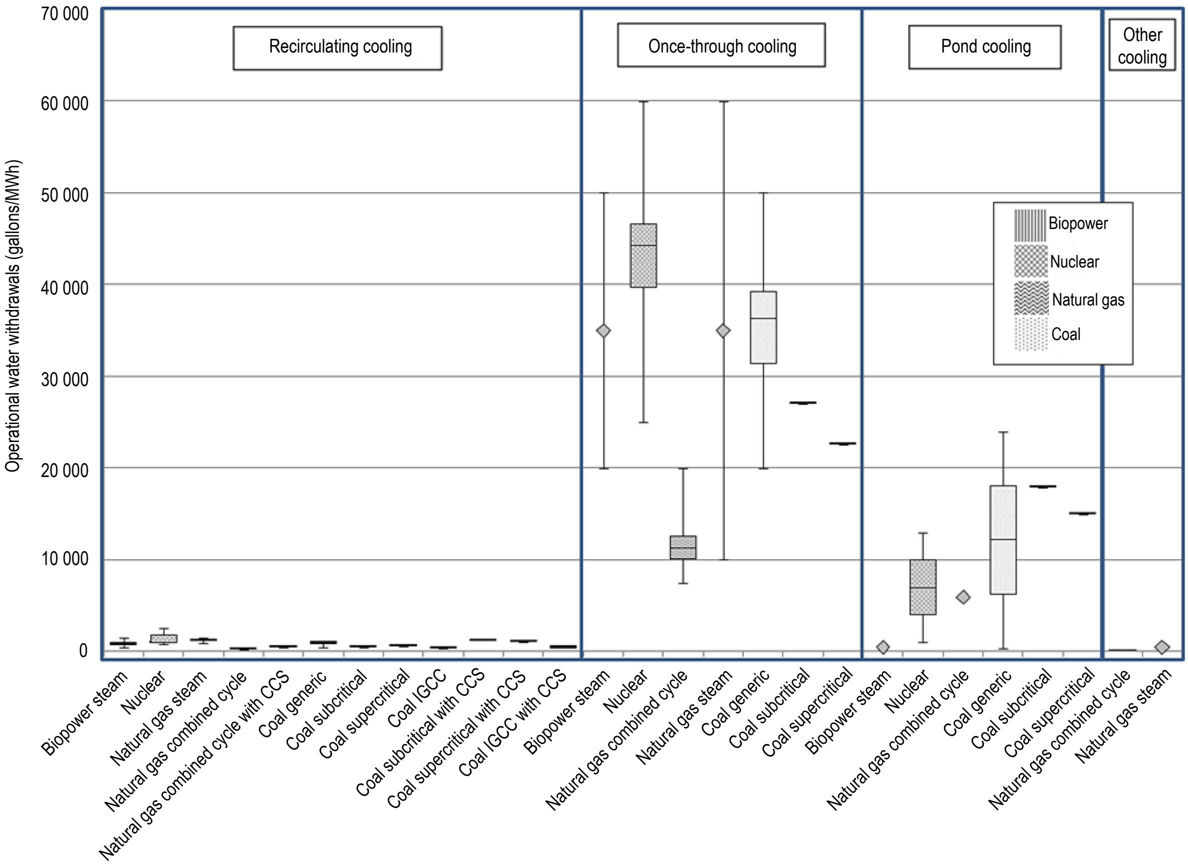
Table 4.1. **Global water cycle**

	Flow (km^3/year)
Global precipitation	500 000
Precipitation on oceans	391 000
Precipitation on land	109 000
River flows into oceans	35 000

Source: Based on Baumgartner, A. and E. Reichel (1975).

Many industrial processes require the disposal of heat at temperatures below 100°C. The generation of electricity has the largest needs for disposing of low-grade heat. In a global sense, the ultimate destination of this low-temperature heat is space via blackbody radiation from large areas of the earth's surface. Thus, the purpose of the air, water vapour or cooling water is to spread that low-temperature heat over large areas. Obviously water, especially freshwater, is vital for the maintenance of life, for agriculture, for other industrial processes and as a medium for transportation and material transport. Thus, the increasing frequency of droughts and heatwaves will result in sharp competition for supplies of freshwater. In planning adaptation to a warming climate in the coming decades, it is therefore imperative to reduce the currently very large uses of freshwater for power generation, either by more effectively using existing supplies of freshwater or by using air or seawater as a coolant.

Figure 4.1. **Operational water withdrawals for electricity generating technologies**



IGCC = integrated gasification combined cycle; CCS = carbon capture and storage.

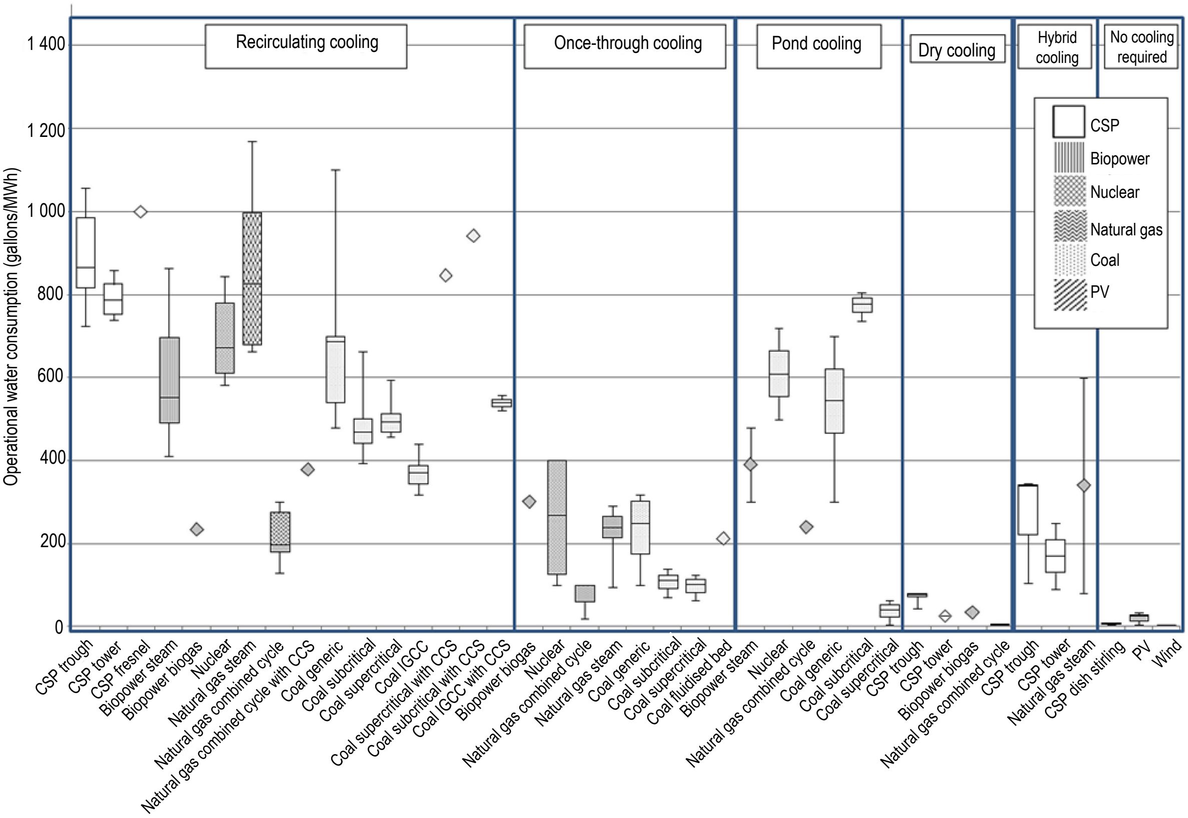
Note: Whisker ends represent maxima and minima. Upper and lower ends of boxes represent 75th and 25th percentile, respectively. Horizontal lines in boxes represent medians.

Source: Macknick et al. (2011).

Two parameters for comparing water use in electricity generation are withdrawal and consumption. Withdrawal is the volume of water removed from a river, lake, ocean or other water source per megawatt electrical per hour (MWe/h) of electricity generated to be used for cooling. Whether the water is returned to the body of water or lost to evaporation is not considered. Consumption is the amount of water per MWe/h lost to further use due to evaporation or salt loading. A comparison of water withdrawal and consumption for various generating technologies is shown in Figures 4.1 and 4.2.

Note that the vertical scales in the two figures differ by a factor of 50, showing that quantities withdrawn greatly exceed quantities consumed. Presuming that water used in once-through cooling will be returned to the river or lake, with a large part available for other uses, the critical parameter in judging electricity generation technologies would seem to be consumption rather than withdrawal. By this standard, as can be seen in Figure 4.2, once-through cooling has generally lower consumption than recirculating cooling.

Figure 4.2. **Operational water consumption factors for electricity generating technologies**



IGCC = integrated gasification combined cycle; CCS = carbon capture and storage; CSP = concentrating solar power; PV = photovoltaics.

Note: Whisker ends represent maxima and minima. Upper and lower ends of boxes represent 75th and 25th percentiles, respectively. Horizontal lines in boxes represent medians.

Source: Macknick et al. (2011).

Cooling systems

Cooling is an integral process of the power conversion cycle (usually the Rankine steam cycle), the method by which thermoelectric plants generate energy. In a steam cycle, a closed loop of water is transformed into steam in a boiler, with heat provided by concentrated solar radiation, combustion of a fossil fuel, or nuclear fission. The steam then expands through a turbine which, in turn, drives a generator to produce electricity. Before returning to the boiler to restart the cycle, the steam must be condensed to liquid state. This is accomplished by the action of the condenser, through the tubes of which cooling water passes and removes heat from the steam. For a fixed condenser surface, the cooler the water, the lower the turbine back pressure and the higher the efficiency of the plant. The efficiency of thermoelectric plants operating with higher cooling temperatures (for instance in the Middle East region) can be improved by installing larger heat exchanger equipment, which of course increases the cost of the plant.

Water also plays an important safety role as it is needed to cool other components of nuclear power plants, as discussed below.

Withdrawal constitutes all water extracted from the environment, whereas consumption refers to that portion of withdrawal that is either evaporated or becomes polluted and hence is not promptly returned to the source in clean, liquid form. It is necessary to distinguish between these two categories when examining water use in thermoelectric power plants, as they can vary greatly in magnitude and have different environmental and economic impacts. Water for cooling is characterised by withdrawal and consumption rates that depend on the type of cooling system employed (WNA, 2011). These rates can represent very large shares of available freshwater resources. In the United States, thermoelectric power generation accounts for about 3% and 40% of freshwater consumption and withdrawal, respectively (Wolfe et al., 2009).

At present there exist three major types of cooling systems for thermoelectric plants:

- once-through cooling;
- wet closed-cycle cooling;
- dry cooling.

Once-through cooling consists of drawing water from an external source (such as a river, lake or sea), which is used in the condenser and returned to the source at a higher temperature. Wet closed-cycle systems reuse water which, after passing through the condenser, is itself cooled in either a cooling tower or a pond. When a tower is used, the water is pumped to the top and sprayed into the structure, becomes exposed to an updraft (either naturally or mechanically induced) and is cooled through evaporation. In contrast, ponds remove heat from cooling water without direct exposure and ultimately dissipate this energy by evaporation of the pond water. Dry systems transfer heat to air, either from the steam itself by means of an air-cooled condenser (direct dry cooling) or by means of cooling water using a cooling tower (indirect dry cooling).

As a result of increasing environmental, aesthetic and regulatory concerns (particularly in the United States), hybrid systems employing some subset of the above technologies in combination are becoming more common. One hybrid system, termed parallel wet/dry cooling, consists of a direct dry and a wet closed-cycle system operating in combination so as to reduce water consumption. Another, known as plume abatement cooling, involves a wet closed-cycle system where exhaust generated by the towers is condensed (and hence both eliminated and retained) by indirect dry cooling (Micheletti and Burns, 2002).

A hybrid system of particular interest consists of once-through cooling with a so-called "helper" tower. Such tower offers the flexibility of cooling a power plant using different modes of operation, as dictated by climatic conditions. Specifically, available modes consist of the following (Couture, 2010):

- In "recirculation" or "hybrid" mode, a portion of the water cooled in the tower is discharged and must be compensated for by withdrawal.
- In "discharge" or "helper" mode, all water cooled in the tower is discharged to the source.
- In closed-cycle mode, water intake is limited to make up and no water is discharged, except for the occasional blow-down[1] necessary to maintain the quality of the cooling water. In some areas, during hot humid weather, when the wet bulb temperature is at its peak and evaporation is constrained, closed-cycle operation may not be possible when the plant is at full power. In that case, the plant must either reduce power or change cooling from closed-cycle to hybrid mode.
- In once-through mode, the cooling water returning from the condenser bypasses the tower altogether and is discharged to the source directly. This mode of operation is necessary when the cooling towers are out of service.

The "recirculation/hybrid" and "discharge/helper" modes can be of great use in facilitating compliance with restrictions on thermal releases. Nuclear power plants such as Asco on the Ebro River in Spain (ANAV, 2012) and Vermont Yankee on the Connecticut River in the United States (Entergy, 2012) are equipped with towers and employ such modes on a seasonal basis for this purpose.

Figure 4.3 gives an overview of the type of cooling systems used at nuclear power plants in a selection of OECD member countries having varying geographic and climatic characteristics. Once-through cooling is the overwhelming system chosen in countries with plentiful access to sea or freshwater, whereas wet closed-cycle cooling tends to be used more often in countries not endowed with such resources. Dry cooling is not used in any of the selected countries.

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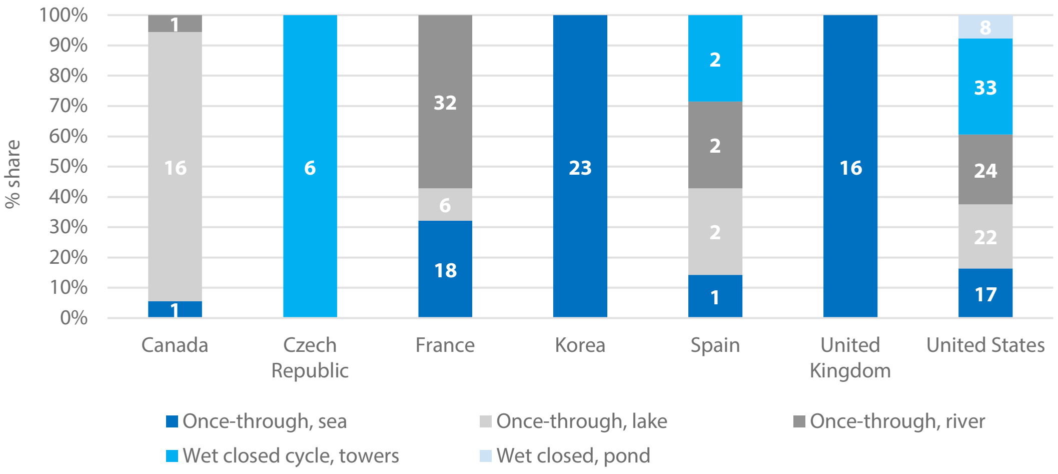
1. Blow-down refers to water released to reduce the concentration of impurities, which increases as a result of evaporation.

From an economic standpoint, the characteristics that determine the relative merits of cooling systems are cost and impact on plant efficiency. Once-through cooling holds the advantage in both areas, as its simple design involves minimal capital and operational costs, and the relatively low temperature of intake water contributes to high efficiency. In contrast, wet closed-cycle systems necessitate significant investment for the construction of towers or a pond, while consumption of electricity (to pump water and, in certain cases, to power draft-inducing fans) raises operational costs and reduces net efficiency and output capacity. The efficiency of these systems is further impacted by the fact that they are often unable to cool their water to a temperature comparable to that of withdrawal from a river, lake or sea (Enercon, 2003). Table 4.3 indicates the relative loss of electrical output for different choices of cooling technologies, taking once-through cooling as the reference. It is also worth mentioning the US Department of Energy study (DOE, 2008) which assumed that converting thermoelectric power (coal and nuclear) plants that use once-through cooling to closed-cycle cooling with towers would lead to an overall decrease of 4% nameplate capacity.

Figure 4.3. **Prevalence of operational nuclear reactor cooling systems**



Source: NEA, 2021.

Note that as mentioned earlier, the Spanish Asco units use once-through cooling on the river Ebro, but are also equipped with cooling towers.

Dry cooling, because of the complexity of design and the inefficiency of heat transfer to air, is least desirable. Dry systems are estimated to cost between three to five times as much as wet closed cycle with towers (Yang and Dziegielewski, 2007), and are the least efficient of all cooling technologies (as shown in Table 4.2). With the exception of the Bilibino nuclear power plant (4 units of 12 MW_e) in the far eastern region of Russia, no nuclear power plant in the world uses dry cooling, though there are examples of fossil fuel-fired power plants that use this technology, in South Africa, Turkey and the United States (Nevada, Texas and New Mexico).

Table 4.2. **Percentage of generating capacity lost relative to once-through cooling**

Cooling system	**Fuel**		
	CCGT	**Coal**	**Nuclear**
Once-through	0.0	0.0	0.0
Wet closed cycle, tower	0.4	1.7	1.7
Dry, indirect*	2.1	8.6	8.5

* Direct dry systems present even greater generating capacity losses (WNA, 2011).

Source: EPA, 2001.

Stability of both cost and efficiency in the face of changing ambient conditions must also be taken into consideration. Once-through cooling when water is withdrawn from large expanses of water (e.g. sites along sea coasts or large lakes) is least impacted by increases in air and water temperature, because of the high thermal inertia of large bodies of water. On the contrary, dry and (to a lesser degree) wet closed-cycle systems are much more likely to experience cost increases and efficiency reductions in such situations (WNA, 2011).

Table 4.3. **Potential loss of electric power output through the use of different methods of cooling for a 1 000 MW_e power station, using direct once-through cooling as the base case**

Parameter		Direct once-through cooling	Mechanical draught wet cooling tower	Closed-circuit air-cooled condensers
Condenser design pressure (mbar)		29	65.0	85.0
Reduction in electrical output (MW sent out)	MW_e	0	42	47.4
	%	0	4.2	4.74
Reduction in overall cycle net thermal efficiency (% points)		0	2.0	2.3

Source: EA, 2010.

In terms of environmental impact, water use is an important criterion for the evaluation of cooling systems. Dry cooling uses a negligible amount of water in terms of both withdrawal and consumption, and hence is the optimal system in this regard. Ranking the remaining two cooling technologies proves to be more difficult. Wet closed-cycle systems reuse water and hence have low withdrawal, but exhibit high consumption as a result of losses due to evaporation and blow-down (which must be compensated for by "make-up" water). Once-through systems have lower consumption but much higher withdrawal, which both reduces the quantity of water available for other uses and can harm aquatic organisms through impingement (impact against debris-blocking screens at the inlet) and entrainment (passage through the plant). Furthermore, thermal releases must be regulated to ensure that their impact downstream of the power plant is limited.

In the United States, Section 316(b) of the Clean Water Act requires (in principle) that new and existing thermoelectric power plants employ wet closed-cycle cooling to minimise environmental impacts (NRDC, 2011). Current trends indicate that this law may be more strictly and widely applied in the future: in 2010, it was implemented in the State of California (SWRCB, 2010) and formally proposed both in the State of New York and in New Jersey (WNN, 2010).

Safety issues are also a topic of concern. Cooling tower plumes can disseminate waterborne pathogens (such as the bacteria causing Legionnaire's disease), cause icing on nearby roadways, and are identified by the US Nuclear Regulatory Commission (NRC) as a potential threat to aviation when formed in the vicinity of airports (NRC, 1998). In addition, the towers themselves can collapse owing to ice formation when exposed to freezing temperatures (Micheletti and Burns, 2002).

Finally, as regards aesthetics, wet closed-cycle systems are disadvantaged as a result of their towers. The visual pollution created by the size and plumes of these structures can be mitigated by adopting low-profile forced-draft towers (WNA, 2011) or plume abatement cooling, albeit at greater capital and operational costs.

Circulating water system and essential service water system

On average, nuclear power plants have greater cooling needs than other thermoelectric generating technologies. This is because:

- additional cooling demand is the result of relatively lower efficiency;
- the need to evacuate residual heat during planned or unplanned shutdowns, implies the necessary confinement of the primary coolant surrounding the fuel.

Main cooling circuit (circulating water system)

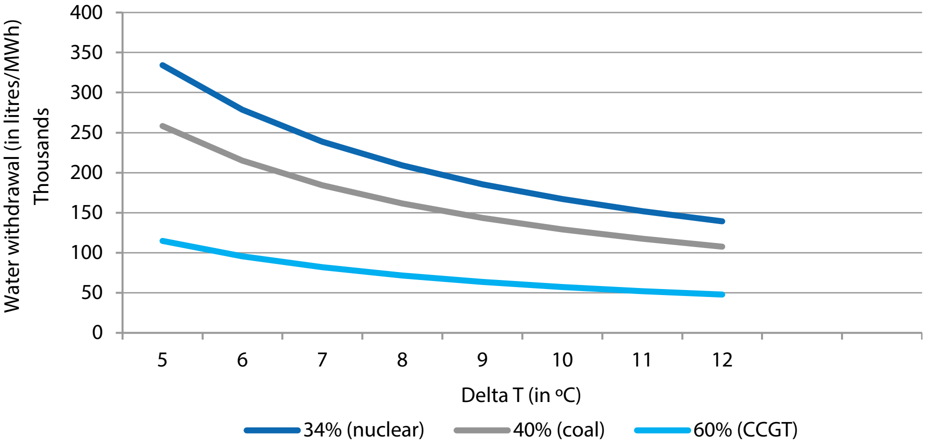
Current water-cooled nuclear power plants have lower thermal efficiencies than combined-cycle gas turbines (CCGTs) and coal power plants, and hence must remove more heat from their internal circuit. Thermal efficiency is positively correlated with the temperature difference between cooling water and the internal boilers. A theoretical expression for water withdrawal requirements for thermal power plants using once-through cooling can be found in Yang and Dziegielewski (2007):

$$L = \frac{860926 \times (1 - e)}{\Delta T \times e}$$

where L is the water withdrawal rate in litres/MWh, e is thermal efficiency and ΔT is the temperature difference between the inlet and the outlet of the condenser (in other words, the temperature rise of the cooling water) in °C.

In Figure 4.4, the withdrawal rates are plotted for typical values of ΔT, and for values of thermal efficiency of 34%, 40% and 60% corresponding respectively to those of generation III nuclear power plants, coal and CCGT plants (WNA, 2011). This graph shows the higher cooling requirements of nuclear power plants compared to more efficient technologies. It also shows that a lower temperature rise of the cooling water necessitates a higher withdrawal rate.

Figure 4.4. **Water withdrawal rates required for once-through cooling of different thermo-electric plants, as a function of cooling water temperature rise**



Source: NEA, 2018.

Cooling to evacuate residual heat (essential service water system)

The main cooling circuit is called the circulating water system (CWS). It is not a safety-classified system.

Following a planned or unplanned shutdown, a nuclear power plant must remove residual heat from the reactor core. This heat is generated by the decay of fission products, and is eliminated either by routine cooling requiring access to an external source of water or, if this system fails, by emergency core cooling systems (not discussed here). Both systems are safety-classified.

Unlike coal and gas plants which can release waste heat as exhaust through a stack, nuclear reactors have to ensure that the primary coolant circulating through the core is confined. A nuclear power plant must, therefore, rely exclusively on heat exchangers separating the primary coolant from other coolant circuits for heat removal. In a pressurised water reactor (PWR), the steam generator plays an essential role in removing heat from the primary coolant by boiling water into steam. In the event of a shutdown, the steam (which is not radioactive) bypasses the turbine and can be dumped directly to the condenser, or even discharged into the atmosphere if the circulating water system cooling the condenser is not available.

Once the decay heat in the reactor is no longer able to vaporise water in the steam generator, the decay heat removal system comes into operation. This is the role of the essential service water system (ESWS) which cools the component cooling water system (CCWS).

In the case of a boiling water reactor (BWR), steam dump to the condenser is followed by residual heat removal through the use of the essential cooling system. There is no release of the (radioactive) steam into the atmosphere.

In a nuclear power plant, the circulating water system, which cools the condenser downstream of the turbine, has far greater water requirements than the essential service water system. The water requirements depend on the configuration (open loop vs. closed-loop).

However, although water withdrawal requirements of ESWS are small, they are highly dependent on the quality and availability of the source, as characterised by the level of water and its temperature. Failure to meet strict criteria can lead to shut down of the plant by the regulator, since the safety of the plant could be compromised if decay heat removal systems are not able to operate as designed.

Safety aspects of the essential service water system

Safety significance of cooling water issues

Whereas the main cooling water system is only used for heat removal during power operation and has no particular safety significance, the service water system of light water reactors fulfils a safety function that has to be ensured in all plant states. After the shutdown of the reactor, the essential service water system is needed for residual heat removal from the reactor core and the spent fuel pool, as well as for the cooling of various items important to safety.

An assumed loss or reduced capacity of the main cooling water system due to high cooling water temperatures or limited availability of cooling water (e.g. low river levels) affects the availability of the plant and consequently the security of the general energy supply. But any deterioration of the essential service water supply implies consequences potentially compromising nuclear safety such as:

- loss or reduced efficiency of residual heat removal from the reactor core and spent fuel pool;
- loss or reduced efficiency of cooling of emergency diesel generators;
- loss or reduced efficiency of air conditioning.

The reason for the loss or reduced efficiency of the ESWS can be either high temperature of the ultimate heat sink (e.g. river, lake or sea) or limitations regarding the available amount of cooling water. Both effects are more likely to affect river or lake sites than coastal sites, where the sea provides for a relatively stable water supply.

Rising water temperatures gradually reduce the efficiency of the essential service water system as the temperature differences in the heat exchangers decrease. At which point the efficiency is reduced to a problematic level from a safety point of view depends on the specific demands of the various systems that require cooling. Low water levels have slightly different consequences with respect to the cooling capacity: Down to a certain plant-specific water level, the ESWS operates at its full efficiency. Only if the water level drops below the suction point of the essential service water pumps is the cooling capacity of the system lost – but in this case completely and almost instantaneously.

If the meteorological conditions lead to low water levels and high water temperatures, there is a considerable probability for a simultaneous occurrence of these two phenomena. But low water levels – in particular at river sites – may also develop during long-lasting frost periods due to the reduced discharge of liquid water in the catchment area.

Typically, the first concern with respect to a degradation of the cooling water supply is the cooling of the reactor core and the spent fuel pool. Whereas this is a significant safety issue in case of a complete loss of the cooling capacity, high water temperatures in the ultimate heat sink are only of limited safety significance: A temperature rise of the ultimate heat sink reduces the temperature difference over the heat exchangers and thus reduces the cooling efficiency. This leads to a slight temperature rise in the reactor pressure vessel and/or the spent fuel pool. By increasing the temperature difference over the heat exchangers, this will restore the cooling capacity. Therefore, high cooling water temperatures lead only to small increases in the water temperatures in the reactor pressure vessel and/or the spent fuel pool, which can be assumed to be minor safety issues. Should the cooling capacity be lost completely because of ultimate heat sink water levels dropping below the suction point of the essential service water pumps, then accident management measures are called for to avoid fuel/core damage.

For safety-related systems with comparatively low intrinsic temperatures, not only low water levels could pose problems but also high water temperatures. Examples are the cooling of emergency diesel generators and instrumentation and control (I&C) equipment. These systems are also needed under shutdown conditions. Therefore, contrary to reactor core cooling, the issues cannot be solved by power reduction or shutdown of the reactor.

Particularly during heatwaves, the availability of the electrical grid is not guaranteed. Assuming the shutdown of the reactor (also as a consequence of the heatwave which is quite likely associated with high water temperatures) implies that the energy supply of the plant relies on the emergency diesel generators. Typically, the assessments regarding the operability of these diesel generators are based on arbitrary assumptions about the cooling water temperatures. Generally, no evaluation of the performance of the diesel generators for temperatures exceeding the assumed values has been performed.

Issues could also arise with regard to the reliability of I&C equipment. Under normal conditions, air conditioning ensures that the temperatures in rooms housing I&C equipment remain within acceptable limits. As air-conditioning systems often rely on the service water system for heat transfer, its operation can be impaired under meteorological conditions involving high cooling water temperatures. A loss in efficiency of the air conditioning, in turn, leads to rising room temperatures with the potential consequence of an increased failure rate of I&C equipment.

Design provisions

Nuclear power plants are designed to withstand a wide variety of natural hazards. The protection against these hazards is provided either by dedicated protection measures or by appropriate qualification of safety-related equipment. The basis for this protection is a site-specific hazard assessment that aims at developing hazard curves (i.e. relationships between the intensities of events and their exceedance frequencies) and defining design basis events with low exceedance frequencies.[2] This systematic approach is well established for major natural hazards such as earthquakes and flooding, but it is not consistently applied to meteorological hazards, in particular extreme temperatures. The design of safety systems with respect to ambient air and river/seawater temperatures is often based on a temperature range that is considered to cover "conservatively" (without in-depth hazard assessment) all historically recorded values in the region of the site. Whereas it is highly unlikely that these systems fail if the design values are slightly exceeded, no formal proof for their effective operating range is available.

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2. Typically, the definition of design basis natural hazards is based on events with exceedance frequencies in the order of 10^{-4}/year.

Depending on the site-specific conditions, specific design and layout provisions are in place to ensure the operability of safety-related systems in case of extreme temperatures and, in particular, low river levels. Intake and pump structures are designed and located so that the amount of cooling water necessary for the supply of the service water system, or even for power operation, can be extracted from the river or sea even in case of very low water levels. Some plants do not (exclusively) rely on a river or the sea as ultimate heat sink, but use cooling towers (wet or dry) or wells to transfer heat from the service water system. In general, these systems are less susceptible to negative effects of high temperatures. In particular, the combination of different options provides a high level of resilience.

For new nuclear projects, a suitable site selection may help to avoid problems with the cooling water supply, because coastal sites are less susceptible to high cooling water temperatures and low water levels. But the benefits due to the large and thermally stable cooling water reservoir are countered by the higher risk caused by tsunamis, storm surges and windstorms in general.

Additional measures

If it cannot be excluded that water temperatures exceed or water levels fall below certain limits, additional measures to ensure a safe plant state can be taken. In this context, although the development of such meteorological conditions is comparatively slow (on the timescale of many days to a couple of weeks), it still allows for ample lead time to implement those measures.

A prerequisite for most measures is a timely shutdown of the plant, because otherwise a large amount of decay heat has to be transferred to the ultimate heat sink. In most instances, early shutdown of the plant can be assumed to be due to restrictions imposed by environmental laws (e.g. water utilisation laws) which set limits for the absolute temperature of the discharged cooling water and/or the temperature difference between the extracted and discharged water. As soon as the decay heat has reached a sufficiently low level, the amount of cooling water needed for service water system (a few cubic-metres per second) is small even compared to the water flow in a small river with low water level.

In the unlikely event of the river water level being too low or the water temperature being too high, other water reservoirs at the plant site (demineralised water storage tank, emergency feedwater tanks or cooling tower basins) can be used to feed the service water system or the component cooling system, applying pre-planned accident management measures. As the water reservoirs available on-site are limited, these measures can be sustained only over a limited period during which an alternative (external) water supply has to be established.

Heatwave/drought events of the past

During the summer of 2003, there was a significant drought and heatwave in Europe. France, where 44 of the 58 reactors are cooled by river water[3], was forced to curtail generation because of either reduced river flows or elevated water temperatures. Bugey on the Rhone, Tricastin on the Drome and Golfech on the Garonne were temporarily allowed to increase their discharge temperatures from 24°C to 30°C.

France is the world's largest electricity exporter with 18% of its generation exported to Great Britain, Italy, Germany and the Netherlands. Because of a decline in hydroelectric generation due to the drought, the curtailment in generation was felt throughout the region.

A list of events caused by drought in the United States over the last decade are shown in Table 4.4. These events occurred at both nuclear and fossil plants as indicated by the plant names. In addition to the disruptions of cooling water, several of the coal-fired plants had their deliveries of coal by barge disrupted because of low water on the Mississippi and Ohio rivers.

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[3] All the others are located on the coast and cooled by seawater, or in an estuary.

Several of the case studies (France, Spain, United States) described in the following chapters deal with heat wave and drought events, which have affected nuclear power plant operation over the last two decades. Specific adaptation measures are also described in these case studies.

Table 4.4. **Examples of recent power plant critical incidents caused by drought, United States 2000-2012**

Year	Plant	Details
2000-2008	Gerald Gentleman Station, Nebraska	Extended drought conditions have forced nuclear power plants to develop alternative methods for providing cooling water to the plant, including installation of a well field and modifications to the plant's cooling system.
Summer 2006	Donald C. Cook Nuclear Plant, Michigan	One of two nuclear reactors shut down because lake water used to cool the facility elevated the temperature reading in the containment building.
Summer 2007	Plant Hammond, Georgia	Record drought and heat reduced releases from Lake Allatoona resulting in Coosa River flows near half the 2Q10 flow. This forced Georgia Power to mitigate thermal impacts by reducing load to a minimum each night, placing aeration spargers to aid intake temperature and supplement dissolved oxygen, and installing temporary mobile cooling towers.
Summer 2007	Gallatin Steam Plant, Tennessee	Energy production reduced because intake cooling water temperature went above the allowable discharge temperature because of heatwave and drought.
Summer 2007	Cumberland Power Plant, Tennessee	(same as above)
August 2007	Browns Ferry Nuclear Plant, Alabama	One of three nuclear reactors shut down because water temperature in the river was too high for cooling due to drought and high air temperature.
August 2007	Riverbend Steam Station, North Carolina	Energy production curtailed because river water temperature was too high for cooling due to severe drought.
August 2007	Allen Steam Station, North Carolina	(same as above)
January 2008	McGuire Nuclear Plant, North Carolina	Because of extreme drought, the water level of Lake Norman dropped to less than 1 foot below the minimum allowed for plant use.
January 2008	Shearon Harris Nuclear Plant, North Carolina	Because of extreme drought, the water level of Harris Lake dropped to 3.5 feet below the minimum allowed for plant use.
February 2008	Joseph M. Farley Nuclear Plant, Alabama	Due to extreme drought, water levels in Lake Lanier were significantly reduced, Prompting potential reductions to lake releases. Reduced flows out of the lake would have impacted the plant which is downstream.
February 2008	Scholz Power Plant, Florida	(same as above)
August 2008	Missouri River Power Plants, Nebraska	Extended drought conditions reduced flows in the Missouri River which led to concerns that discharged waters would exceed permitted limits forcing cut backs in power generation.
August 2010	Browns Ferry Nuclear Plant, Alabama	Power generation was cut in half for over a month to avoid overheating the Tennessee River.
Summer 2011	North Texas Power Plant, Texas	Night-time operations were reduced because extreme heat made it harder for the water to cool down enough to be discharged, and drought, which reduced the volume of water available in the cooling reservoir.
Summer 2012	Braidwood Nuclear Plant, Illinois	The twin-unit Braidwood plant was deeded to get special permission to continue operating during the summer because the temperature in its cooling water pond rose to 102°F, four degrees above its normal limit.
July 2012	All of the US	US nuclear power production hit its lowest seasonal levels in nine years as drought and heat forced nuclear power plants from Ohio to Vermont to curtail output.
August 2012	Millstone Nuclear Plant, Connecticut	Millstone had to shut down one of its reactors because the water it drew from the Long Island Sound was too warm to cool critical equipment outside the core.

Source: Lew, 2012.

Nuclear power plants in hot/water-scarce environments

This chapter has focused on cooling issues for nuclear power plants, so it may come as a surprise to some readers to learn that nuclear power plants are operating or being built in water-scarce environments, or very hot climates.

The Palo Verde nuclear power plant in Arizona, United States, is the largest nuclear power plant of the country. Yet it is sited in one of the most arid regions of the country, the Arizona desert. Located about 45 miles from Phoenix, it is the only large nuclear power plant in the world that is not located near a large body of water for cooling. Instead, the power plant evaporates the water from treated waste water (sewage) from several nearby cities and towns to provide the cooling of the steam that it produces (Day, 2015). Use of non-traditional water resources such as waste water is thus an option for operating nuclear power plants in areas that lack sufficient amounts of natural sources of water (rivers, lakes, sea). Jordan, which has been looking at building a nuclear power plant for a number of years, has a very limited coastline on the Red Sea, and has thus been looking at the Palo Verde cooling option as a solution for its own nuclear power plant (Tawalbeh, 2018).

Other examples in the MENA (Middle East North Africa) region include the construction of the Akkuyu nuclear power plant in Turkey, sited on the southern Mediterranean coast of the country, and that of the Barakah nuclear power plant in the United Arab Emirates. This nuclear power plant, consisting of 4 APR1400 pressurised water reactors built by Korea, is located on the Persian Gulf, a body of water with very high salinity, shallow depths and high surface temperatures (that can exceed 35°C) compared to other seas. The designers of the nuclear power plant have adapted the design of the APR1400 reactor, already built and in operation in Korea, to those conditions, in particular by designing larger heat exchangers (including the condenser) to compensate for the loss in efficiency due to the high cooling temperatures (Kim, 2007).

Impact of climate change and weather-related external events on the front-end of the nuclear fuel cycle: focus on water issues

While this chapter deals mainly with the cooling issues of nuclear power plants, there are other parts of the nuclear fuel cycle that can be affected by the impact of climate change, notably the uranium mining sector. Flooding caused by torrential rain can seriously affect mining activities. In 2011, the Ranger mines in the Northern Territories of Australia were flooded by torrential rains, which caused the mines to be shut down for six months, at a reported cost of AUD 154 million (ABC, 2012). Water is also an essential part of mining processes.

- In open pit mining, water is used to suppress dust and to wash equipment.
- In underground mining, water can be used to transport the ore to the surface. Groundwater may need to be pumped out of the mine shafts prior to and during operation. Freezing may be used to reduce the inflow of ground water.
- In in-situ leach (ISL) mining, groundwater from the aquifer containing the ore is used. It is pumped and circulated hundreds of times. About 70% of the water pumped is returned, the remaining 30% is sent to an evaporation pond.

Lack of water, through drought or reduction in currently used resources (for instance aquifers) or priority given to other uses (human consumption, sanitation, agriculture) can affect mining activities. Excessive amounts of water, as shown by the Ranger mines events, can bring operations to a halt. Of course, the vulnerability of these activities depends on the location. Adaptation measures which industry can develop will depend on the appreciation of risks, the governance of the companies and regulatory requirements. It is to be noted that the mining sector in general (beyond uranium) is very much aware of the possible risks related to climate change, and adaptation strategies with respect to water issues exist and can be deployed (Hodgkinson et al. 2010).

Besides its role in uranium mining activities, water also plays an important role in other front-end activities. Table 4.5 from (Stempien, 2013) shows how technological improvements in conversion, enrichment and fuel fabrication – can lead to significant reductions in water consumption. The water consumption for the front end of the nuclear fuel cycle represents about 2% of the water consumption during operation of nuclear power plants (about 140 L/GJt).

Table 4.5. **Water consumption in front end activities**

		Facility	Consumption (L/GJt)
Best practice	Mining/milling	Ranger Open Pit Mine, Australia	0.1140
	Conversion	Malvesi/Pierrelatte, France	0.0301
	Enrichment	National Enrichment Facility, New Mexico, United States (gas centrifuge)	0.037
	Fuel fabrication	Westinghouse Columbia, South Carolina, United States	0.0129
	Best practice total: 0.194 L/GJt		
Worst practice	Mining/milling	Arlit/Somaïr Open Pit, Niger	2.38
	Conversion	Malvesi/Pierrelatte, France	0.0301
	Enrichment	EURODIF, France (gaseous diffusion)	2.82
	Fuel fabrication	Savannah River, Georgia, United States	0.173
	Worst practice total: 5.407 L/GJt		

Source: Stempien, 2013.

In conclusion, climate change can affect the front end of the nuclear fuel cycle, in particular mining activities. Even if the front end represents a very small fraction of the total nuclear fuel cycle's water consumption, water use is an issue, especially in arid areas. Excessive rainfalls, floods, and forest fires can represent a risk to mining activities. The impact of climate change on closed uranium mines needs to be addressed. The mining industry is increasingly aware of risks related to climate change, especially large mining companies. This awareness can lead to decisions to invest in adaptation measures, taking into account risk management, governance of the companies, local and national regulations, as well as international standards and "sustainability" certifications which companies aim to comply with.

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The following chapters describe a number of case studies provided by the Expert Group members on extreme weather events that have had either a direct or an indirect impact on the operation of nuclear power plants, or on energy infrastructures such as electricity grids. These past extreme weather events were not necessarily linked to climate change per se, but they are characteristic of the type of events that are likely to occur in the future, and are thus important sources of information to assess the vulnerability of nuclear power plants, and the adaptation measures that can be developed to improve their resilience against climate change.

Chapter 5. **The 1998 ice storm in Canada**

This case study relates to the 1998 ice storm in Canada, and even though no nuclear power plant was directly impacted, a large part of the electricity grid was severely damaged, causing electricity generation plants to trip and shut down. It shows that the impact of climate change on the electricity system requires an integrated analysis that includes both generation and transmission and distribution.

Introduction

In January 1998, a severe winter storm struck Canada. Some areas accumulated more than 80 mm of freezing rain instead of snow – double the amount of precipitation experienced in any previous ice storm. The result was a catastrophe that produced the largest estimated insured loss in the history of Canada. The same storm ran across northern New York and parts of Vermont, New Hampshire and Maine in the United States. The electric power infrastructure, with its lengthy transmission lines, was severely damaged, stranding some residents and farmers without power for as long as four weeks. Almost 5 million people were without power at some point during the storm, and the severity of the damage caused the authorities to consider the evacuation of the city of Montreal.

The opposite is true with a freezing rain event, when there is an inversion – i.e. temperature increases with height – that is typical in a rising pressure system. Precipitation will form as snow or rain in the cloud and then fall towards the surface through a relatively mild layer that melts the precipitation into rain until it encounters a shallow cold sub-freezing layer near the surface – the inverted layer – where the rain droplets become super-cooled. The super-cooled rain droplets do not freeze while they continue to fall but do freeze on contact with objects on the surface. The ice deposit forms either as super-cooled water droplets freeze on impact or by a slower freezing of the warmer droplets in contact with the cold surface.

The ice storm aftermath

Severe winter storms combined with a loss of power can have devastating consequences, even in a highly developed region such as Ontario-Quebec and the north-east United States. Starting on 6 January 1998, a severe freezing rainstorm hit eastern Canada from Ontario to New Brunswick. The ice storm lasted about five days and ended on 10 January. By the end of the storm, 50 mm to over 100 mm of freezing rain had fallen over a broad corridor extending from Kingston to Ottawa to Montreal to the Monteregie area south and east of Montreal, and on into New Brunswick. The freezing precipitation held on for more than 80 hours, nearly double the normal annual total. The total water equivalent of precipitation exceeded 73 mm in Kingston, Ontario, 85 mm in Ottawa and over 100 mm in areas south of Montreal. Those totals included ice pellets and snow, but were mainly in the form of freezing rain. The previous Montreal freezing rain record, which left 30 to 40 mm of ice, had been set in 1961 (Statistics Canada, 1998).

Hydro-Quebec assets

At the time of the storm, Hydro-Quebec's assets were 40 hydroelectric power plants and 29 thermal power plants with a total generating power of 31 400 MW. More than 93% of this power was hydroelectric and more than two-thirds of the generated power came from plants located thousands of kilometres from the end-users. In 1998, the hydroelectric power plant St Marguerite 3 was in construction with a generating power of 880 MW when it came online in 2001.

Hydro-Quebec also controls most of the power generated by the 5 400 MW Churchill Falls hydroelectric power plant.

Transmission system

TransEnergie, a division of Hydro-Quebec responsible for power transmission, is managing a power transmission network more than 32 000 km long. Five lines carry energy produced by the Churchill Falls and Manic-Outardes power plants complex. Six lines bring the energy produced by the *La Grande* complex to the consumer. A twelfth line brings direct current from James Bay to south-eastern Quebec and the Boston region.

Distribution network

The Hydro-Quebec distribution network has more than 3 000 lines with a total length of almost 100 000 km – more than 90% is an aerial-type network. About 70% of the hydro poles are shared with other public service entities. Some 9 000 km of the underground network is found in high-density urban centres. In certain industrial areas, the distribution network was interred and the additional costs are shared with various municipalities and building managements. Just as for the transmission network, the efficiency of the energy distribution effort is measured in numbers of hours of service interruptions per client per year. Hydro-Quebec improved its interruptions to its clients from 9 hours in 1980 to 3.7 hours in 1996.

The storm's aftermath

The sheer weight of the ice on power transmission lines and towers caused massive failures of infrastructure with over a thousand transmission towers collapsing and 30 000 wooden utility poles breaking (Statistics Canada, 1998). This resulted in massive power outages.

Analysis of damages on transmission lines in Quebec

Transmission lines

In the damage assessment, Hydro-Quebec categorised four types of lines: old lines, Manic-Churchill lines, new lines and lines on wooden poles. At the storm's peak, the total power loss amounted to 9 million kW in Quebec.

Old lines

Old lines were built before 1974 under the standards of the Canadian Standards Association (CSA) of the time. As per Hydro-Quebec's calculations, these lines could take up to 35 mm of radial ice as a theoretical limit. These lines' capabilities may have diminished with time owing to fatigue and usage, in particular those of insulators and accessories during their more than 40 years of service. Before the ice storm of 1998, their quality was deemed as good, except for minor repairs. During the 1998 ice storm, these old lines incurred critical damages, in particular to insulators and accessories, problems related to conductors as well as damages to the neighbouring structures: some 80 power transmission towers in one case. Considering the amount of ice accumulated, far over their specifications, the damages sustained were inevitable. These damages were multiplied by the lack of anti-cascading towers designed for full loads and also because of the ageing of insulators and accessories. It is worth mentioning that even if the standard loads were adjusted upwards after 1974, reinforcement of the old towers would have been judged unfeasible at the time.

Manic-Churchill lines

The 735 kV Manic-Churchill lines strung on steel transmission towers are equally old. This power transmission corridor is along the north shore of the Saint Lawrence River. It is because this corridor is particularly prone to icing that the Manic-Churchill line is resilient to ice storms. Since the line was just outside the area hit by the 1998 ice storm, it contributed to a better understanding of high-tension power line behaviour in an event like this. In the past, icing had caused relatively frequent problems to these lines. In 1969, a major freezing event caused the loss of 30 towers in the Charlevoix region. In 1973, another icing event led to the loss of 32 towers near Riviere-Pentecote. Following these incidents, critical sections of Manic-Churchill lines were modified to higher, more robust standards. Since the completion of the upgrades, with the exception of two service interruptions due to the icing of the anchorage cables, the performance of the Manic-Churchill lines was deemed acceptable.

New lines

This category comprises all the lines on power transmission towers built with steel after 1974 – after the damages suffered in the 1969 and 1973 incidents mentioned above for the Manic-Churchill lines. At the time, Hydro-Quebec decided to comprehensively review the design criteria for all the power lines across Quebec.

Their ability of the power transmission lines in the Saint Lawrence Valley to withstand ice loads was improved after studies on climatology and cost optimisation. This capacity was increased from 35 mm to 45 mm radial ice. In addition to this, steps were taken to obtain better optimised designs and to add anti-cascade towers capable of withstanding maximum loads. Most of the power lines built after 1976 have these improvements. Their performance before the 1998 ice storm was excellent. During the storm, some of these lines outperformed expectations – one of them demonstrated remarkable resilience being located in the area of highest ice accumulation. While there was some damage, it was limited to a few towers with the exception of Boucherville-Saint-Cesaire, which suffered numerous collapses.

Lines on wooden poles

Many power companies resorted to wooden poles for the distribution networks because of their low costs. These lines are characterised by a great disparity in their ability to withstand excessive loads and as such they are sensitive to cascading failures owing to their limited longitudinal resistance. During the storm, lines with wooden poles suffered widespread failures within the impacted locations, in some cases causing the totality of the wooden power line infrastructure to fail where the ice accumulations were the most severe. Nevertheless, the wooden lines performed according to expectations.

Distribution lines

The intense effort to collect damage data and the statistical analysis undertaken to evaluate the failure of the distribution network are worth mentioning. In a few cases, the analysis was not able to determine whether the existing infrastructure was built according to appropriate engineering standards; it seems clear instead that in certain cases the infrastructure was not built according to proper specifications. Following this finding, Hydro-Quebec decided to institute a programme to document the maintenance and construction activities to ensure that the infrastructure is installed and maintained according to appropriate standards.

Though the poles in the distribution network are all designed according to the CSA standards for both power and telecommunications applications, depending on the structural load on each pole, some poles may be more or less resistant than others. Following a statistical data analysis of the damages, it was not a surprise to find that the affected poles actually performed as expected according to their use and the extra load from ice deposit. The conclusion of this analysis also confirmed that the pole's category, size, usage, anchoring and the size of the top traverses, are all essential factors in forecasting the behaviour of a distribution network during an ice storm.

Furthermore, it is useful to note that the verticality of the poles is an important factor in maintaining their structural integrity. Repositioning of the poles should be a key element in all the programmes seeking to improve the distribution networks.

Additionally, the distribution network analysis indicated that a disproportionate amount of damage was the result of falling trees and therefore another key component to improving distribution networks is to fully implement vegetation containment programmes in urban environments.

Though a large portion of restoring services was completed within five days, the pace of restoring services decelerated dramatically afterwards. Service to about 1 million clients was restored within 5 days, but it took another 25 days to restore the services to the remaining 400 000 clients. The last 100 000 clients to have their services restored waited at least 15 days. In total, the repairs and restart of service to clients took about one month to complete.

Total damages

Overall, in Canada, there were 28 deaths, 945 injured or infected and an estimated total cost of over CAD 4.5 billion. The same storm caused 17 deaths in the United States, as well as damages exceeding USD 1 billion in New York and New England states – one-third of which was from losses to electric utilities and communications (DeGaetano, 2000). Combined Canadian and US insured losses stood in excess of USD 1.2 billion as of 1 October 1998. Total Canadian insured and uninsured economic losses were approximately USD 4 billion (CAD 6.4 billion).

The ice storm produced more than 835 000 insurance claims from policy-holders in Canada and the United States. This was 20% more claims than were created by Hurricane Andrew, at that time the costliest natural disaster in the history of the United States.

The aftermath of the ice storm revealed the wide spectrum of insured and non-insured losses that can materialise from a single natural catastrophe, including:

- property losses (e.g. roof damages, burst plumbing and car accidents);
- business interruption losses (19% of the employed Canadian workforce was unable to get to work);
- health/life losses (including losses incurred during recovery operations);
- additional living expenses for people relocated to temporary housing;
- a host of agricultural losses, ranging from livestock deaths, to interrupted maple syrup production, to milk production;
- disruption and damage to recreation and tourism infrastructure;
- disaster recovery costs, including personnel and overtime expenses, provision of backup electric generators and fuel, debris clearing, temporary shelter for displaced citizens, and disaster assistance payments to victims.

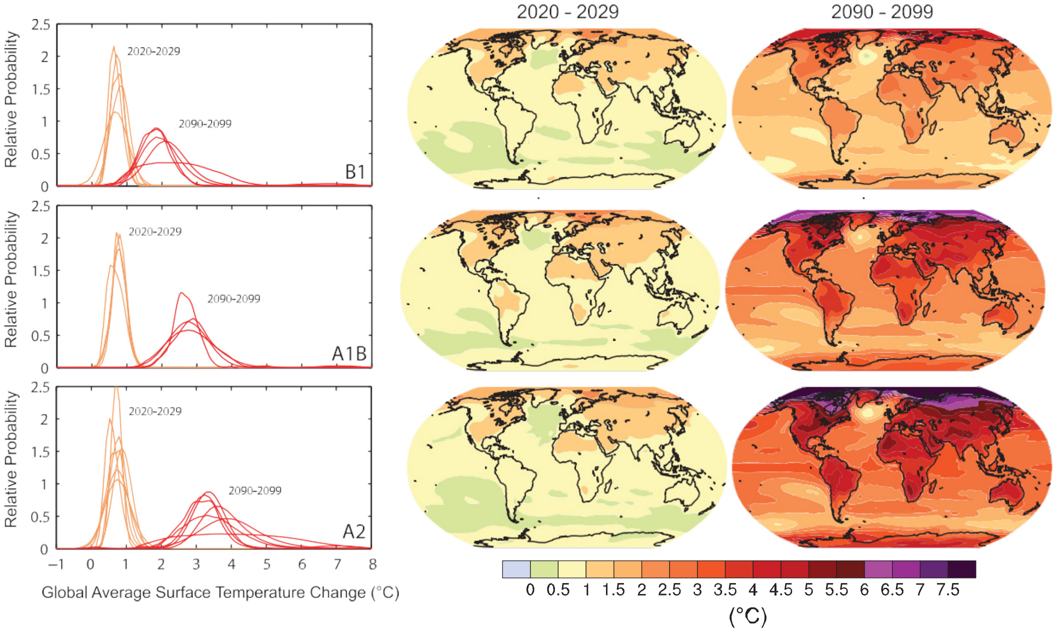
Review of projected climate change for North America

According to the IPCC 2007 report, warming is very likely across North America during this century, and in most areas the annual mean warming is likely to exceed the global mean warming. The warming is expected to be greatest in the northern regions of the continent during the winter. By the end of the 21st century, the ensemble mean temperature increase in the northern parts of the continent in the winter may be as much as 7°C and as little as 2°C in the summer.

The surface temperature changes for the early and late 21st century relative to the period 1980-1999 have been projected and illustrated in Figure 5.1. The central and right panels show the Atmosphere-Ocean General Circulation Model (AOGCM) average projections for the B1 (top), A1B (middle) and A2 (bottom) Special Report on Emissions Scenarios (SRES) averaged over the decades 2020-2029 (centre) and 2090-2099 (right). The left panels show corresponding uncertainties as to the relative probabilities of estimated global average warming from several different AOGCM and Earth System Model of Intermediate Complexity studies for the same periods. Some studies present results only for a subset of the SRES scenarios, or for various model versions. Therefore, the difference in the number of curves shown in the left-hand panels is due only to differences in the availability of results.

In south-eastern Canada, in the Great Lakes-St. Lawrence River corridor, an ensemble-mean projection of seasonal increases in temperature by the year 2050 relative to 1961-1990 ranges from 3°C to 3.5°C for the summer and 3.5°C to 4°C in the winter (Government of Canada, 2008).

Figure 5.1. **Projections of surface temperatures**



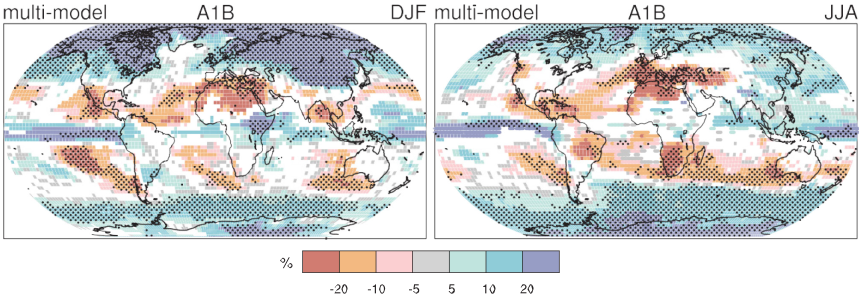
Source: IPCC, 2007.

As the Intergovernmental Panel on Climate Change (IPCC) 2007 report forecasts, there is more consensus for greater increases in precipitation in the winter for northern regions of the continent and decreases in the summer to the south. On the other hand, the Government of Canada (2008) suggests that the seasonal precipitation will not change by more than 10% over 1961-1990 levels by 2050 in the southern portions of the Great Lakes region. According to the data presented by the Government of Canada in 2008, some decrease by less than 2.5% may occur in the southern Great Lakes region in the summer.

Furthermore, the length of the snow season and the depth of snow are very likely to decrease in most of North America, except in the northernmost part of Canada where maximum snow depth is likely to increase with increased precipitation in the winter (IPCC, 2007).

Relative changes in precipitation (in percentage) for the period 2090-2099, relative to 1980-1999, are shown in Figure 5.2, where values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree with the level of change and stippled areas are where more than 90% of the models agree with the indicated change.

Figure 5.2. **Projected patterns of precipitation changes**



DJF: December, January, February; JJA: June, July, August.

Source: IPCC, 2007.

Climatic perspective of the 1998 ice storm

There are several remarkable features of the 1998 ice storm related to the storm's unusual persistence and the way in which both precipitation and Arctic air were resupplied during the storm. The storm occurred in the middle of a strong El Niño event, with very warm sea surface temperatures across the eastern equatorial Pacific Ocean.

A number of previous studies have theorised that El Niño contributed to the large-scale atmospheric flows and the resupply of warm, moist air from the Gulf of Mexico, generating the ice storm's prolonged precipitation with pronounced flooding to the south of the area of ice accumulation. For example, Barsugli et al. (1999) used a forecasting model developed by the National Centers for Environmental Prediction to show a statistical correlation between El Niño and the 1998 storm. Moreover, according to Higuchi et al. (2000), an apparent connection exists between a positive phase of the North Atlantic Oscillation (i.e. when pressures in Iceland are much lower than in the Azores) and a persistent high-pressure system in northern Quebec, as evidenced by three out of the four major freezing rain events since 1961, including the 1998 ice storm.

At this time the debate continues and the question of whether there was a causal relationship between El Niño and the 1998 ice storm remains open. The question of whether global climate change and accompanying variations in weather patterns will produce more frequent and severe freezing events is a topic that requires additional research.

Although there is growing acknowledgement about the earth's rising temperature, there also remains some uncertainty whether it is cyclical or permanent in nature. In Chapter 3 of the report titled *Coping with Natural Hazards in Canada*, Etkin and Brun (1997) advise that most numerical climate models predict that a doubling in CO_2 over the next half century will lead to:

- an average overall warming of the earth's global climate by between 1.5°C and 4.5°C and a proportional increase in global average precipitation;
- an increase in certain types of extreme events as strongly suggested by various theoretical and empirical studies.

Predicting future ice storms in central/eastern Canada

In the case of extremes that are not represented at all in climate models, secondary variables may sometimes be used to derive them. For example, freezing rain, which results in ice storms, is not represented in climate models, but frequencies of daily minimum temperatures on wet days could serve as useful surrogate variables (Konrad, 1998).

Milder winter temperatures will decrease heavy snowstorms but could cause an increase in freezing rain if average daily temperatures fluctuate about the freezing point. It is difficult to predict where ice storms will occur and to identify vulnerable populations. The ice storm of January 1998 left 45 people dead and nearly 5 million people without heat or electricity in Ontario, Quebec, and New York (CDC, 1998; Francis and Hengeveld, 1998; Kerry et al., 1999). The storm had a huge impact on medical services and human health. Doctors' offices were forced to close, and a large number of surgeries were cancelled (Blair, 1998; Hamilton, 1998). One urban emergency department reported 327 different injuries resulting from falls in a group of 257 patients (Smith et al., 1998b).

Historically, during the period 1909-2002, 22 major ice storm events were identified for the northern US states bordering southern and eastern Ontario. Icing-related collapses of communication towers occurred during several of these storms, eight of which had also produced 20 mm or more of freezing rain in southern and/or eastern Ontario.

The storm track analysis for the significant Ontario and northern United States ice storms during 1948-2002 identified at least three common features:

- A warm moist mid-upper level flow originating in the Gulf of Mexico and in some cases an additional moisture source from the Atlantic Ocean.
- Presence of a cold Arctic high-pressure area to the north of these storms, generally centred over Quebec.
- Slow moving storm systems.

It is clear that ice storms occur regularly in North America, although severe and prolonged damage is rare. Large urban centres in Canada may be vulnerable to major storms, including Winnipeg, Toronto, Ottawa and Montreal. Many communities are not prepared for an extreme winter storm, particularly combined with the loss of electric power. The 1998 ice storm is a case in point.

The IPCC 2007 report states that:

> In a warmer future climate, there will be an increased risk of more intense, more frequent and longer-lasting heatwaves … greater risk of drought … increased chance of extreme precipitation … suggesting an increased chance of flooding … future tropical cyclones could become more severe … general tendency for more intense but fewer storms outside the tropics … (IPCC, 2007)

Overall, the probability of extreme weather is predicted to change in the future as climate changes and climatic zones shift northward. Increases in the frequency and intensity of extreme weather events are one of the greatest concerns regarding climate change. Experience indicates that natural disasters, such as drought, flooding and severe storms, often exceed our ability to cope, resulting in significant environmental and socio-economic impacts.

Cheng et al. (2011) attempted to project the changes in the future daily freezing rain events in eastern Canada based on historical synoptic weather records (1958-2007) as well as downscaled future climate data (based on CGCM2-A2). The results of this study show that in the coldest months, eastern Canada may experience more freezing rain events in the future compared to historical records. Furthermore, the risk of daily freezing rain increases in number progressively from south to north and from south-west to north-east across eastern Canada by the period 2081-2100. The study projects that severe freezing rain events (≥6 hours per day) will increase by 35% in southern Ontario and by about 80% in south-eastern Ontario/south-western Quebec. Northern Quebec is projected to experience an increase of about 80% to 100% of severe freezing rain events. The south-eastern Atlantic region (New Brunswick and Nova Scotia) is projected to see a 20% increase in severe freezing rain by the period 2081-2100.

Proactive and precautionary adaptive measures are recommended to help reduce losses associated with current climate variability, as well as increased risk of extreme climate events such as severe ice storms.

Ice storm over Gentilly-2 nuclear power plant

During the ice storm of 1998, the Gentilly-2 nuclear power station continued to operate at full power to supply electricity to the region of Mauricie (Trois-Rivières). The Mauricie region was less impacted by the storm than the Montreal region, which is approximately 150 km south-west of Trois-Rivières. Gentilly-2 did not experience direct or indirect impacts to its plant structures or its supporting facilities nor was off-site power interrupted. The grid structure around the Mauricie region and the associated industrial park allowed isolation from the rest of the provincial grid which made it possible for Gentilly-2 to continue to provide electricity to the region. As soon as the grid was repaired in the Montreal region and put back in service, all production units were resynchronised to the grid to restore the electricity supply to Montreal and its surrounding region.

Adaptive measures taken by Hydro-Quebec

General considerations

The 1998 ice storm caused service interruptions on large scales and of long durations that could have had far worse consequences had the temperatures not been moderate during the days following the event. Given the rigour of Quebec winters and the fact that the population depends heavily on electricity for heating, the prolonged interruptions of service are unacceptable. As a consequence, Hydro-Quebec set the following objectives: i) maintain essential services such as medical services; ii) maintain minimal power needs to ensure that the health and well-being of its clients are met. Additionally, immediately after the storm, Hydro-Quebec undertook a series of corrective measures. Most urgently, the necessary repairs were performed and service re-established for the affected clients without necessarily reinforcing the network. The process of approval of a number of projects that strengthen the power supply to vulnerable centres was accelerated. Fortunately, most of these projects had already been assessed during previous years and, therefore, the task associated with these projects was primarily to implement them before the onset of winter 1998/1999. At the same time Hydro-Quebec proposed a plan for the transmission network reinforcement over the course of the next ten years. The main purpose of this plan is to design and install an ensemble of strategic corridors able to withstand a storm of the magnitude of the 1998 ice storm. Hydro-Quebec undertook the studies for developing such corridors for three regions: Montreal, Quebec and the North East. Each of the corridors was to have at least one strategic line, such as the 1 250 MW interconnection with Ontario commissioned in 2009.

The strategy chosen by Hydro-Quebec for the proposed and approved projects is the following:

- ensure the supply of at least 50% of the peak charge in the conditions similar to those brought by the 1998 storm to all the important areas;
- feed every 735 kV distribution point by at least one strategic line.

A reinforcement strategy of the distribution network was developed together with a programme for the preliminary reinforcement of the transmission lines. The goal is for both transmission and distribution to ensure a level of power supply sufficient for maintaining the essential services and make sure that most of the population will not need to relocate during such an event.

Projects approved for the transmission network

Hydro-Quebec approved the following projects for the first phase of its network reinforcement:

- looping of the 735 kV Monteregie network between the distribution stations Hertel and Des Cantons;
- integration of the distribution centre of Monteregie with the regional 120 V network;
- looping[1] of the Montreal downtown 315 kV network between the distribution stations l'Aqueduct and Atwater.
- looping the Outaouais 315 kV network between the distribution centres Grand Brule and Vignan;
- looping of the 315 kV network in the Quebec-Mauricie corridor;
- add an interconnection with the high-power Ontario network.

These measures were designed to guarantee an increased level of viability, necessary in the light of the serious consequences produced by a prolonged interruption of service which for the Montreal region had enormous social and financial repercussions.

Projects proposed for the transmission network – strategic power transmission lines

In its ten-year plan, Hydro-Quebec plans to reinforce certain power transmission lines so as to be capable of delivering a sufficient amount of power to sustain the loads required by the essential services in an extreme event such as the 1998 ice storm. From this perspective, the proposal to rapidly integrate the Beauharnois and Carillon power plants into the Montreal network received the same amount of priority as the Monteregie loop, and consequently became one of the approved projects.

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[1] In the context of power supply networks, "looping" means adding a parallel power transmission circuit.

While the concept of "strategic lines" is sound, critical assessments for economic justification were undertaken. A strategic line must validate the three criteria:

- high probability of sustaining the severe challenges of an extreme ice storm;
- any incurred damages must remain minor such that repairs and return to service may be rapid;
- the strategic line must be de-iceable.

The strategy acknowledges that ensuring supply to the major population centres of Montreal and Quebec is critical and therefore must take priority with regard to strategic lines development. Considering the network configuration, the strategic lines in the North-East may not be as high a priority as long as the main urban centres can be sustained even in the face of losing the 735 kV lines of the North-East zone.

Strategy for reinforcing the distribution network

As an immediate first step to increase the viability of the distribution networks, maintenance programmes and quality control programmes are to be improved. A commitment has also been made to complete maintenance and manufacturing documentation.

It has been recommended that the distribution network reinforcement projects be co-ordinated with power transmission line reinforcement projects. Equal attention should be paid to issues like the rapid restoration of service, improvements to the network configuration by, for example, repartitioning networks, the use of mobile generation stations, de-icing technology deployment, and underground lines.

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Chapter 6. **Climate change impact on cooling in the Laurentian Great Lakes, Canada – an ecological approach**

Introduction

Canada's four commercial nuclear power plants are located along the shores of large cold-water systems – three of which along the Laurentian Great Lakes. Pickering nuclear power plant (PNPP), Darlington nuclear power plant (DNPP) and Bruce Power nuclear power plant (BNPP) all utilise once-through cooling (OTC) technology to condense the turbine exhaust steam back to liquid. In an OTC system, a large volume of water is drawn from a cool water source. Heat is transferred from steam to the cooling water, and the warmed water is returned to the source waterbody (Coutant, 1970) that can efficiently act as the heat sink. Once-through cooling is an efficient method of condensing steam back to liquid in the power generation industry. However, there may be ecological risks associated with the often extensive thermal plumes created by the large volumes of cooling water discharged by the nuclear power stations.

In the provinces of Ontario and New Brunswick, where nuclear power plants are currently operational, 70% of the power generation capacity in 2010 was associated with thermal and nuclear power (Statistics Canada, Table 127-0009). In Ontario, nuclear power plants (Pickering and Darlington) generate over 50% of the electricity generated in the province and currently all of these power plants use OTC technology for cooling. The volume of heated effluent discharged from Canadian nuclear power stations along the Great Lakes ranges from 153 000 litres per second (OPG, 2007) to 167 200 L/s (Bruce Power, 2005a). The proposed Darlington New Nuclear Project would likely require 228 400 L/s of lake water to cool its condensers if the project were to go ahead (Senes, 2009). At the existing Darlington plant, the regulatory limit for the spatial extent of the thermal plume at the water surface is 1 km^2 at the edge of the 2°C isotherm. In contrast, the combined maximum areal extent of the 2°C above ambient limit of the thermal plume from the operation of all 8 units of Bruce A and Bruce B plants is estimated to be 67 km^2 (Bruce Power, 2005b).

The increased productivity associated with warmer waters may induce eutrophication of the local water column, especially where urban sources of nutrients exist as in the case of the north shore of Lake Ontario. Algal blooms due to eutrophication, typically caused by Cladophora species, result in habitat substrate being smothered in large mats of algae and clogging of OTC intakes when these mats become loose (Senes, 2011).

At the Pickering and Bruce Power plants, where the thermal discharge is conveyed through an open discharge channel to the waterbody, the discharge typically behaves like a jet plume where a large volume of continuous flow of heated water pushes out against the waterbody. This often results in a deflection of suspended sediments, plankton and larval fish carried along by ambient currents which in both lakes Ontario and Huron generally flow parallel to the shoreline (Bruce Power, 2005a; Senes, 2007; Golder, 2011). In the case of plants utilising diffusers at the OTC outfall, because of the high discharge velocities at the diffuser ports, scouring may result in the substrate (Golder, 2011). Additionally, during the winter months when near-shore ambient temperatures in the water column are near 0°C, warm thermal discharges may form a sinking plume because water becomes less buoyant as it approaches 4°C. The warmer plume of water sinks to the bottom and displaces the ambient colder (more buoyant) water, resulting in large lake bottom areas that may be significantly warmer than the ambient conditions.

Biologically, as obligate ectotherms, fish are highly heat-conductive without the ability to produce sufficient metabolic heat, to overcome rapid loss of heat through the gills and epidermis (Brett, 1971). This obliges fish to having body temperatures which cannot be independent of their environment (Coutant, 1970). As a result, water temperature affects fish more than any other abiotic factor, which in turn plays a major role in the distribution and physiological/behavioural ecology of fish (Beitinger and Fitzpatrick, 1979; Fry, 1947). Temperature affects growth, migration, feeding, spawning and egg incubation (Coutant, 1972).

Direct effects of thermal discharge include cold-shock or heat-shock caused by rapid temperature reductions or elevations. Additionally, thermal shock can manifest as acute (death) or latent effects in fish embryos, which may be especially vulnerable to temperature changes during incubation. Thermal-shock stress occurs when a fish has been acclimated to a specific water temperature or range of temperatures and is subsequently exposed to a rapid decrease or increase in temperature, resulting in a cascade of physiological and behavioural responses and, in some cases, death (Donaldson et al., 2008). Even if a fish survived the shock, the stress could render the fish susceptible to predation or, if severe enough, make it susceptible to secondary fungal infections (Horning and Pearson, 1973). Thermal shock scenarios could occur following the commencement of an outage with the associated shutdown of OTC pumps resulting in potential cold shock, or following a restart of a reactor after an outage which may result in a heat-shock scenario.

Optimal temperature ranges vary widely among species of fish and depend on genetics, developmental stage and thermal tolerances (Beitinger et al., 2000). For cold water species with narrow tolerances to changes in water temperature, sustained (i.e. chronic) or episodic (i.e. acute) increases in lake water temperature beyond a certain threshold could result in lethal or sublethal effects to the organism and its embryos (Griffiths, 1980). Sinking plumes, which may occur in winter in the Great Lakes, could have both acute and sublethal effects. If the plume’s temperature is within a tolerable range, then as the warmer water sinks to the bottom where fish eggs would likely be incubating, little acute effects would result; however, embryo development would likely be accelerated resulting in an advanced hatch (Griffiths, 1980; Senes, 2007). With advanced hatch, there is a potential de-synchronisation of food availability to the larval fish as an indirect effect of the thermal discharge. Many larval fish in the Great Lakes depend on zooplankton for food and the emergence of zooplankton depends on lakewide conditions rather than local conditions. Other indirect biological effects of thermal discharge are the displacement of thermally sensitive species due to avoidance or because of temperature barriers and their replacement with species tolerant/ attracted to warmer waters (BEEMS, 2011).

In assessing thermal discharge effects on fish, several approaches can be taken either independently or in concert. These approaches include the comparison of thermal plume behaviour throughout the water column against temperature criteria, mapping thermal plumes against critical habitat and modelling the survival during a thermally sensitive life stage of a sensitive fish species. According to the Canadian Council of Resource and Environmental Ministers (CCREM) Canadian Water Quality Guidelines (CCREM, 1987), temperature criteria should include criteria for acute exposures such as short-term (hourly and/or daily) changes to water temperature that may result in heat-shock and cold-shock scenarios and criteria for chronic sublethal exposures such as maximum weekly average temperature.

Maps are valuable tools that can help visually evaluate intersections of critical habitat and environmental conditions – in this case, thermal plumes. Given the thermal sensitivities of the egg incubation stage, for coldest water species the critical habitat most relevant to thermal discharges is spawning habitat. Thermal plume maps based on real temperature data overlaid against the critical habitat is a powerful way to identify the significance of the effect of a thermal discharge on a thermally sensitive species. Since critical habitat depends on the biological preferences and needs of the sensitive species, critical habitat maps need to include physical characteristics that are relevant to the species such as bathymetry, substrate-type, algae cover, etc. Statistical representation of thermal plumes overlaid against critical habitat maps helps to reveal critical habitats that may be exposed to a thermal plume.

The third approach is based on numerical modelling of the biological effect – acute (survival/ death); chronic (growth/fecundity) – of thermal discharges. Numerical models calibrated to predict biological responses to a given thermal regime are another powerful approach because of their ability to quantify the biological response. Griffiths (1980) developed round whitefish embryo survival models based on laboratory studies that measured embryo survival in waters exposed to constant elevated temperatures and abrupt and small-scale periodic temperature changes. Griffiths observed that his models adequately predicted mortality rates under different temperatures.

Recently, the Canadian Safety Standard Group (CSA, 2012) published a criterion for ambient temperature change, or ΔT, stating that 3°C above ambient temperature would be protective in most waters in the absence of site-specific and species-specific information. The CSA criterion was originally proposed by Turnpenny and Liney (2007). The maximum ΔT of 3°C above ambient was proposed as a temperature "uplift" limit for all waters of good to bad ecological status while a ΔT of 2°C above ambient was proposed for receiving water bodies classified as having high ecological status, which is defined as being consistent with undisturbed conditions (Turnpenny and Liney, 2007). The aquatic ecological conditions in the vicinity of the nuclear generating stations may be appropriately classified as disturbed.

Sensitive species

Identification of sensitive species that are relevant to the site being assessed is critical for the detection of any significant effect of a thermal discharge. Historical and current data on cold water fish communities in the vicinity of Pickering and Bruce nuclear power plants were reviewed to determine the most thermally sensitive species that are historically and contemporarily in relative abundance. The review was based on fish community surveys conducted during the coldest (winter) months because the impact of thermal plumes is likely to be greatest when ambient temperatures are coldest and when a sensitive life stage, such as embryonic development, is occurring. Temperature sensitivity data in literature were also analysed to identify the most thermally sensitive life stage and the temperature tolerance/optimal ranges for that life stage.

At both the Pickering and Darlington sites, the round whitefish (*Prosopium cylindraceum*) occur historically and contemporarily in significant abundance. With the exclusion of the burbot, the egg incubation (embryo) life stage of the round whitefish is the most thermally sensitive among cold water species found in these waters. Therefore, the round whitefish was selected as the most appropriate species to consider for thermal effects assessments at all three nuclear power plants with particular attention to the egg incubation period during the winter season.

The selection of appropriate sensitive species is an important starting point for assessing the effects of a thermal discharge into an aquatic or marine environment. One of the challenges with identifying sensitive species is that many fish species migrate while some do not. Fish may migrate from deep to shallow waters seasonally or daily, from a foraging area far offshore to spawning habitats nearshore. The habitat needs and preferences are diverse and adaptive. For example, in colder northern lakes, round whitefish are known to spawn in shallower depths (Bryan and Kato, 1975). Likewise, different populations of the same fish species may have adapted to the particular habitat conditions of different water bodies from which they originate. Therefore, it is important to study the fish communities site-specifically and over all seasons to ensure that all important species are detected and considered. More specifically for the purposes of detecting thermal effects, particular attention should be given to data during the parts of the season where thermal sensitivities are known.

As part of the selection of the sensitive species, a review of the biology of the species being considered is necessary for identifying critical habitat, thermally sensitive life stages and any significant biological synchronisations. Round whitefish spawning has been reported to take place from early to mid-December along the north shore of Lake Ontario when water temperatures drop to 2-4°C (Griffiths, 1987). Adult round whitefish spawn nearshore and the fertilised eggs are broadcast in depths ranging from 1 to 8 m over substrates with sufficient interstitial spaces (e.g. honeycomb rock, boulders, rubble, gravel) to protect developing embryos from ice, currents, waves, and predators (Wismer and Christie, 1987). McKinley (1983) noted that lab-reared round whitefish embryos began hatching 123 days after fertilisation and all embryos finished hatching 131 days after fertilisation. Furthermore, in setting criteria, it is also important to identify any sub-phases of embryonic development or other life stages where responses to thermal inputs are distinctly different and discrete. For example, Griffiths (1980) found that the embryonic developmental stages could be divided into three distinct blocks of which blocks 1 and 3 were found to be thermally sensitive. Block 1 encompasses stages 1 to 9 in embryonic development and block 3 extends from stage 19 to completion of hatch.

Larval round whitefish are sedentary until their yolk-sac is almost completely resorbed, about 7-10 days after hatching (Pope, 1995). Free-swimming larval round whitefish stay on or close to the lake bottom at depths of 3 to 7 m (Pope, 1995). These depths and substrate correspond to inferred locations of spawning shoals at Pickering and Bruce Power (Golder, 2010; Todd, 2010). Owing to the difficulty of capturing whitefish larvae, uncertainties regarding the exact spawning locations remain, though general characteristics of round whitefish spawning habitat are known (Stantec, 2004; Bruce Power, 2006).

Thermal criteria

The evaluation of temperature data requires the establishment of short-term and chronic thermal criteria, which is consistent with the CCREM Canadian Water Quality Guidelines. Together, the short-term and long-term thermal criteria result in a more realistic assessment of the effects of a thermal discharge that may change in extent and intensity with ambient currents or adjustments in discharge rates. Thermal criteria could be merely adopted from existing regulatory requirements or else more specific criteria could be developed from site/species-specific thermal tolerance requirements found in literature. The findings published by Griffiths (1980), the Canadian Nuclear Safety Commission and Environment Canada, in consultation with Ontario Power Generation (OPG), confirmed three thermal criteria: maximum weekly average temperature (MWAT), short-term daily maximum (STDM) and hourly (HI) for each of the three developmental blocks of the round whitefish embryo developmental life stage.

HI, STDM and MWAT criteria were documented in the receiving waters at Pickering. The most stringent criterion is the MWAT. It has been concluded that short-term extreme temperatures can influence the survival of developing embryos, and this finding is valuable for determining the risk posed by thermal discharges. However, quantifying how many eggs will survive is not possible with temperature criteria alone.

Even though the criteria were based on egg survival information published by Griffiths (1980), the criteria themselves merely indicate that an exceedance may lead to adverse effects on the embryos affected. It is not possible to estimate quantitatively how the magnitude and frequency of the exceedances will affect the survival of the embryos. The advantage of using temperature criteria exclusively is their simplicity. The only data analysis that is required is a comparison against the criteria and decisions on thermal discharge behaviour that can be made rapidly.

Critical habitat mapping and thermal plumes

Critical habitat mapping data for sensitive species of interest in the vicinity of nuclear power plants provide valuable information about the significance of the potential impact of the thermal discharge. Since the incubation period is the most critical life stage for thermal impacts, spawning habitat – where the eggs are laid and fertilised – is effectively the key critical habitat for thermal effects on whitefish.

Round whitefish are broadcast spawners (Bryan and Kato, 1975) that prefer substrate with interstitial spaces such as gravel and boulders at depths ranging from 3 to 7 m in Lake Ontario (Griffiths, 1987) and similarly at depths of 3 to 7 m in Lake Huron (Balesic and Martin, 1987). Identification of substrate and bathymetry in the vicinity of the nuclear generating stations that correspond to the biological preferences of the round whitefish enables the creation of a map of potential spawning habitat. Fish community/abundance data can corroborate the validity of potential spawning habitat mapping. The fish community/abundance data, which is based on gillnetting samples of adult fish, show that round whitefish occur at significant abundance in the vicinity of all three nuclear power plants during the spawning season (i.e. early winter).

In contrast, OPG translated the thermal plume data for the Darlington plant from 15 December 2011 through 13 April 2012 into plots of embryo survival that correspond to the plume isotherms against potential spawning habitat based on preferential spawning depths for round whitefish. OPG Rivieres identified the area of Lake Ontario between 5 and 10 m deep in the vicinity of Darlington nuclear power plant as a potential round whitefish spawning habitat.

Physical variability in water levels and the number of nuclear reactor units in operation over a given time will likely have an effect on the size of the thermal plume and the potential habitat available for spawning. If historic low water levels were reached again at Lake Huron, the 2 m deep contour would be instead 0.5 m, which likely would render it unsuitable for round whitefish spawning. Furthermore, the difference in the thermal plume impact between Bruce and Darlington nuclear power plants may be attributable to the fact that Bruce discharges cooling water directly to surface waters while at Darlington, the cooling water is discharged through a diffuser. This diffuser is installed at 10-12 m deep with numerous directional ports (Golder, 2011) resulting in the dispersion of the thermal plume into deeper waters away from much of the critical habitat. Climate change is likely to exacerbate low water levels in the Great Lakes.

With the use of numerical models, it is possible to predict relative survival loss. The numerical models enable the quantification of biological effects of the thermal discharge on incubating round whitefish embryos – namely the percentage of relative survival. The combined results of blocks 1 + 3 relative survival loss indicate that approximately half the stations would be predicted to lose 10% or more embryos relative to reference stations. Establishing what level of loss – how many sampling stations or what percentage of loss – would be deemed ecologically significant is challenging.

The updated Gagnon (2011) model – which was based on the lab data reported by Griffiths (1980) for embryo survival – was applied to temperature data to predict biological effects at both Darlington and Pickering

Results of the relative loss of survival of round whitefish embryos near Darlington and Pickering indicate that embryo survival at Darlington within was similar to all the sampling stations, including the reference site (Gagnon, 2011). Pickering experienced greater losses of embryos. Relative to reference stations, the Pickering data from the 2009/2010 winter show nearly half the stations exceeding relative survival losses of 10% combined from blocks 1 and 3. For both nuclear power plants, the Gagnon model predicted that the greatest losses would occur within block 3.

Embryo survival data alone may be misleading in determining the significance of the thermal plume effects. Potential round whitefish habitat mapping for Darlington ensures that the survival data are in the context of real conditions – that the losses in survival constitute a small fraction of the total potential habitat available for round whitefish spawning. In contrast, at Pickering, while a potential spawning habitat map was not developed, it was assumed, on the basis of numerous gillnetting studies for round whitefish during late autumn, that the sampling stations were located within the spawning habitat. The embryo survival predictions indicated that nearly half the stations would experience 10% or more embryo survival loss compared to reference stations.

One particular uncertainty associated with the numerical models is the challenge of incorporating hatch advance into predictions of embryo survival. Griffiths (1980) has documented that hatch advance occurred in the development of round whitefish embryos under the influence of the thermal discharge. Gagnon also developed a numerical model for hatch time based on the mean hatch times reported by Griffiths (Gagnon, 2011). Round whitefish eggs hatched approximately 600 degree-days after fertilisation described by the following equation:

$$D = \frac{600}{T+1.5} \quad (3)$$

where D is the days to hatch and T is the average temperature.

As indicated earlier, round whitefish spawning season may begin early in December and extend to mid-December on the north shore of Lake Ontario (Griffiths, 1987). The time to hatch has been mathematically modelled to be linearly related to the average temperature over the course of the incubation period. Griffiths temporally identified the round whitefish embryo developmental blocks as 1 December to 5 January for block 1 and 9 March to 17 April for block 3 (Griffiths, 1980). Griffiths also reported days to hatch at time weighted average temperatures, where the days to 100% hatch decreased from 122 days at 3.9°C to 76 days at 6.8°C, indicating a hatch advance of 46 days as a result of an increase of 2.9°C on average over the incubation period. With a hatch advance of 46 days, if fertilisation occurred on 1 December, 100% hatch would be occurring on 15 February which is 22 days before the beginning of the block 3 period. Similarly, if fertilisation occurred on 15 December, then 100% hatch would be occurring on 1 March in a non-leap year which is still eight days before the commencement of the block 3 date. The predictions for embryo survival based on Gagnon (2011) models did not account for hatch advance but rather calculated survival based on the temperature data for blocks 1 and 3, as if the embryos went "full term" irrespective of accelerated development due to thermal input. Secondly, if hatch advance is accounted for, then the embryos hatching in mid- to late-February would be progressing through block 3 during typically the coldest period of winter, mid- to late-January to mid- to late-February, rather than during the rapidly warming period in late-March to mid-April. As indicated earlier, the greatest survival losses at Pickering occurred within block 3; however, if hatch advance had been accounted for, the survival losses may have been significantly less.

Climate change implications

Cooling for the existing Canadian nuclear power plants in the Laurentian Great Lakes will be influenced by the predicted climate change scenarios into the late 2040s. Refurbishment projects to ensure continued operation of Darlington and Bruce nuclear power plants for likely 30 additional years are ongoing. The proposed new build project at the Darlington site, though not confirmed, will likely extend the operation of nuclear power generation and the use of OTC on Lake Ontario until well into the 2080s. There is evidence that warming of the Great Lakes, especially Lake Ontario, is already affecting the operation of the nuclear power plants. Increasing water temperatures in summer have caused the Pickering plant to derate to comply with regulatory limits on cooling water delta T's (Senes, 2007). Though it is a lakewide issue, *cladophora* algae clogging intakes at Pickering has been documented as well. OPG has noted that in midsummer and autumn, as the *cladophora* dies and sloughs off substrate, these algae can form "balls" that may become entrained in the Darlington nuclear power plant intake structure (Senes, 2011). Local thermal discharge around the Pickering nuclear power plant has been associated with a sixfold increase in *cladophora* biomass in the vicinity of the thermal plume, and lakewide water temperature increases due to climate change are expected to favour *cladophora* annual production (Hecky, 2006).

Overall warming of air temperatures is predicted to linearly increase water temperatures to a range slightly over 1°C by 2040 and surpassing 2°C by 2040-2070 period at both Lake Ontario and Lake Huron. The refurbished Darlington and Bruce nuclear power plants would be entering their last years of operation by the 2041-2070 period and, therefore, for the latter operational phase of these nuclear power plants, a moderate increase of about 2°C in ambient water temperatures may be expected. This increase over the current thermal regimes may begin to have significantly greater impacts on the round whitefish habitat near the nuclear power plants. For example, the extent of the 3°C quartile limit isotherm may extend far beyond the range that is predicted under current conditions, impacting a much greater portion of the spawning habitat.

Between 2071 and 2100, Lake Ontario is expected to experience an increase in water temperature of 3.2°C to 4.8°C and Lake Huron a rise of 2.6 to 3.9°C (Trumpickas et al., 2009).In both Lake Ontario and Lake Huron in the vicinity of the nuclear power plants, the round whitefish spawning habitat is likely to be impacted by the earlier spring warm-up and later period in autumn to reach optimal spawning temperatures. Overall, this means that by the time the proposed Darlington new build reactors enter their last years of operation the period of cold water during which round whitefish embryos can develop will be much shorter.

Many authors have predicted that with warming surface waters in the Great Lakes, the thermocline will form at deeper depths and summer stratification of the lakes will last longer (McCormick and Fahnenstiel, 1999; Magnuson et al., 1997; Austin and Colman, 2007). Among many of the implications of these predictions, the ability for OTC systems to cool the nuclear reactors is an important concern. In Lake Huron near the Bruce Power plant, according to recent records, thermal stratification starts in June with the thermocline passing through 10 m depth in July and remains shallower than 30 m through August (Golder, 2005). However, with increasing depth of the thermocline and extended length of stratification, the intake structure at Bruce Power plant, which is at a 12 m depth (Golder, 2005), will be taking in increasingly warmer water for cooling as climate change progresses. Likewise, the Darlington plant's intake, which is at a depth of 10 m (Senes, 2011), is likely to be faced with similar challenges at Lake Ontario.

Compounding the increasing depth of the thermocline and the extended period of stratification are potential changes in lake levels. The government of Canada (2008) projects that though water levels and outflows in the Great Lakes are regulated, water levels have ranged from 50 to 80 cm higher and 50 to 80 cm lower than the average between 1934 and 2002. It also concluded that, although most scenarios of future climate projections predict increased precipitation, the increase in evaporation due to the higher temperatures will outpace precipitation increases, resulting in an overall reduction of lake levels.

Conclusions

Because of the prevalence of round whitefish habitats and adults in spawning condition in the immediate vicinity of the three nuclear power plants, the assessment of thermal discharge was evaluated by using round whitefish data. The three tools used to assess the level of risk posed by the thermal discharge on the aquatic environment individually have strengths and challenges but, taken together, can form a robust scientific approach. This study shows that numerically modelled predictions of biological effects, applied to critical habitat mapping and information on the extent of the thermal plume, along with an assessment of thermal discharge behaviour against temperature criteria, allow for an effective assessment of the thermal discharge.

Potential climate change effects that may have an impact on the operation of the nuclear power plants and on the round whitefish population in the vicinity of the plants were also considered. In the near term to 2040, slight increases in water temperature would likely not cause large changes in the state of thermal effects on the round whitefish population. However, as the refurbished nuclear power plants approach end of life, greater impacts due to longer stratification periods, deeper thermocline, lower water levels in the case of Bruce, and overall higher water temperatures will likely progressively increase the risk to round whitefish at both the Darlington and Bruce nuclear power plant sites. In the case of nuclear new build projects such as the proposed new Darlington plant, it would be prudent to carefully consider climate change effects before deciding on the type of cooling technology. If OTC is selected, the location of the intake and outfall should be designed to adapt to future climate change-related effects.

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Chapter 7. **Scenarios of weather events for Finland's nuclear power plants**

Scenarios of sea level rise, seawater temperatures, freezing rain, snow storms and other relevant weather events for Finnish nuclear power plants

Introduction

Very rare weather phenomena that trigger sudden or prolonged sea level variations, abundant freezing rain or excess snowfall as well as extremely cold and warm episodes need to be included in the calculations of risks to nuclear power plants. Adverse and extreme weather events may also affect the safety of the plants indirectly, e.g. by having a negative impact on the transport sector, causing injuries and damages.

The following phenomena, among others, have been considered in studies in Finland: extremely high or low air temperature; heavy precipitation (rain or snow); length of dry, hot or cold spells; extreme enthalpy; blizzards; freezing precipitation; small-scale phenomena such as thunderstorms, lightning, large hail and tornadoes; short-term very high water levels in the Baltic Sea. In addition, scenarios for mean sea level rise and short-term sea level variations have been discussed by Tietäväinen et al. (2011 and 2012) and by Jokinen et al. (2013a).

The occurrences and probabilities of extreme events with different durations have been analysed on the basis of observations, and weather datasets and climate models have been reanalysed.

In Finland, there are no known cases of severe ice storms where the ice accumulation due to freezing rain is substantial. In Sweden and Russia, such events have been severe at some locations, and even catastrophic in Canada in 1998 as described in Chapter 5 and also (Jokinen et al., 2013a).

The focus here is on freezing precipitation, blizzards and snow storms, scenarios for the mean sea level rise, and surface temperature in the Baltic Sea. Geographical patterns and future trends of extreme weather events in Northern Europe are also briefly discussed.

Freezing precipitation

Freezing precipitation is rain or drizzle that occurs when surface temperatures are below 0°C. In other words, the precipitation particles are supercooled and in liquid form. These supercooled drops freeze when in contact with any object, such as road surface or power lines. In Finland, freezing drizzle is typically observed about seven times a year and freezing rain only once a year in some part of the country. About 30% of all cases are observed in January. However, the worst cases have occurred in November, February and March (Laine, 2008; Tietäväinen et al., 2011; Jokinen et al., 2013b).

Most events (over 70%) of freezing precipitation in Finland take place as a weak drizzle (Laine, 2008). The eight most significant freezing rain episodes since the 1950s caused 4 to 7 mm of freezing rain, which is very little compared to the real ice storms in Canada (30 to 100 mm). On the basis of 1 200-year-long climate model simulations, extreme freezing rain in Finland could reach 20 mm during a freezing rain episode (Jokinen et al., 2013a). Beyond 30 mm, freezing rain is known to cause damage to infrastructure.

There were no clear signals in model simulations that climate change could have caused severe and more frequent freezing precipitation events in southern Finland (Jokinen et al., 2013a).

The frequency of freezing precipitation at European airports from 1982 to 1997 was analysed by Vajda et al. (2011). In many locations in Central and Eastern Europe, there were more than 144 hours of freezing precipitation per year while in most of Western Europe the annual number was less than 72 hours. The large spatial variation is due to the effect of the local terrain on temperature inversions that are required for freezing precipitation to occur. The phenomenon is most typical in isolated valley areas.

Blizzards and snow storms

A blizzard is a severe storm condition defined by low temperature, sustained wind or frequent wind gusts and considerable precipitating or blowing snow.

According to observations in 1965-2005, heavy snowfall events in combination with high wind speed in the southern and south-western parts of Finland occur most often in December and January. In February and March, snowstorms are less frequent and typically have lower wind speeds. In early winter, cold air associated with relatively warm seawater creates favourable circumstances for heavy snowfall, especially near the south-western coastline (Niinimäki, 2008).

Vajda et al. (2011) considered a blizzard to occur when the following criteria were met: snowfall exceeding 10 cm/24 hours, wind gust ≥17 m/s and daily mean temperature below 0°C. The authors' analysis for Europe indicated a relatively low frequency of blizzards during the study period 1989-2010. Blizzard conditions occurred predominantly over the Alps and Northern Europe (30 to 40 cases in 30 years). The most affected regions are the western coast of Scandinavia and Iceland, with more than 140 cases in 1989-2010 (~10 cases/year). However, Vajda et al. (2011) stated that the frequency of blizzard events is perhaps underestimated.

The "lake-effect" snow is a phenomenon where intense snow showers are formed over relatively warm waters and then moved to the coast. The worst-case scenario in Finland could bring approximately 80 to 110 kg/m^2 of snow in a few days (as in Sweden). The ideal conditions for heavy lake-effect snow exist in November and December (Jokinen et al., 2013a).

Geographical patterns and future trends of extreme weather events in Northern Europe

In Northern Europe (Fennoscandia, Russia – north of 55° latitude, Iceland and the northern part of Denmark), the areas most impacted by winter extremes are located north of 65° latitude, e.g. Lapland and Iceland, recording the highest probability of extreme cold spells (20 to 35 days/year for a daily mean temperature under -20°C in Lapland), heavy snowfall (40-50 days/year with 10 cm/day on the western coast of Norway and Iceland), blizzards (locally over 140 cases between 1971 and 2000), and extreme wind (especially over Iceland). Heavy rainfalls are frequent over the fjord coast and the westerly exposed mountain ranges of Norway. Conversely, the frequency of hot spells is the lowest within the Northern European zone – typically 5 to 15 days/year with maximum temperature over 25°C (Vajda et al., 2011).

In the future, with global climate change, the frequency and intensity of many weather and climate extremes are likely to alter:

- The winter extremes are projected to moderate, with a substantial decrease in the frequency of cold spells, blizzards and snowfall events, while heavy snowfalls (>10 cm/day) indicate a mixed behaviour. They are projected to become more frequent over Scandinavia by 1 to 5 days by the 2050s (Vajda et al., 2011).
- As anticipated in a warming climate, heatwaves (>25°C) are expected to occur more frequently (about 5 days/year) in Scandinavia and northern Russia. However, the projected increase is not as robust as in Southern Europe, where precipitation extremes (>30 mm/day) record a slight intensification (1 or 2 days). Wind gusts show a tendency of strengthening over the Baltic Sea and weakening over the land areas, although there were fairly mixed results between models (Vajda et al., 2011).
- The probability for severe sea ice winters is expected to decrease. The average maximum fast ice thickness is likely to have decreased by 30 to 40 cm in 2060 relative to the control period 1971-2000, leaving the southern areas of the Baltic Sea coast largely ice-free (Vajda et al., 2011; Luomaranta et al., 2014).

Mean sea level rise

The sea level is rising globally, mainly because of changes in seawater density (thermal expansion) and melting of land-based glaciers and ice sheets in a warming climate. The global average sea level rise in the 20th century was 1.7 mm/year (Bindoff et al., 2007). The sea level rise is projected to accelerate in the future: 20 to 200 cm during this century. The large uncertainty in these scenarios is especially due to insufficient knowledge about the behaviour of the large continental ice sheets (West Antarctica and Greenland) in a warming climate. The global sea level rise is not evenly distributed; the share on the Finnish coast is projected to be smaller than the global average (Johansson et al., 2012).

On the Finnish coast, the post-glacial land uplift proceeds at a rate of 4 to 10 mm/year, counteracting the sea level rise. Local meteorological conditions also affect the Baltic Sea level. Johansson et al. calculated sea level scenarios for the Finnish coast by combining these factors. The different land uplift rates result in different scenarios along the Finnish coastline.

Sea surface temperature in the Baltic Sea

The Baltic Sea has a strong seasonal cycle. In February-March, the surface temperature is near the freezing point. During these months the seawater becomes supercool so that the surface temperature may go below local freezing point. Warming starts in spring at the beginning of April and is fastest in May and June. The maximum annual sea surface temperature occurs at the very beginning of August. In September, waters begin to cool rapidly and this lasts until January on average. The average maximum temperature in the open coastal waters is about 16°C with a standard deviation of about 3°C. Thus, normal summer temperature is between 13°C and 19°C. Extreme values may be even 3°C higher or lower. Hence in summer the range is between 8°C and 22°C. The cool temperatures occur after strong upwelling events that bring deeper cool water to the surface.

Air temperature in the coastal area is above sea surface temperature on the average between the beginning of April and the mid-August. During this time the sea surface temperature follows air temperatures with a difference of about 1.5 to 2°C.

The well-mixed upper layer is typically 15 to 20 m deep. Thus, the surface layer temperature is more or less the same as in the whole upper layer even though the average temperatures at 10 m depth seem to be 3°C lower than surface temperatures. However, the maximum surface values occur on calm sunny days and there may be a strong temperature gradient in the uppermost layer of the sea. On the other hand, the warm layer can reach depths of more than 20 m. This means that the temperature of the water used for cooling the reactors can vary depending on the depth of intake.

Surface waters in mid-summer may have become 1 to 2°C warmer than in the 1970s. It has been observed that spring comes a bit earlier and the maximum temperatures occur a bit later than some decades ago.

In the sea, the deeper layer temperature varies annually, too. This variation is far from symmetric, because the deeper the layer is, the later the temperature maximum occurs. On the other hand, the overturning in spring and autumn mixes the water in the ~50 m-deep upper layer to the temperature of maximum density, which is somewhere between 2.7 and 3.3°C in the open coastal waters. However, temperature can be even 2 to 2.5°C higher in semi-enclosed shallow coastal bays than in the open seawaters.

Adaptation measures at TVO nuclear power plants against extreme weather conditions

TVO operates two nuclear power plant units, Olkiluoto 1 (OL1, commissioned 1978) and Olkiluoto 2 (OL2, commissioned 1980) in Olkiluoto, Eurajoki municipality, on the west coast of Finland. Both are boiling water reactors (BWR) with a capacity of 880 MW. A third nuclear power unit, Olkiluoto 3 (OL3), is under construction at the same site. It uses Areva's European pressurised water reactor (EPR) with a capacity of 1 600 MW.

Evolution of design values of weather conditions at TVO nuclear power plants

The design values of weather conditions are presented in a final safety analysis report (FSAR) of the power units and the assessments of the frequencies of extreme weather conditions are done in a probabilistic safety analysis (PSA). The FSAR of the new OL3 power unit defines the design basis for the following weather phenomena:

- maximum air design temperatures;
- minimum air design temperatures;
- maximum external humidity conditions;
- wind speed;
- strong wind speed return periods;
- tornado return periods;
- cooling water temperature;
- seawater level;
- low seawater level;
- rainfall;
- snowfall;
- lightning;
- hazards with potential effects on plant parts such as cooling water intakes, air intakes;
- site proximity hazards.

The PSA report also includes an evaluation of each hazard, including results from multiple events (screening analysis).

Heavy snowfall and air intake for emergency diesel generators

An example of continuous improvement of preparedness against extreme weather conditions is the arrangement of combustion air intake for emergency diesel generators. The risk, which is foreseen, is blockage of the air intake as a consequence of simultaneous snowfall and wind.

For OL1 and OL2, the original air intake gratings have been back-fitted with a pressure-difference sensor to detect the blockage and automatically change the combustion air to be taken from inside the diesel building. Considering the improved reliability of diesel generators, the cost of the project was moderate.

For OL3, the measures against snowfall were taken into account already at the design phase. Measures are taken to prevent blockage of the air intakes of heating, ventilation and air conditioning, diesel generators or other systems, which rely on an air supply to maintain their function. Protection against intake of snow is provided by grids in the air intake and the design of special "concrete noses". There is a required minimum free distance below the air inlet in order to prevent the snow from piling up to the level of the intake. All air intake and outlet openings are heated.

Rainfall and seawater level

Protections against external flooding have been set up in part to prepare for a changing climate. The capacity of storm draining in the yard area of OL1 and OL2 has been recently increased. This was done after several spells of unusually heavy rainfall in nearby regions.

The likelihood of seawater level increasing as a result of global climate change has been studied extensively. The land uplift phenomenon, which is typical for coastal regions around the Gulf of Bothnia, will compensate the possible effects of climate change in the region for coming decades. According to recent projections, the original design for flooding protection up to 3.5 m (N60) at TVO's plant area has been judged to be adequate. The probability of reaching this water level is very low.

The outside doors of TVO's power units do not meet water tightness requirements. However, some cliff-edge analysis was done recently, and outer door tests were performed at the OL3 Nuclear Island. Doors were found to be leak-tight up to the level of 15.5 m (N60) – the leak was less than 10 litres per hour.

Seawater blockages due to frazil ice

Power plant shut downs caused by frazil ice formation have occurred in Olkiluoto in 1988, 1995 and 2008. All occasions were quite similar.

Seawater flow for OL1 and OL2 is about 30 m^3/s (per unit) while in normal operation. The seawater is cleaned before entering the process by three successive screens. First, the seawater flows through an open seawater inlet channel to inlet rakes. This screen consists of carbon steel rods that are 10 cm apart from each other. After this, the seawater flows to an inlet tunnel, and then to a seawater screening plant.

In the seawater screening plant there are coarse screens, which consist of bars that are 2 cm apart from each other, and a band screen, which consists of baskets that are fastened to a chain. The baskets rotate around the shaft of the band screen, which has a 2 mm-sized mesh. After the seawater screening plant, the seawater is pumped by main pumps through the turbine condenser and to a surge chamber, an outlet tunnel, an outlet channel and back to the sea.

During the frazil ice formation incidents, the seawater was frozen to band screens in the seawater screening plant when the seawater temperature dropped rapidly below -0.3°C. This caused the seawater pumps to stop because of the low water level on the suction side of the pumps that, in turn, caused a pressure increase in the condenser, and as a consequence, a turbine trip. After the turbine trip, the steam was supposed to be directed through the turbine bypass straight to the condensers, but because of the loss of primary heat sink, the steam could not be led to the condenser. This caused a reactor scram and the steam was directed to the wet-well, which is a condensation pool inside the reactor containment building.

There are three major factors that enable the seawater temperature to decrease so low that frazil ice occurs:

- air temperature below zero; especially with snowfall at the same time;
- wind velocity and direction; especially when the sea is not frozen;
- seawater salinity decrease due to freshwater pulses.

In a coastal area, the wind direction and salinity are interconnected because the wind may bring a float of lighter freshwater to the inlet channel. The salinity of the seawater in the Olkiluoto area is about 0.5%, and this corresponds to a freezing point of -0.3°C.

Two means of preventing frazil ice formation are applied in OL1 and OL2:

- warm water pumping;
- electrical heating of inlet rakes.

After the frazil ice blockage in 1995, special equipment was built to prevent the incoming cooling water from getting below the freezing point. Warm water is pumped from the surge chamber after the condensers of OL2 to the beginning of the covered inlet channels of the OL1 and OL2 units. The temperature of the pumped water is about 13°C, and the flow is about 1 m^3/s per unit. This was originally enough to raise the cooling water temperature by 0.4°C. In case of shutdown, the surge chamber is filled with warm water, and this gives time for both units to recover. The pumping system was to be started when the seawater temperature drops below -0.2°C. At one point in 2008 the system had difficulty starting, causing a blockage, so the pumping is now started when the seawater temperature drops below +2°C. The total cost of the project, including research and planning, was around EUR 1 million (in current value).

Probabilistic risk assessment has showed a significant reduction in the core damage frequency thanks to the warm water pumping system.

The normal seawater flow was recently increased and the warm water pumping system can only increase the temperature by about 0.25°C. Plans to increase the capacity of the system to the original level of +0.4°C are in progress.

Frazil ice starts to form on any solid surface that the sub-cooled water hits. In rivers this means that solid ice starts to grow from the bottom. In cooling water channels, this means that the inlet rakes are the first place where a blockage can occur, and the coarse and band screens are the next ones. In Olkiluoto, ice formation on the inlet rakes is prevented by electric heating: electric current is led into the steel structure of the rakes from one corner and out from the other. The average density of the heat flow is 500 W/m^2, and according to boundary layer heat transfer, this raises the temperature of the rake structure by 0.6°C as an average and by 0.9°C as a maximum value above water temperature.

Adaptation measures at Fortum’s Loviisa nuclear power plant

Fortum Ltd operates two VVER-440 pressurised water reactors in Loviisa on the south coast of Finland. The units, currently 488 MW each, were commissioned in 1977 and 1980.

Air cooling system

In 2014, it was decided that a new air-cooling system, independent of seawater cooling, will be constructed for Fortum’s Loviisa nuclear power plant. The system will improve the plant’s preparedness for extreme conditions, when seawater for some reason becomes unavailable for its normal cooling function (such as an oil catastrophe in the Gulf of Finland, frazil ice, or an exceptional natural phenomenon such as excessive algae growth). The plant is already equipped with backup systems for loss of seawater, but the new air cooling towers will reinforce its safety even further.

The cooling system consists of two air-cooling towers per unit, one of which will be used for removing decay heat from the reactor, the other for dealing with the spent fuel pools as well as for cooling off other equipment critical from a nuclear safety point of view. The towers will be located in square buildings, each measuring 10 x 15 m and about 10 m-high.

Fortum studied and developed the new cooling system for several years. The air cooling towers also became a development target in the safety assessments carried out by the Finnish Radiation and Nuclear Safety Authority (STUK) in 2012 as part of the so-called stress tests within the European Union (Fortum, 2013; STUK, 2011).

High seawater levels

At the Loviisa site, the rise of the sea level is caused by weather phenomena. If all the factors identified were at their estimated maximum level simultaneously, the sea rise level would be at 2.13 m. The impacting factors include the total volume of water in the Baltic Sea (contributing 83 cm to the rise), the rise in the mean sea level as a result of strong wind (60 cm), the specific phase of a standing wave (20 cm), low air pressure (40 cm) and tide (10 cm). The highest experienced sea level was 1.77 m in January 2005 and no problems were encountered. Seawater is expected to rise to its peak level at a rate of 10 cm/h.

If the sea level rises by 1.3 m above the average level, inspections to lower plant compartments are increased. When the level exceeds 1.75 m, preparations for shutdown are initiated and at 1.95 m the plant is shut down. The critical sea level is 2.1 m during an outage (it will increase to 2.45 m after gate modifications) and by 3 m during power operation. Sea levels are significantly higher during winters. Plant annual outages are scheduled to occur in the summer time, when electricity demand is at its lowest. During power operations, large volumes of seawater could get into the plant yard. This is possible if seawater rises more than 2.5 m and if the surge from a certain direction carries water into the yard area, or if the seawater level rises above 3 m. New ideas on flood protection will be investigated in detail in the future (Fortum, 2011).

High seawater temperatures

The design basis for intake seawater temperature is +23°C, but loss of ventilation in the instrumentation room would cause the temperature to rise above +35°C. High seawater temperatures have caused production losses twice after hitting the +32°C maximum temperature limit of the discharged cooling water. The maximum temperature limit on discharged cooling water has been increased to +34°C in the plant's new environmental permit. Therefore, further production losses are not expected.

The intake seawater's maximum temperature has increased slightly during the Loviisa plant operation. It is expected that the trend will continue. Simulations indicate that a 2°C increase on average temperatures can be expected at the Loviisa site during this century.

A deep seawater intake has also been studied that could decrease the intake temperature during summers, improve the turbine efficiency and mitigate environmental impacts. At Loviisa, this solution requires a tunnel of about 5 km and additional pumping power. So far, studies indicate this deep water intake is economically unviable in the current situation.

Frazil ice

The probability of frazil ice blocking the cooling sea water intakes is highest during cold weather, but only when accompanied by high wind, and when the sea surface is not yet covered with ice. In order for frazil ice to enter the cooling water tunnel, a cold easterly wind must prevail and blow the wind-chilled water against the east-west oriented shoreline. The wind should turn to blow from south-west and carry the supercooled or icy water to the water intake channel opening.

The frequency estimate of a frazil ice occurrence is 2.2 10^{-2}/year according to the licensee's analysis. A wind speed of 5 to 10 m/s is strong enough to generate frazil ice. The stronger the wind, the stronger frazil ice.

The cooling water is taken from the south-west side of the Loviisa nuclear power plant. There are three parallel inlet flow ports, each with a capacity to supply 50% of the cooling water needed in normal operation. In a shutdown mode, the need for cooling water is essentially lower. Each inlet has a mechanical screen-cleaning system to remove impurities. One coarse screen has a section that can be heated with electricity in frazil ice situations. Inlet flow ports can be closed in flow direction with a sluice before the coarse screen.

After the flow ports and coarse screens, seawater flows to both Olkiluoto units in a 70 m^2 rock tunnel which later breaks up into individual tunnels for both units. In unit-specific seawater systems, there are four parallel suction chambers in the circulating water treatment system. Each suction chamber, including fine screen and basket filter, can be isolated with sluice gates.

There is a pipeline from the LO1 and LO2 seawater systems which can be used to divert part of the warmed seawater back to the inlet sea chambers. This system is used if water temperature at the inlet is close to frazil ice formation.

In case the inlet is blocked for some reason, e.g. because of algae or oil slick, seawater is circulated between the two units with the LO2 service water system pumps. This applies only for cooling safety-related systems. It is also possible to use the LO1 service water pumps for recirculation if those of LO2 are not available.

The Loviisa nuclear power plant is also prepared for the blocking of fine screens or basket filters. In this case, it is possible to take cooling water for the service water system through the outlet tunnel and discharge warmed water to the surge chamber at the inlet. This applies for both units.

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Chapter 8. **Heatwaves in France**[1]

Introduction

During the heatwaves that affected France in 2003 and 2006, nuclear power plant safety functions were ensured in compliance with the general operating rules. Electricity generation equipment was also operable at all times. The design basis margins of the requisite cooling systems, and the application of the specific operating rules and provisions stipulated for such climate conditions, completely and effectively fulfilled their purpose.

However, during these heatwaves, because of high air temperatures over long periods of time, the increased temperatures of the river water used for electricity generation resulted in decreased power, and even shutdowns, in order to comply with the temperature limits and/or temperature rises laid down by French regulations. Lost generation totalled 5.5 TWh in 2003 and 2.5 TWh in 2006.

At the peak of the heatwave, the risk of a potential failure of the generation and electricity consumption balance (risk of blackout) meant that the state had to adopt temporary modifications to these regulatory limits for some of the nuclear and fossil fuel power plants. In 2003, four nuclear reactors out of a total of 58 operated under these temporary provisions for just over 10 days. In the 2006 heat wave, these provisions were also in place but not used for the nuclear power plants.

On the basis of operating experience from these two heatwaves and with the prospect of such extreme events becoming more frequent with climate change, *Électricité de France* (EDF) initiated the "heatwave project" (Projet Grands Chauds) in 2008. This project incorporates periodic reviews (every five years) of climate changes (air and water temperatures) and their consequences on structures, systems and components design bases. It was also decided to make modifications to make the plants more robust, both for nuclear and conventional safety, mainly by increasing effective cooling.

New regulatory texts on the limits of thermal release were defined after research did not highlight any specific impact on the fish fauna of thermal releases from nuclear power plants located on rivers, as this impact is more localised than that attributable to climate change. The new regulatory texts extend the predefined ranges of thermal release during exceptional climate conditions. The admissibility of these values was substantiated by an impact study that followed. Thanks to these provisions, temporary modifications of the requirements will be limited in the future to the most exceptional conditions.

A thermal release working group set up in 2006 at the initiative of the French Ministry of Ecology, the French Nuclear Safety Authority (*l'Autorité de sûreté nucléaire,* ASN) and EDF, assessed existing knowledge on the impact of water temperature rises on the biocoenosis, so as to improve this knowledge with a structured research and development (R&D) programme (2008-2012) conducted at a European scale.

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1. This chapter is, to a large extent, adapted from the contribution of A. Vicaud and E. Jouen (EDF) to a special issue of *Revue Générale du Nucléaire* published in 2015 on nuclear energy and climate, Vicaud (2015) – and was provided as a case study for this NEA publication.

Power plant cooling needs

As discussed in Chapter 4 (see also EDF, 2015; EDP Sciences, 2014), all thermal power plants (fossil fuels and nuclear) need a cooling heat sink to ensure electricity generation and, in the case of nuclear power plants, to guarantee safety cooling functions. Depending on the location of the sites and the type of equipment concerned, these cooling heat sinks come from either air or water (sea, river and groundwater).

The main cooling functions, which relate both to electricity generation and to nuclear safety, are classified into four categories:

- heat removal from the nuclear reactor core in normal operating conditions (nuclear safety and power generation);
- residual power removal from reactor after shutdown in normal operating conditions or after an accident (nuclear safety);
- steam condensation at the turbine outlet (power generation);
- air conditioning of premises and equipment cooling (nuclear safety and power generation).

Air/air, water/water and water/air heat exchangers contribute to these functions. They were designed in the 1970s to withstand specified outside temperatures known as design temperatures and to cope with the calorific contribution from equipment estimated as an envelope value.

The water needs to ensure the safety functions, in normal as in shutdown conditions, are around 1 m^3/s per reactor, which is far below flow rates available in the relevant rivers, even in the case of severe low water during drought.

As far as the withdrawal of water required for these functions is concerned, nuclear power plants have administrative permits for water withdrawal and release into the environment granted by the public authorities: state departments and the ASN. These permits are drawn up on the basis of the impact study provided by the operator, who is in charge of carrying out detailed analysis of site environmental and health consequences, and especially so for every release. Given the potential impact and also the operating experience and results obtained with the best available technologies, the administrative authorities stipulate the limit not to be exceeded. Thermal release from the condenser cooling system is also covered by regulatory limits depending on the rivers concerned: maximum temperature rises upstream and downstream, and/or maximum temperature downstream.

Over the past ten years, France has experienced several periods of high temperatures and/or drought: the intense heatwaves of long duration in the summers of 2003 and 2006 and severe drought early on in 2003, and at the end of spring to the start of summer 2011. What were the consequences of these phenomena for nuclear power plant operations? What adjustments were necessary? In more general terms, what measures were taken by EDF to guarantee nuclear safety and power generation, and to resolve these climate issues which could become more frequent as a result of climate change?

A few figures for the heatwaves of 2003 and 2006

The heatwave of August 2003 lasted two weeks, from 1 to 15 August, and was exceptional in terms of intensity and extent, with air temperatures of over 35°C measured in two-thirds of the weather stations in metropolitan France, and with peaks above 40°C in 15% of the stations, including in Brittany, which had never happened before since the start of temperature measurements.

Several rivers experienced significant average temperature rises previously unheard of, for example 0.5°C per day in the Seine and the Moselle *départements* at the beginning of August. Maximum temperatures in the Loire exceeded 30°C with a daytime to night-time difference of 3°C and similar figures for the Garonne and the Moselle rivers. The whole of France was affected by drought from February to September 2003, sometimes with a rainfall deficit of 20% to 50%.

The 2006 heatwave occurred in July and lasted for almost 20 days (from 10 to 28 July 2006). This heatwave was longer than that of 2003 (purple curve), but less intense and not as widespread. It was nonetheless ranked second most severe among the heatwaves experienced in France since 1950 after that of 2003 and ahead of the 1976 and 1983 heatwaves.

In 2006, precipitation was largely in keeping with the norm in the northern third of France, with a surplus in Poitou-Charentes and Alsace. Two significant snow episodes occurred at the beginning of the year in the north and in the south, with an especially rainy month in March. Maximum air and water temperatures recorded near nuclear power plants were slightly lower than those of 2003.

Main consequences for nuclear power plant operations

The safety of the French nuclear fleet was maintained throughout the heatwaves of 2003 and 2006, in compliance with the general operating rules. Electricity generation equipment was also operable at all times and specific operating rules and provisions were applied: strengthened checks of safety-related heat-exchanger effectiveness, limited use of fire load inside rooms, use of the entire adjustment range with displacement, if need be, of the set points required for cooling equipment, start-up of backup chiller units and fans, water atomisation of air intake, etc.

In order to comply with regulatory water temperature limits, decreased generation and even plant shutdown were required. The plants that were the most affected are those with the once-through cooling system.[2] Bugey, Saint-Alban and Tricastin on the Rhône and Blayais on the Gironde estuary were affected, but also Golfech with a closed-loop cooling system. Lost generation reached 5.5 terawatt-hour in 2003 and 2.5 TWh in 2006.[3] At the peak of the heatwaves, on 12 August 2003 and on 22 July 2006, potential failure of the generation and electricity consumption balance, with significant impact on the French electricity system (potential blackout), meant that the French state had to temporarily modify the authorised limits for a number of nuclear and fossil fuel power plants.

In 2003, three units of the Tricastin nuclear power plant[4] and one at Golfech operated just over ten days as part of these temporary provisions to guarantee security of supply. In 2006, no exemptions were used.

The Heatwave Project

In addition to the operating measures taken in the short term (called PACS, which stands for "Heatwave and Drought Action Plan"), EDF launched the Heatwave Project in 2008 to review the climate change prospects (climate monitoring, including climate change), analyse the impact on structures and make the necessary adjustments for nuclear power plant safety and capability.

Factoring in climate change

Adjustments of design temperatures for both air and water were defined on a site-by-site basis for long-lasting heatwaves and for short-term exceptional operating conditions. These temperatures were determined by using data collected over the past 30 years with an extrapolation method of the trends in extreme values. This innovative method was subject to external validation by the scientific community. *Météo France* (the French national meteorological service) states that, given the state-of-the-art knowledge on the subject, the method and results

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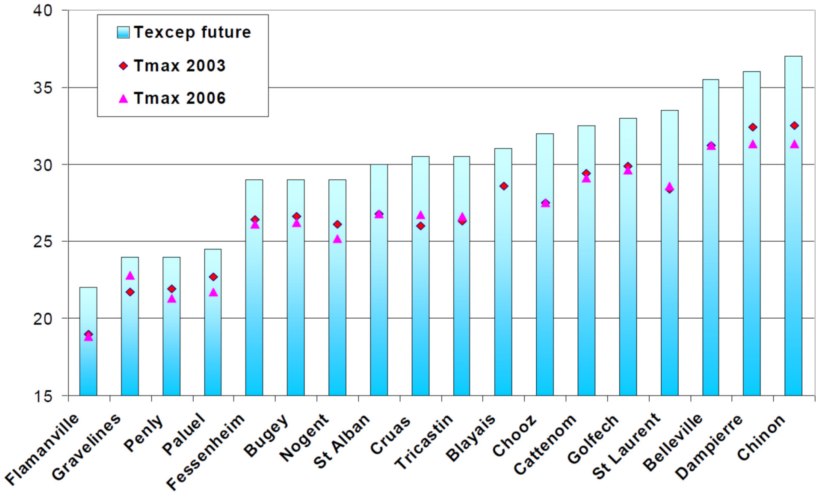
[2] Temperature rises induced in summer by plants with a closed-loop cooling system are very low: a few tenths of a degree, lower than the natural differences in a river, which can reach a few degrees of daytime to night-time variation such as in the Loire in 2003.

[3] This loss of capacity is similar to that affecting nuclear power generation when the temperature is higher than over a normal year, which can range between 0 and 2.5 TWh per year, mainly from June to September.

[4] Operation of the Tricastin units was necessary to fulfil continuous electricity supply needs of the Eurodif plant.

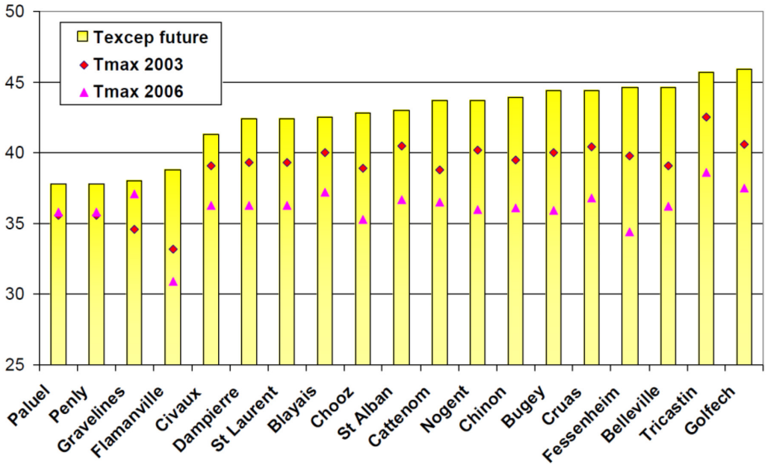
presented by EDF are entirely reasonable and do not indicate any obvious contradiction with the appraisal carried out by the research community of the trends in temperature to be reached by 2030. The results obtained for the period of 2020-2030 are consistent with long-term climate modelling, such as the scenarios presented by the Intergovernmental Panel on Climate Change (IPCC). The analysis accounts for exceptional conditions, including margins for temperatures compared to those observed in 2003 (see Figures 8.1 and 8.2). For example, 37°C for the Loire at Chinon, as opposed to 32.5°C observed in 2003 and 46°C for the air at Tricastin, as opposed to 42.5°C observed in 2003.

Figure 8.1. **Evaluation of maximum river water temperatures (°C) by the year 2030**



Source: SFEN, 2015.

Figure 8.2. **Evaluation of maximum air temperatures (°C) by the year 2030**



Source: SFEN, 2015.

Updating the heatwave safety reference base

These new temperature values are combined with a set of safety requirements, i.e. the new heatwave safety reference base for high air and water temperatures. These requirements are designed to guarantee nuclear safety in all operating conditions, at power, during outages and accidents, at the highest temperatures.

The project also stipulates implementation of climate monitoring so that the relevance of the reference base temperatures can be reassessed on periodically, especially at the time of periodic safety reviews. The data was thus updated in 2009 by incorporating the period 2004-2008. The findings did not cast any doubt on the heatwave baseline temperature values.

After discussing this reference base with the Nuclear Safety Authority, EDF embarked on studies to adapt the heatwave reference base to all the French nuclear power plants and prepared to update the corresponding equipment and documents.

These changes mainly consist of:

- replacing the chiller units and increasing their capacity to produce chilled water;
- adding air-conditioning units, some of which are safety-classified;
- increasing the exchange capacity of the water-to-water heat exchangers;
- checking equipment resistance to temperatures higher than those stipulated in initial design, or modification of some equipment to ensure its resistance to temperatures higher than those adopted in the initial design.

The following measures ensuring substantially enhanced robustness were implemented:

- After the heatwaves of 2003 and 2006, application of EDF Heatwave Project: preventive cleaning of heat exchangers and cooling coils, deployment of mobile cooling equipment, incorporation of heatwave situations in the operating documentation, etc.
- From 2011, deployment of temporary means of protecting sensitive equipment against high air temperatures once the heatwave reference base adjustment studies have been completed.
- Application of the specific operating rules for heatwaves, which stipulate the equipment and organisational measures to be taken on-site to face high air and water temperatures. Mobile cooling equipment is deployed every summer for some ventilation systems.
- Incorporation in the summer of 2007 of the modifications designed to increase exchange capacity of water-to-water heat exchangers at the most sensitive sites (addition and/or modification of exchange plates at Chinon and Dampierre) and enhanced backup raw water flow rate at Chinon in 2007 and Blayais in 2010-2011.
- After 2007, incorporation of equipment modifications, mainly increased exchanger capacity on some complex sites (Saint-Laurent in 2008, Chooz in 2009 and Belleville in 2011) and replacement of chiller units with more powerful units as from 2010.
- Replacement of some components to improve resistance to temperature: replacement and rewinding of certain motors as from 2008.

Implementation of additional adjustment measures is then staggered over the ten-yearly safety reviews specified by the regulations.

Thermal performance improvement actions

As part of the Heatwave Project, EDF has also initiated an equipment refurbishment and maintenance programme to improve thermal performance of the cooling towers. All nuclear power plants concerned have also been fitted with thermal performance monitoring systems, which mainly provides for optimised action plans specific to each of the heat exchangers. Extensive renovation work has been carried out on the cooling towers at the plants as and when required: fill pack renovation, shell and internal structure repair and construction of scale prevention facilities. New means of cleaning fill packs were developed.

The environmental monitoring stations that measure the water's physico-chemical parameters have also been completely renovated since 2003 to control on-line environmental measurements, especially temperature. All these actions contribute to the National Climate Change Adaptation Plan (NCCAP) set up by the government in 2011.

Changes in thermal release conditions

In the summers of 2003 and 2006, at the peak of the heatwave, the French state temporarily modified the temperature limits authorised for some nuclear and fossil fuel power plants to prevent a risk of blackout. According to the regulatory requirements, nuclear power plants are not allowed to operate above water temperatures of 28°C. The regulations also concern sites equipped with cooling towers, where the temperature rise incurred during summer (a few tenths of a degree) is typically lower than the natural differences encountered in the river, which can be a few degrees during a heatwave. Reinforced environmental monitoring during the heatwave periods did not highlight any short-term impact on the fish population caused by thermal releases.

Independently of plant thermal releases along rivers, as a result of the dominant effect of climate change, water temperatures will likely breach the current regulatory thresholds in the future.

Since 2006, a multi-disciplinary working group on thermal releases was set up at the initiative of the French Ministry of Environment, the regulator ASN and EDF to better understand the effects of heatwaves and climate change, to share and develop knowledge on the effect of the rise of water temperatures in rivers. A R&D programme in hydrobiology was carried out over the period (2008-2012) by EDF and the National Research Institute of Science and Technology for Environment and Agriculture (IRSTEA) with the objective of assessing possible changes to the current regulations.

Improved knowledge of temperature impacts on the biocoenosis

This R&D programme conducted at a European level provided enhanced knowledge on thermal tolerances of a score of fish species.

In-depth thermal monitoring was carried out downstream of Bugey (on the Rhône) and Golfech (on the Garonne) nuclear power plants from 2007 onwards. At Bugey, a thermal plume is typically formed on the right riverbank over several kilometres with a cooler water vein on the left riverbank. At Golfech, the measurements show a slightly heated zone on the right bank over a few hundred metres with, in the same way as for Bugey, cooler zones on the other riverbank, potential refuges for cold water fish.

During the summers of 2007 to 2011, fish monitoring at Golfech did not highlight any lesions or traces of parasites. Observation of fish assemblages (variety and abundance of fish species in a given waterbody) shows few differences between the zones heated and the zones not heated by plant thermal release. At Bugey, in 2003, cold water fish were captured in lesser numbers than in previous years but the trout and minnow populations probably sought refuge in the cooler water zones and then reappeared in November. The effects observed in 2003 were similar upstream and downstream of the nuclear power plant. A study over the period 2000-2014 for the Rhone river was published by EDF in 2016 (EDF, 2016).

Regulatory changes

As a result of climate change, the increasing risk of encountering heatwave situations should be factored into the regulations, with specific provisions to reduce the need for exemptions. Since recent research did not highlight any specific impact of thermal releases from river-based nuclear power plants on the fish fauna (this impact being more concentrated and localised than that attributable to the trends in water temperature), the French Nuclear Safety Authority updated its policy in May 2012 on the decision-making process applicable to nuclear power plants in the event of a heatwave. The following main guidelines were adopted:

- The use of temporarily modified requirements shall be limited to exceptional operating conditions. In order to do so, the requirements for withdrawal and release at nuclear power plants will stipulate specific limit values applicable to thermal releases in exceptional climate conditions, as the acceptability of these values was substantiated in the impact study and its updated version. Application of these provisions will be limited to the situations where the *Réseau de transport d'électricité* (French Transmission system operator) (RTE) requires the plant to operate or if the electricity consumption-generation balance requires the plant to operate. These provisions shall stipulate how long these operating conditions will apply, any additional compensatory measures (strengthened environmental monitoring and limited temperature rise) and procedures for providing information.

- For sites that have not factored in these exceptional situations, or if the situation breaches the conditions stipulated in the texts, or if the operator requests temporary modification within a deadline that is incompatible with the regulations (see paragraph II of Article 18 of the Decree dated 2 November 2007), it will nonetheless be possible to grant these temporary modifications to water withdrawal and release requirements without applying the previous requests for proposals normally required, as long as they comply with the regulations (see paragraph II of Article 25 of the same Decree) and if the following conditions are fulfilled:
  - The government has notified the French Nuclear Safety Authority that it considers continued reactor operation to be a public necessity.
  - The need and degree of urgency of the temporary modifications are justified by climate or hydrological conditions that the Nuclear Safety Authority, on the basis of the justifications supplied by the operator and after requests for proposals from the specialists (*Météo France*, Department for the Environment, etc.), considers as exceptional operating conditions.

In order to be properly prepared for such operating conditions, an exercise was run in June 2011 and involved all stakeholders.

The three stages of adaptation: forward planning, monitoring and emergency response management

The process of protection against climate contingencies involves several types of action:

- **Forecast**, **forward planning and prevention**, such as in the Heatwave Action Plan described above.
- **Operational monitoring of meteorological and hydrological conditions**. The sites have hydrological forecasts at their disposal compiled by an EDF expert entity and the weather forecasts of *Météo France*. Hydro-climatic conditions are subject to discussions between all relevant entities at periodic meetings of the EDF water management co-ordination committee. Depending on the conditions, the levels of deployment (monitoring, vigilance, pre-alert and alert) are defined on a zone-by-zone basis (see map).
- **Event management actions** with the setting-up of an organisation to make sure that the decisions for limiting the consequences of exceptional operating conditions can be taken at the appropriate level:
  - During the monitoring stage, the power plants monitor cooling water flow rates and temperatures, and air temperature on a regular basis. Site climate threats are reported to the competent authority.
  - During the transition to vigilance mode and then possibly to pre-alert and alert modes, with a risk of adversely affecting the electricity supply and demand balance, a generation contingency management team is set up at the corporate level. It co-ordinates actions by various entities (generation, power management and engineering) and studies of the scenarios for the coming days and weeks, depending on the weather forecasts and future power plant operating conditions (factoring in safety contingencies and requirements). It provides support for decision making concerning the criteria for exceptional operating conditions stipulated in the individual regulatory permits for each power plant, and even the request for liaising with the public authorities for temporary modifications of these permits.

It should also be added that following the 2003 heat wave, EDF made changes to the way outages of its nuclear fleet were organised. Since nuclear power plants located on the sea coast are much less vulnerable to heat waves, EDF reorganised the outages of those plants so that they are in operation during the hottest months of the years, thereby guaranteeing electricity generation to meet demand.

2018 and 2019 heat waves

The summer of 2018 in France (and across the whole of Europe) was again marked by intense heatwaves, with consequences on the operation of nuclear power plants in Germany, Sweden, Switzerland and France (NW, 2018). The Cruas-3 and Dampierre-3 units were temporarily shut down, and other units (St Alban, Bugey, and Fessenheim) had to reduce power output for environmental reasons. According to the French Technical Safety Organisation IRSN, the safety of the plants was never compromised (IRSN, 2019). In 2019, two successive heat waves, in June and in July, affected most of Europe, again with some consequences on thermal power plant generation. In France, the Golfech nuclear power plant (two units) was shut down for a week in July, and power production reduced for several other units (Saint-Alban, Bugey and Tricastin). This reduction in output is, according to data published in Le Monde newspaper (Wakim, 2019), very limited on a yearly basis, as it represents less than 0.25% of the global nuclear electricity production.

A comprehensive report published by S. Sqvist (Sqvist, 2019) in 2019 looked at the impact of the European heat waves of 2003, 2006, 2018 and 2019, not just on nuclear power generation, but on all types of generation, to put the perceived vulnerability of nuclear power plants to droughts and heat waves in perspective. Over the period 2000-2019, Sqvist reports that French nuclear power plant output was reduced by approximately 12 TWh due to heat wave curtailment, corresponding to 0.14% of total nuclear generation. The effect of heat waves on other types of generation, hydro or on-shore wind, can be much more significant. In the case of wind power, heat waves are often associated with what are called "wind droughts". In July 2018 for instance, wind speeds in Northern Europe were down by 20% compared to yearly averages. This puts the vulnerability of inland nuclear power plants in perspective.

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Chapter 9. **Climate change impacts in Spain**

Impacts in the Mediterranean region

According to several studies and to the European Environment Agency (EEA, 2012), the Mediterranean region has been subject to major impacts over recent decades as a result of decreasing precipitation and increasing temperature, and these are expected to worsen as the climate continues to change. The main impacts are decreases in water availability and crop yields, increasing risks of droughts and biodiversity loss, forest fires and heatwaves. A recent report by the Intergovernmental Panel on Climate Change (IPCC, 2014) found that:

- climate change has already made heatwaves more severe in southern Europe and the Mediterranean (*high confidence*);
- climate change is very likely to increase the frequency and intensity of heatwaves, particularly in southern Europe (*high confidence*) with mostly adverse implications for health, agriculture, forestry, energy production and use, transport, tourism, labour productivity, and the built environment;
- southern Europe is particularly vulnerable to climate change (*high confidence*) as multiple sectors will be adversely affected;
- climate models show significant agreement for all emission scenarios of warming (magnitude and rate) all over Europe, with strongest warming projected in the Mediterranean region in summer.

According to the projections of future streamflow droughts in Europe carried out under the EU ENSEMBLES Project[1] (Forzieri et al., 2014), by the end of the century, southern Europe would be most affected by drought, with flow levels of rivers and streams in the Iberian peninsula reduced by almost 40% because of climate change alone. With global warming, many river basins in Europe are likely to be more prone to severe water stress and in particular southern parts of Europe, where droughts are projected to become considerably more severe over the 21st century.

Some evidence of climate change in Spain

The climate of Spain is extremely varied, as a result of its complex topography and geographic location. Interannual climatic variability is high and is conditioned to a great extent, specifically with regard to rainfall, by atmospheric circulation patterns in the northern hemisphere, in particular by the North Atlantic Oscillation (NAO). During the 20th century, temperatures in Spain showed a general increase, with a magnitude above global average. This is more accentuated in winter. The following facts have been recorded (Oficina Española de Cambio Climático – OECC) (OECC, 2012):

- ***Temperature***: Temperatures have increased throughout the territory by between one and two degrees Celsius from 1850 to 2005. The seven hottest years in the whole historical record have been 2011, 2009, 2006, 2003, 1997, 1995 and 1989. The year 2011 was the hottest year in the whole series as recorded by the Spanish Meteorology Agency-*Agencia Estatal de Meteorologia* (AEMET), with an average temperature of 16°C, which is 1.4°C higher than the average in the reference period 1971-2000. The series of annual average

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[1] The ENSEMBLES Project was supported by the European Commission's 6th Framework Programme, www.ensembles-eu.org.

temperatures in peninsular Spain and the Baleares islands for the period 1980-2006 show an upward trend of 3.7°C/100 years.

- ***Precipitation***: Annual precipitation has decreased significantly in the last three decades compared to the 1960s and 1970s. The decade 2000-2010 shows the lowest values since 1950. Nevertheless, the evidence of the effect of climate change in terms of annual precipitation is not as clear as in the case of temperature.
- ***Snow and glaciers***: A general decrease in the number of snow days per year has been observed. Active glaciers in the Pyrenees have lost 90% of their surface since the beginning of the 20th century. From 34 glaciers described in 1982, only 18 remain nowadays.
- ***Biodiversity***: Significant effects have been observed, such as modifications in species distributions, like a recent colonisation by African bird species and a significant reduction in butterfly populations due to changes in habitats, related to climate change. Evidence has also been found on impacts on plant phenology and seasonality; for example, spring events like blossoms have been occurring earlier with rates ranging between 6.5 and 7 days per degree Celsius. This same trend has been observed in the southern part of the country, in key species like olive trees or vineyards.
- ***Tropicalisation***: With greater frequency fish species and other subtropical marine groups appear and expand to the north. In the Canary Islands more than 30 new species of tropical fishes have been found in the last years.
- ***Biological invasions***: Freshwater tropical algae *Tetrasporidium javanicum*, an indicator of high temperatures, has been present in several locations throughout the country since 2005.
- ***Sea level***: Sea level rose globally between 1961 and 2003 at an average rate of 1.8 ± 0.5 mm per year. In the northern part of the country, it rose during the second part of the 20th century by between 2 and 3 mm per year. The Mediterranean has seen significant increases since the 1990s of between 2.4 and 8.7 mm per year. The trend in surface water temperature has also been increasing, describing a pattern coherent with a climate change scenario.
- ***Droughts/heatwaves***: An increase in the number and duration of heatwaves has been observed in the Iberian Peninsula, describing a continuous upward trend in the last decades.
- ***Water temperature***: There is a significant increase of water temperature in rivers, recorded in particular during episodes of droughts or heatwaves.
- ***Desertification***: A large part of the Spanish territory suffers from desertification. Different numbers have been reported: one-fifth of the land is currently at risk of turning into a desert; at least 31.5% of the land has already been affected by desertification. Desertification at present is mainly due to forest fires, the loss of soil fertility of irrigated land by salinisation, and erosion. Climate change has been described as having caused the deterioration of soil fertility through a loss of carbon from the soil.

Future trends

According to different models, the temperature increase projected for the Iberian peninsula is uniform throughout the 21st century, with an average tendency of 0.4°C per decade in winter and 0.7°C per decade in summer for the less favourable scenario (A2 according to the IPCC[2]), and of 0.4°C and 0.6°C per decade, respectively, for the most favourable scenario (B2 of IPCC[3]).

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2. IPCC A2 scenario assumes a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
3. IPCC B2 scenarios assume a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (but lower than in A2) and intermediate economic development.

For rainfall, the change tendencies throughout the century are not generally uniform, with important discrepancies between the global models, and therefore less reliable results. All the models, however, coincide in a significant reduction in total annual rainfall, somewhat greater in scenario A2 than in B2. The reductions are maximum in spring and somewhat lesser in summer.

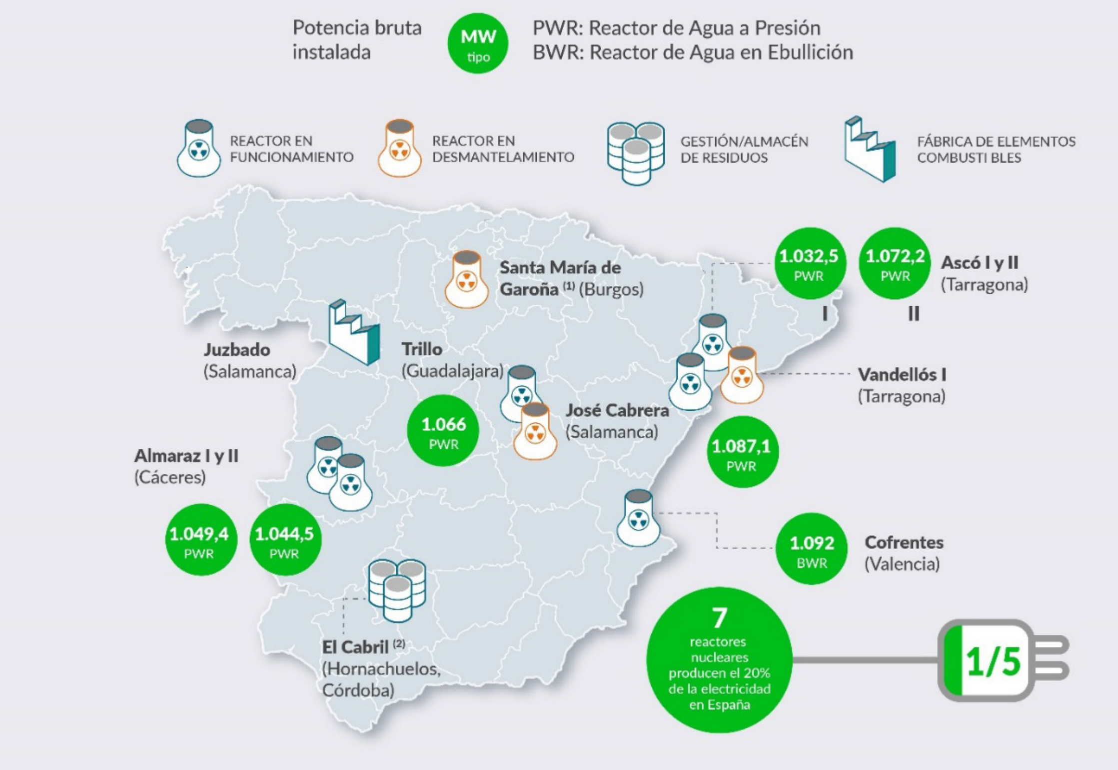
The main results for climate change projected throughout the 21st century for Spain, under different climate models, include:

- A progressive tendency to an increase of average temperatures throughout the century, significantly greater in summer than in winter, and greater in the inland areas than on the coast or the islands.
- A generalised tendency towards less annual accumulated rainfall.
- A greater range and frequency of monthly temperature anomalies (more days with extreme maximum temperatures on the peninsula, especially in summer).

Climate change and nuclear power plants

Currently, Spain has several nuclear facilities in different sites, including seven nuclear reactors in operation, the fuel manufacturing facility at Juzbado (Salamanca), and a low and medium radioactive waste-disposal facility at El Cabril (Córdoba) (see Figure 9.1). The seven nuclear reactors in operation produce about 20% of the total electricity of the country. Renewables (hydro, wind, solar) represented in 2018 about 40% of the generation, so nuclear remains an important part of the low-carbon electricity in Spain.

Figure 9.1. **Nuclear power plants in Spain**



(1) Cease of operations: Ministry decision August 1st 2017

(2) Very low, Low and Intemediate Level Waste Disposal Facility

Source: Foro Nuclear.

Nuclear power plants, as all thermal power plants, require significant amounts of water for cooling. Some Spanish regions, as other large areas in the south of Europe, are affected by water scarcity and competing uses that increase demand. Both energy supply and energy demand are sensitive to changes in climate, in particular in temperature. Furthermore, the increasing frequency of extreme weather events, including heatwaves, droughts and potentially storms, poses additional challenges for energy systems. In particular, thermal power plant efficiency and output can be adversely affected by a rise in temperature or a decrease in the availability of water for cooling.

Some of these weather pattern changes have been already observed in Spain, such as changes in the demand pattern, with electricity consumption peaking in summer because of a higher number of hot days, and falling in winter thanks to milder weather conditions. This effect can be seen year after year in the approximation of the peak power demand in summer to the values demanded in winter (Moreno et al., 2005). This trend will probably increase energy demand for cooling, which may further exacerbate peaks in electricity supply in the summer.

Higher surface water temperature can also lead to cooling problems for thermal plants and in particular for nuclear power plants. In most cases, a higher coolant temperature will result in a reduction in efficiency, implying a loss of output. According to a European study (EC, 2011), the rising surface water temperatures, particularly during summers, could have the largest impact on the operation of nuclear power plants. This is likely to be the case in Spain. River temperatures are more susceptible to changes in regional climatic conditions. Hot summers may lead to relatively small differences between inlet and outlet water temperatures, resulting in lower thermal efficiency. Inlet and outlet water temperatures are a standard element of the mandatory safety and environmental reviews for nuclear facilities in Europe, and exceptional circumstances have already forced regulators to grant exemptions from environmental regulatory requirements to nuclear power plant operators.

On the other hand, further increases in temperature and droughts may affect the hydropower production and limit the availability of cooling water for thermal power generation, particularly in summer. According to existing climate projections, the main issues of relevance for nuclear power plants in Spain may be the effects of water temperature and availability, as well as air temperature increases.

In power plants at inland river locations, the availability and temperature of cooling water may cause problems, particularly during heatwaves. In such cases, the plants may have to reduce their operating power, usually in response to environmental regulations, which leads to a loss of revenue. Regulatory bodies may and in fact do grant temporary exemptions from the cooling water restrictions in certain cases. With increasing temperature, as predicted in climate scenarios, high cooling water temperatures are expected to occur more frequently, so that nuclear power plants may increasingly need to adapt.

For power plants situated by the coast, which uses sea water for cooling, there is hardly any climate impact to be expected, since the predicted rise of the sea water temperature is moderate.

Periodic safety reviews (PSRs) of nuclear power plants are part of the licence requirements and are carried out at least every ten years. Safety issues related to the impacts of climate change are regarded as part of the PSR, and the costs of modifications as a result of the outcome of these assessments are considered part of the regular maintenance costs. Issues related to the temperature of cooling water and air, and the effects of extreme situations on the nuclear plants are therefore included in the PSRs, and implementing the required remedial measures is mandatory. The nuclear operators and the regulator do not foresee any drastic safety -or operability-related problems due to climate change.

A review of the licensees events reports (LERs) submitted by the plants to the Nuclear Safety Council from 1981 to 2012 shows that the meteorological events that have had impacts on the operation of power plants (reduced load or disruption) from 1980, relate mainly to the massive development of macrophytes, strong winds, water scarcity (drought), and increase of water temperature. The conclusion is that the meteorological events that have been more often reported are storms, and much less often droughts, high temperatures or water scarcity. This difference can be explained by the fact that water scarcity is considered a structural problem in Spain: industry, regulators and other water consumers are used to having to deal with water scarcity and high temperatures. Measures and strategies are therefore taken into account at the very preliminary phases of commissioning an installation. In the design phases, measures are taken to cope with this problem and to adapt to the foreseen impacts of climate change. The higher predicted impacts that will take place after the nuclear power plants' lifetime are also taken into account.

Table 9.1. **Notifications to the Spanish Nuclear Safety Council (CSN) due to meteorological events 1981-2012**

	 José Cabrera	 Trillo	 Almaraz	 Vandellós	 Ascó	 Garoña	 Cofrentes
1981							
1982	▨			🟩			
1983				⬛			
1984				🟦			
1985							
1986							
1987							
1988							
1989					▨	▨ 🟦	
1990					🟩		
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1992							
1993	🟨 ▨				▨	▨	
1994							
1995	🟨						▨
1996							
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2000							
2001	▨						
2002	🟥			▨	🟩		
2003							
2004	▨			▨ ⬛			
2005					🟩		
2006						🟥	
2007							
2008							
2009			▨		🟩		
2010					🟩		
2011					🟩 ▨		
2012					🟩		▨

⬛ Strong storms
▨ Storm
🟦 Strong Winds
🟥 Increase in water temperature
🟨 Drought
🟩 Macrophytes

Source: CSN, 2018.

Apart from the periodic safety reviews, the exhaustive safety analysis carried out by the nuclear plant operators in response to the application of the EU stress tests in the aftermath of the Fukushima Daiichi accident has provided useful information on the resilience of nuclear power plants to external natural events. Operators have assessed whether the plant can withstand the effects of natural disasters, including earthquakes, flooding, extreme cold, extreme heat, snow, ice, storms, tornadoes, heavy rain and other extreme natural conditions. The stress tests showed that Spanish nuclear power plants are prepared to cope with these natural events and proposals were made to increase the pre-existing margins, including the provision of alternative cooling. The stress tests analysis carried out by the licensees and assessed by the Spanish Nuclear Safety Council (Consejo de Seguridad Nuclear, CSN) has therefore included an extensive review of the external hazards that may affect every Spanish nuclear power plant site. As a result, no major issues related to the possible impact of extreme heat have been identified.

In order to take into account all the conclusions of the stress test process in the Spanish plants, on 15 March 2012 the CSN issued a binding Complementary Technical Instruction (ITC-STs) to each of the licensees. These ITCs include all the relevant conclusions stemming from the stress test process carried out in Spain from June to December, 2011. The ITCs included all the proposals of the licensees and some additional improvements deemed appropriate by the CSN. As a part of these improvements, the plants will have to inform about extreme weather conditions on the following terms:

- Verification of weather conditions that were used as design basis for various plant systems, structures and components: maximum temperature, minimum temperature, various types of storms, heavy rainfall, high winds, and other.
- Postulation of proper specifications for extreme weather conditions, if not included in the original design basis.
- Assessment of the expected frequency of the originally postulated or redefined design basis conditions.
- Consideration of a potential combination of weather conditions.
- Conclusion on the adequacy of protection against extreme weather conditions.
- Consideration of measures that could be envisaged to increase plant robustness against extreme weather conditions and that would enhance plant safety.

All the above, and the associated plant modifications, guarantee that the plants are aware and prepared to cope with the possible impacts of future natural events, if necessary.

Examples of adaptation measures and strategies

Several actions are being carried out in the power sector to include adaptation to climate change as an important issue, since it allows the companies to be prepared for the impacts of climate change and, more specifically in Spain, to deal with the impacts of more frequent and longer episodes of water scarcity and increased temperature. A few examples are presented below.

Regulatory measures and water management

Temperature limits for water discharges

The temperature of water discharged into the rivers is regulated through a European Directive that has been transposed into the legislation of the EU member states. Usually, the authorisation for discharges sets two limits for river water temperature downstream the water outlet of the power plant, one relative and another absolute, for the stretch in the river where the water mixes at different temperatures. The relative limit corresponds to a maximum temperature increase of 3°C between the temperature of the water in the outlet and that in the mixture zone. At this point, a second maximum absolute temperature limit of 30ºC is fixed. Compliance is verified daily in all the plants. In certain occasions, the authorities have allowed the operators to surpass temporarily the legal limits, for instance when the water temperature in the river is higher than the temperature of the water released by the plant.

Water uses and drought management

To accommodate water demands for the different uses and the structural problem of water scarcity in Spain, the legislation sets a list of priority uses, as follows: 1st water supply in urban areas, 2nd irrigation, 3rd industrial uses for power generation, 4th other industrial uses, 5th fish farming, 6th recreational uses, and 7th navigation.

Additionally, there is a restriction considered for the maintenance of ecological flows, fixed when needed as the second priority use after water supply. Nevertheless, the experience acquired during several drought episodes demonstrated the need for new regulations and adequate drought management measures. A new legal framework deals with drought planning and management through modifications introduced in the Water Act. For instance, the government may authorise the river basin authority to set up water interchange centres (water banks) to enable user rights to be waived by voluntary agreements.

The National Water Plan Act states that the Ministry for the Ecological Transition and the Demographic Challenge must establish a global hydrological indicator system (HIS) and river basin authorities must prepare drought management plans and submit them to the respective river basin councils and the Ministry for approval. The HIS has been elaborated using different parameters (inflows, outflows and storage in reservoirs, flow river gauges, precipitation and piezometric levels) for each management system. Municipalities have also developed emergency plans for urban water supply (more than 20 000 inhabitants) to ensure that water services are preserved under drought conditions.

Drought management plans (DMPs) are therefore tools designed to guarantee the water availability required to sustain a population’s life and health, to avoid or minimise the effects of droughts on water bodies (specially on environmental flows to avoid any permanent negative effects), and to minimise effects on public water supply and on economic activities, according to the priority uses set by legislation. During unusual droughts, the competent authorities may adopt exceptional measures, even if concessions (rights of water use under certain conditions) have been granted.

When preparing DMPs, authorities should:

- Include indicators providing a quick drought status early enough to act according to the forecasts of the plan.
- Provide information on the resource system and its vulnerability.
- Provide information on the demand system and its vulnerability to droughts, organised by priority levels.
- Present structural and non-structural alternatives to reduce drought impacts.
- Determine the cost of implementing measures.
- Adapt the administrative structure for the DMPs follow-up and co-ordination among the different administrations involved (e.g. the ministry, regional governments and municipalities).
- Discuss plans, results and follow-up with all interested parties, ensuring full public participation to avoid social conflicts.

Basin authorities have been able to elaborate plans according to the local situation and needs, to declare the drought status according to the HIS threshold, and to initiate measures included in the plan depending on the severity of the drought. Monthly maps of the drought situation in the different management units within each Spanish basin are being developed and can also be found on the website of the Ministry. This information is also very useful for plant operators to design their water strategies.

Macrophytes control in Ascó

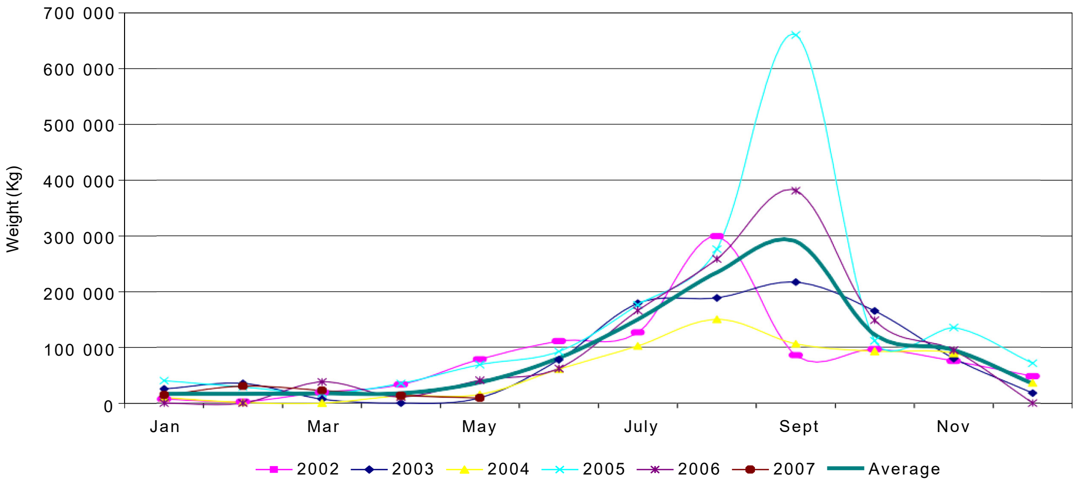
The Ascó nuclear power plant is located in the municipal area of Ascó (province of Tarragona, north-east Spain), on the right bank of the Ebro River. The plant has two pressurised light water reactor (PWR) units supplied by the US company Westinghouse.

The forced draught cooling tower is 160 metres high and 120 metres in diameter at its base. Its construction was not part of the initial project, but it was built in 1995 with the purpose of providing additional cooling capacity and to comply with environmental regulations. The plant uses water from the lower Ebro River for refrigeration. The Ebro River flow is heavily regulated by large dams, in particular Mequinenza and Ribarroja[4], built in the 1960s, that significantly modified its hydrological regime. Although the river still experiences natural floods, its physical and environmental conditions have changed remarkably within the last decades. The area has been registering high water and air temperature increases and water scarcity. Apart from the possible effect of climate change, the water inputs to the two reservoirs have been falling for decades because of a big increase in water demand and to a lesser extent to changes in land use (crops abandonment, reforestation…), also affecting the hydrological balance of the basin.

During the summer months, with the increase in temperature and water flow regulation, the proliferation of macrophytes covers much of the Ebro riverbed and causes numerous problems to water users and economic losses affecting navigation, water abstraction for irrigation and also the activity of the Ascó nuclear power plant (Prats, 2004). When the entrainment of aquatic vegetation is higher, with higher air and water temperatures, the decrease of the inflow for cooling can impact the operation of the plant. (see Figure 9.2)

The macrophyte proliferation is also seen as the main cause of a plague of black flies (*Simulium spp.*), which became a major threat to public health.

Figure 9.2. **Monthly weight (kg) of macrophyte biomass withdrawn from the water intake in Ascó in 2002-2007**



Source: URS, 2010.

The biomass withdrawn between January and May is very little compared to the annual total biomass, which proves that the biomass increases from the month of May.

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[4] Mequinenza reservoir: 1 530 hm^3; hydropower generation capacity: 324 MWh; Ribarroja reservoir: 218 hm^3; 262 89 MWh.

Macrophytes started to spread over the lower Ebro River at the end of the 1990s and since then a massive development has been affecting the operation of the nuclear power plant, obliging it to reduce production capacity to avoid the collapse of the refrigeration system. This proliferation is expected to be exacerbated in Spanish rivers by the increase in water temperature both in freshwaters and sea water. Several methods have been implemented to control this effect, like visual monitoring, sample collection and analysis, bathymetries of the river, planimetry from high resolution aerial images, or manual and mechanical withdrawal of macrophytes at several river sections.

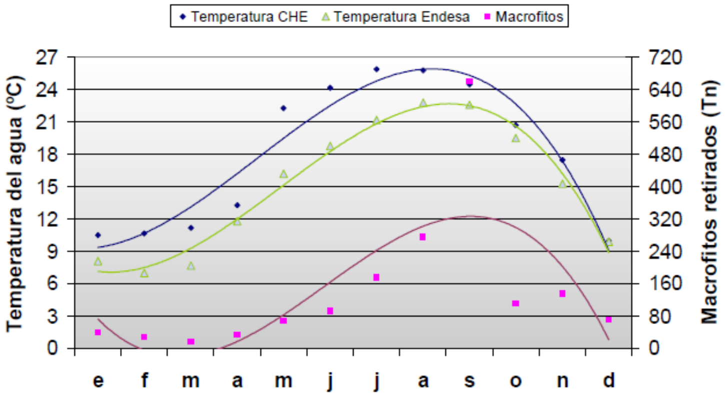
The plant operator and the administration have developed a series of tools to control this phenomenon, to minimise the impacts and to adapt to an expected higher frequency and magnitude of the blooms. Since 2002, artificial floods (flushing flows) of short duration (one or two days) are released from the Ribarroja dam once or twice a year in order to reduce macrophyte density. Hydroacoustic methods combined with geostatistics have been used to monitor spatio-temporal trends of submerged macrophytes. Controlled water releases are therefore designed, monitored, and modelled with the objective of removing the excess of macrophytes and keeping sedimentary activity in the channel.

The dominant macrophytes in the area are *Myriophyllum spicatum*, *Ceratophyllum demersum* and *Potamogeton pectinatus*. These species have found in the lower Ebro river ideal conditions of temperature, nutrient content, light and flow regulation, which favour its fast development.

Their senescence period starts in October and, during the colder months, they remain latent with fragments and seeds buried in the sediment or suspended on the edge of the riverbed.

The main factors regulating the presence and growth of aquatic macrophytes are light, space, nutrients and temperature. Water temperature regulates their annual biological cycle, and therefore shows a strong correlation with the temporal evolution of macrophyte biomass, as seen in Figure 9.3. It was therefore chosen as an indicator to schedule the artificial floods.

Figure 9.3. **Relationship between the water temperature variation and the biomass withdrawn at the water inlet of the Ascó nuclear power plant in 2005**

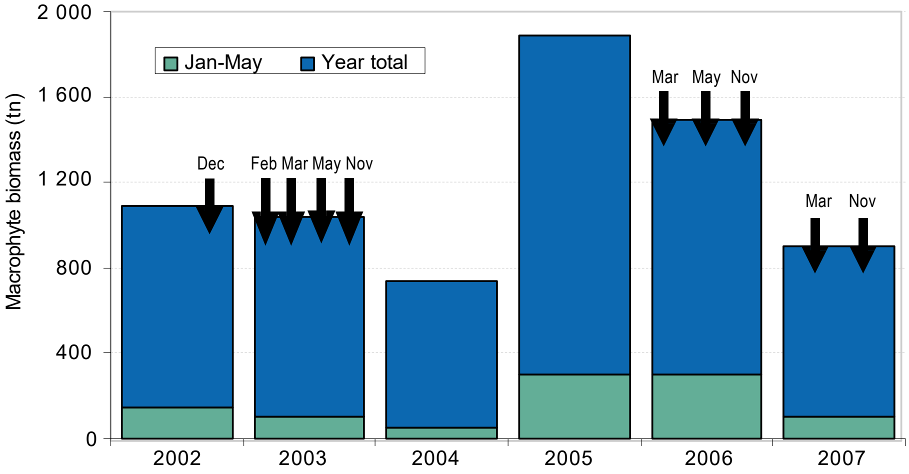


Source: URS, 2010.

Figure 9.4 shows the efficiency of the designed floods to control macrophytes. The natural or artificial floods are represented by black arrows. The years with more floods (natural or artificial), like 2003, determine a lower quantity of biomass for the next year (2004), while if there are no flows, as in 2004, there is a sharp increase in biomass the following year (2005). It is worth noting that the follow-up studies indicate unequivocally that when the macrophyte biomass in the river is very high, floods are comparatively less efficient in removing vegetation from the riverbed.

Apart from environmental aspects, the artificial floods regime has been designed as an economic policy instrument. It is based on a voluntary agreement able to generate public and private incentives to deliver the artificial floods designed ad hoc by the private operator of the hydropower dams. The instrument also includes a public-private partnership to create, disseminate and use all the available information to identify the appropriate actions able to improve the ecological potential of the river.

Figure 9.4. **Total annual biomass withdrawn at the Ascó nuclear power plant water intake thanks to natural or artificial floods (black arrows) for the period 2002-2007**



Source: URS, 2010.

The voluntary agreement was signed in 2002 by the hydropower company, the water authorities, and the scientific community. It considers the possibility of compensating the hydropower utility for the water used to produce the flushing flows. This has been performed twice a year (in spring and autumn) to maximise macrophyte removal. This implies the delivery of more than 30 million m^3 in 13 hours in each controlled flood, and it has become part of the river management system. The opportunity cost for the power utility depends on many factors and may range from a zero (or even negative) value in exceptionally wet years (where the value of stored water is at a minimum) to severe dry years (when the value of stored water is at its maximum). Simulation results indicated that measuring the opportunity cost of every flood was expensive, and bargaining on those costs every season was also institutionally challenging. Nevertheless, enough evidence from simulation models reveals that the long-term average cost of a single flood was not significant if compared to the overall turnover derived from selling power back to the grid, and was also small if compared to the existing alternative to remove invasive macrophytes. Regarding social costs of artificial floods (a few euro cents per person living in the area), they are also negligible when weighed against people's willingness to pay to restore the river ecology. However, it has proved to be a very useful tool that allows, among other benefits, the operators to adapt to the increased frequency of macrophytes in the river, which is expected to be exacerbated by climate change.

In any case, the controlled floods are not a final solution, but a measure to control and attenuate the development of macrophytes. The River Basin Authority, as the competent body for the conservation of the ecological status of the river, should consider additional measures, such as massive mechanical macrophyte withdrawals, in order to maintain the effectiveness of these controlled floods.

Changes in refrigeration systems at Almaraz nuclear power plant

The Almaraz nuclear power plant consists of two 2 947 MW thermal power pressurised light water reactors, with three cooling circuits each. Both units employ low-enriched uranium oxide, and have electrical power ratings of 1 049 MW and 1 044 MW. Almaraz is located in Extremadura and delimited by the rivers Tiétar and Tagus, forming a triangular area with over 80 kilometres along the east-west axis and 30 kilometres maximum separation between the two rivers.

Exhaustive monitoring of the water temperature is carried out in the Arrocampo and Torrejón reservoirs, which consists of measuring and evaluating this parameter at various points to guarantee, at all times, plant cooling capability and to be aware of the thermal impact on the water bodies. The measurement programme consists of four automatic continuous measuring points of the vertical temperature profile in various areas of the Arrocampo reservoir by means of thermistor chains fitted with local recording systems, together with another two points in the Torrejón reservoir, located up- and downstream from the Arrocampo spillway.

Continuous sampling and recording systems are available for temperature, pH value, dissolved oxygen and flow rate of the water in the Arrocampo spillway.

In summer 2012, a *project to improve the Almaraz Nuclear Power Plant cooling system* was commissioned. It was a combination of actions of great magnitude, incorporating a complete administrative procedure under the Environmental Impact Legislation, given the proximity of areas of important ecological value.

The cold water source for the Almaraz nuclear power plant consists of the Arrocampo reservoir, which was specifically constructed on the Arrocampo stream for this purpose. It has a volume of approximately 35.5 Hm^3, through which the cooling water from the power plant condenser is recirculated, losing the approximately 4 000 MW_{th} of added heat, by natural dissipation. To make the process more efficient, a thermal separation screen is placed, forcing the hot water to follow a circuit of about 25 km.

A supply of cold water is available from the reservoir of Torrejón-Tajo, authorised by an administrative concession. It is only used when the temperature of the water needs more cooling. The reservoir releases a given quantity of water through an overflow as it works at constant level, once it has attained the maximum cooling.

During the construction of the plant, the Administration established the maximum temperature of the discharges at 40°C from Arrocampo. Since the construction of the plant, the Hydrographic Confederation in 2004 requested that the plant review its cooling system with the objective of reducing the maximum temperature of the discharge to 30°C.

An environmental impact evaluation of the potential environmental degradation resulting from the project was carried out in 2006, particularly in relation to the Special Protected Zone for Birds (ZEPA) of the Arrocampo reservoir. This implied the participation of the Department of Ecology at the University of Extremadura. The conclusion was that there were no adverse environmental effects caused by the project. But this evaluation process resulted in the electricity line route being redesigned, to minimise the impact on the ZEPA.

Adaptation strategies in power companies

Climate change will affect the whole power sector and may require significant changes in operation and maintenance conditions, but also in the generation, transformation and distribution infrastructure, as well as in the behaviour of the entire energy market.

The Spanish Ministry of the Environment studied the main impacts of climate change in several sectors. Table 9.2 summarises the results for the power sector:

Table 9.2. **Key impacts of climate change in several sectors in Spain**

	Rainfall		Temperature (T)		Wind		Other
	Increase	Decrease	Increase	Decrease	Increase	Decrease	
Power generation	Positive (hydropower)	Negative	Negative*	Positive*	Positive for wind power	Negative for wind power	Solar radiation positive
Transport and distribution	Negative	Positive	Negative	Positive	Negative if very high	Neutral	
Commercialisation Demand	Neutral	Neutral	Negative**	Negative**	Neutral	Neutral	Negative when combining T/humidity and T/wind increases

Source: Preliminary assessment of climate change impacts in Spain. Ministry for the Environment.

* Affects the efficiency of thermal, nuclear, cogeneration, biomass, and solar thermal power plants. Also photovoltaic plants find it more difficult to dissipate heat.

** Considered negative as assumes a higher demand of the resource.

Power companies are undertaking research on the impacts of climate change and possible adaptation strategies as additional scientific information becomes available. An example is the following project, undertaken by Endesa to assess the effects of climate change and include adaptation as part of the company's strategies.

Adaptation project in Endesa

The objectives of the project were (i) an internal vulnerability assessment to identify and prioritise climate events likely to create risks for business activity; and (ii) an evaluation of the benefits and opportunities of future plans regarding climate change and energy, and of the different international mechanisms designed to encourage adaptation projects within the energy sector, especially those with a financial character.

As a result of these efforts, a roadmap has been designed to enable Endesa to include climate change adaptation in its decision-making processes as a core component of all corporate decisions.

Methodology: The definition for adaptation embraces both minimising risks and taking advantage of the potential benefits of climate change. Endesa has carried out an internal project to determine potential opportunities within its market. On the one hand, it has analysed national objectives for energy expansion and generation aligned with climate change policies. On the other, it has evaluated international funding sources for projects related to adaptation and energy. The energy plans of Endesa have been designed as a response to four common goals: guarantee energy supply, reduce dependence on foreign energy, use national resources, and diversify the national electricity mix.

The method of Endesa is based on the structure defined by the United Nations Framework Convention on Climate Change, which describes vulnerability as the combination of three parameters: exposure, sensitivity and adaptive capacity. Questionnaires were specifically elaborated for each type of facility. The results and the climate projections allowed a risk analysis to be done for Endesa. Each case study evaluated two aspects to build the risk profile of each facility:

- climate impacts which are likely to affect the facility (exposure);
- potential effects and consequences (sensitivity).

The adaptive capacity analysis used a top-to-bottom approach based on the "energy vulnerability index" (EVI), which shows the capacity to adapt of the entire company. EVI is a tool that allows to compare the efforts and advances of companies in the electricity sector with regard to their vulnerability and adaptive capacity to climate change. EVI is based on public information available on the different companies and is structured in two main steps: vulnerability assessment and adaptive capacity. Vulnerability scores vary between 0 and 100 points. The lower the score, the less vulnerable is the company to climate change. Adaptive capacity is also rated from 0 to 100. The higher the score, the better prepared is the company to face climate change effects. A high adaptive capacity score combined with a low vulnerability score will result in a higher position within EVI.

Companies with business strategies that consider adaptation to the risks and impacts of climate change, and that involve internal and external stakeholders in the process, will have a high adaptive capacity. Vulnerability will be determined on the basis of the technological and geographical diversity of the facilities of the company. For example, if a company has all of its assets in countries that are less vulnerable to climate change and has a wide range of technologies, its vulnerability will be low.

The method considered two factors. First, the adaptive capacity of a single facility cannot be separated from the global operations of the company, especially in the electricity sector, where regulations and national and international implications are high. Secondly, to obtain data on the adaptive capacity of each facility would require a large amount of time and effort, which could cause the project to deviate from its main objective.

The analysis of vulnerability in the power plants of Endesa included the nuclear and distribution infrastructure in all the countries where it operates, and the potential effects of certain climate risks on generation and distribution systems.

Impacts were selected on the basis of the technology and country of location, and a value was assigned to probability and occurrence. Both aspects were evaluated through available scientific data and direct information collected from the power plant operators of Endesa. This made it possible to determine a set of risks that can affect power generation at the plants being analysed. Risks were identified for each country and technology, and later compared with the information sent from each power station.

An adaptive capacity variable was added to the risk profile (through a top-down approach) to evaluate vulnerability. This analysis considered three time frames (short, medium, long), which were compared to a reference scenario in order to visualise the risk profile and its evolution for each station.

The following impacts were selected for the power plant analysis:

- increase in air temperature;
- increase in water temperature;
- possible rainfall reduction (from drought events).

The risk analysis led to the following conclusions:

- Drought episodes will increase considerably, with potential impacts on hydroelectric plants in Spain.
- For thermal power plants, risks associated with water availability will have significant consequences (mostly by the end of the century) since energy production depends directly on water availability for cooling processes. The fact that most of these power stations are located near the coast is also relevant.
- An increase in air temperature will bring a risk for almost all facilities.
- An increase in water temperature will affect mainly the cooling process of the power plants.
- Nuclear power plants present the same risks as other thermal power stations, but thanks to stricter risk management in this technology, effects could be less important.

Overall, the analysis determined that rainfall and temperature will influence power plants, but most often without catastrophic consequences, wherever they are located. So, climate change effects projected for 2030 represent low to very low risks.

In conclusion, climate change management in the power plants of Endesa located in Spain is optimal (considering climate change as a risk, in some specific cases). Climate risk management is also being considered in the facilities of Endesa (though not necessarily as climate change adaptation).

As a result of the internal vulnerability assessment and the opportunity analysis, a roadmap has been designed for climate change adaptation. It defines specific objectives and actions for Endesa to pursue, with a firm commitment to integrate climate change adaptation in its policies and business plans. Planning will include three strategic lines, each one comprising a series of action programmes:

- *Knowledge*, designed to provide Endesa with tools and instruments that will help build its capacity to evaluate possible risks to its business activities, and to prioritise actions to avoid these risks.
- *Positioning*, with the objective of providing support in including climate adaptation as part of its sustainability policy, to improve institutional relationships with governmental authorities in countries where Endesa operates, and to create new ones with funding entities that invest in projects related to energy and adaptation.
- *Action*, to bring solutions to the challenges posed by climate change, focusing on reducing the vulnerability of the power plants of Endesa. This strategic line works closely with the *knowledge* line, since measures and intervention options must be based on the information given by the vulnerability assessment.

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Chapter 10. **Weather events and their impact on nuclear plants in the United States**

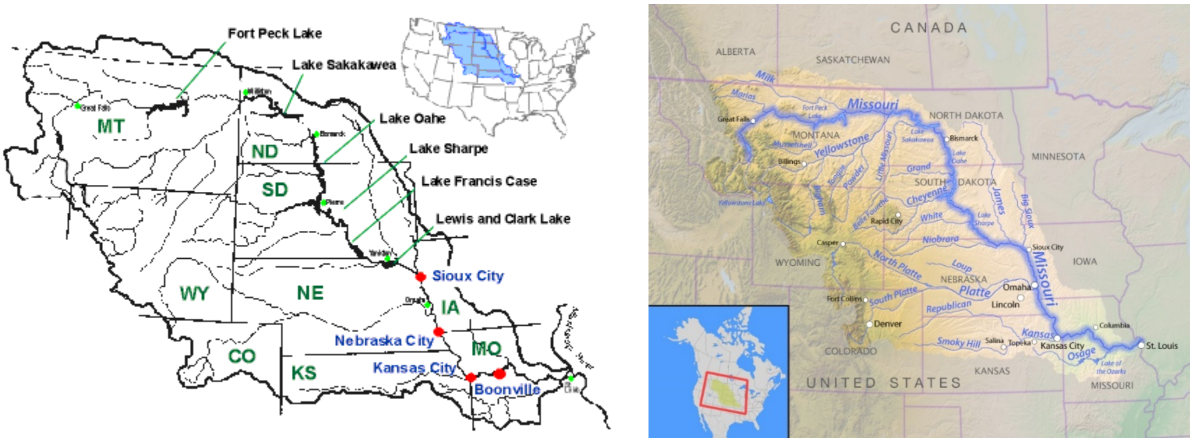
Introduction

It is difficult to link individual severe weather events to long-term global climate change, though the average severity and frequency of such events is expected to increase. Three recent events in the United States provide meaningful indications of probable future events and are useful case studies on the preparation and responses that will be needed. Those severe and widespread weather events were the Missouri River flooding of 2011, the severe drought in the Midwest in 2012 and Hurricane Sandy (sometimes called "superstorm") along the north-eastern coast of the United States in October 2012.

Missouri River flooding, 2011

The winter snowpack in the northern Rocky Mountains during the winter of 2010/11 was 212% of normal. Wide variations in the snowpack are not unusual and since 1933, the US Army Corps of Engineers (USACE) has built and operated a series of dams and reservoirs along the Missouri to generate electricity, control flooding, recharge the underlying aquifers and provide recreational opportunities. A map of the Missouri River drainage is shown in Figure 10.1 and characteristics of the various dams along with the June 2011 release rates are shown in Table 10.1.

Figure 10.1. **The Missouri River drainage**



Source: Shannon1, Creative Commons.

Table 10.1. **Major dams and reservoirs along the Missouri River**

Name of dam (reservoir)	State	Normal pool elevation (m)	June 2011 release (m^3/s)	Height (m)	Storage capacity (km^3)	Capacity (MW_e)
Fort Peck	Montana	685	1 900	76	23.1	185
Garrison (Sakagawea)	North Dakota	565	4 000	64	29.4	515
Oahe	South Dakota	502	4 531	75	29.0	786
Big Bend (Sharpe)	South Dakota	440	4 200	29	2.4	493
Fort Randall (Francis Case)	South Dakota	417	4 000	50	7.0	320
Gavins Point (Lewis and Clarke)	SD, Nebraska	368	4 200	23	0.6	132
Mouth at Saint Louis		123	Length = 3 767 km			

Source: NEA based on www.nwo.usace.army.mil/Missions/Dam-and-Lake-Projects/Missouri-River-Dams.

In addition to the snowpack, the upper Missouri River basin received more than its average annual rainfall between 15 and 31 May 2011, presenting the USACE with a choice between a massive flood for a few weeks and a controlled flood for two to three months. The USACE reduced the flooding, though the Missouri was still 1 m above flood stage at Omaha on 28 August.

There are three nuclear power plants along the Missouri above its confluence with the Mississippi at Saint Louis: Fort Calhoun and Cooper, north and south of Omaha respectively, and the Calloway plant in central Missouri. Fort Calhoun and Cooper are directly adjacent to the river, while Calloway is about 8 km north of the river on an elevated site and thus was not directly affected by the flooding.

Fort Calhoun nuclear power plant

The Fort Calhoun nuclear power plant is owned by the Omaha Public Power District (OPPD) and is located about 30 km north of Omaha. Commissioned in 1973, the combustion engineering 484 MW_e pressurised water reactor (PWR) is the smallest operating commercial plant in the United States. Its licence was extended in 2003 to 9 August 2033. The plant was shut down on 24 October 2016.

On 6 April 2011, the reactor was shut down and defueled for a scheduled refuelling. On 6 June the Missouri River rose above flood stage at the plant and on 7 June an electrical fire occurred in a switch room, interrupting cooling at the spent fuel pools for 90 minutes. By 14 June, the plant was completely surrounded by flood waters and personnel, fuel and other supplies had to be brought in by truck and boat. Critical buildings at the plant were protected by a 2.4-metre-diametre, 610-metre-long, water-filled flood barrier. On 26 June, the barrier was punctured by a bobcat loader, causing an interruption in the external power supply and load transfer to the station diesel generators. On 27 June, Chairman Gregory Jaczko of the US Nuclear Regulatory Commission visited the plant. On 30 June, a worker was burnt while refuelling a seepage pump and had to be airlifted to a hospital in Lincoln. On 11 July, a new flood barrier protecting the electrical substation was installed.

There were two long-term changes as results of the flood. First, in August 2012, OPPD signed a contract for Exelon Nuclear Partners to manage the plant, although OPPD would maintain ownership. Secondly, OPPD spent USD 180 million and had to clear 450 corrective items issued by the US Nuclear Regulatory Commission before the plant could return to full power on 26 December 2013 after an outage of nearly three years. After a series of other technical issues which called for additional maintenance and upgrades, the plant was finally shut down for economic reasons in 2016.

Cooper nuclear station

The Cooper nuclear station is owned by the Nebraska Public Power District (NPPD) and located about 100 km south of Omaha, directly adjacent to the Missouri River. It is a General Electric 770 MW_e boiling water reactor (BWR) with a Mark 1 containment and was commissioned in 1974. Its licence has been extended to August 2034. The plant is 275 m above sea level. NPPD brought in 4 500 tonnes of sand, barricades and HESCO barriers in anticipation of flooding.

The reactor was refuelled during April and May 2011 and on 8 May returned to operation. On 14 May, it was at full power and continued at full power throughout the flood. The Missouri crested at the plant on 19 June and on 12 July the plant ended its emergency status because the river had dropped to 273 m, 1 m lower than the emergency status level.

Comparison of Fort Calhoun and Cooper experience

Given that these two plants are within 200 km of each other and experience comparable conditions, it is perhaps worthwhile to consider why the outcomes were so different.

First, the contour of the river valley and the fact that Cooper is located on slightly higher ground may have lessened the impact of the flood. Secondly, the two fires and the damage to the flood barrier demonstrate the importance of secondary accidents when dealing with a major event. Thirdly, during the summer the output from Cooper was needed because Fort Calhoun was shut down and coal deliveries by barge were impeded by the flood. Fourthly, the fact that Fort Calhoun is closer to Omaha and was undergoing a major outage immediately before the flood caused (or allowed) more pointed and longer-duration consideration of readiness for return to operation. And finally, the timing of the flood was more favourable, by a few days, to Cooper than to Fort Calhoun.

Drought of 2012

The drought of 2012 covered many of the areas affected by the Missouri River flooding in 2011. According to the US Department of Agriculture (USDA, 2013), it was the most severe in at least the last 25 years and the most severe in the states of Kansas and Missouri.

On 26 June, generation for the 104 US nuclear plants in the United States fell to 94 171 megawatts, or 93% of capacity, the lowest seasonal level since 2003. The total that day was down by 2.6% from the five-year (2007-2012) average of 96 725 MW.

Exelon's Byron 1 and Byron 2 plants in Illinois began operating below full capacity on 28 June. Generation at the 1 164-MW Byron 1 reactor slowed to 80% of capacity, while Byron 2 operated at 84%. Production fluctuated because adjustments to cooling tower operations vary with weather conditions. As a result, the plants initiated a year-long maintenance project to allow the upgrade of equipment inside the cooling towers.

During July the twin-unit Braidwood nuclear plant, also in Illinois, needed to obtain special permission to continue operating because the temperature in its cooling-water pond rose to 39°C, that is 2°C above its normal limit. Vermont Yankee, the 620-MW plant operated by Entergy Corp., reduced power to 83% of capacity on 17 July because of low river flow and heat. Finally, during August, Millstone nuclear plant, Connecticut had to shut down one of its reactors because the water it drew from the Long Island Sound was too warm to cool critical equipment outside the core.

Hurricane ("superstorm") Sandy

Hurricane Sandy was caused by the merger of a tropical storm coming north along the US Eastern Seaboard with a frontal system coming down from Canada during the period 22 to 31 October 2012. Its winds spanned 1 800 km and reached 185 km/hr. The storm turned west towards land and struck the New York/New Jersey region, rather than heading east over the open Atlantic as is usual for most tropical storms.

Sandy caused 286 fatalities in 7 countries, 160 of those in the United States. Damages were estimated at USD 68 billion, primarily in northern New Jersey and New York City, where the storm hit on 29 October, flooding streets, tunnels and subway lines and cutting power. Substations were disabled by winds, saltwater spray and driven rain. Most of Manhattan south of 42nd street was without power. On 30 October, fires fed by broken natural gas mains destroyed 111 structures in Breezy Point, Queens.

Impacts on electrical infrastructure

Since New York City is such a vertically integrated city, with underground power transmission lines, subways, railway and highway tunnels, the damages due to rain and the storm surge were extensive. Furthermore, outages at open air substations along the Hudson and East Rivers due to driven rain and salt spray caused arcing and the failure of switchgear.

On 29 October at about 20h30, the Consolidated Edison (ConEd) substation along the East River at 13th Street and the Franklin D. Roosevelt East River Drive (FDR) was flooded and drenched with spray. Transformers exploded and the power went out for the area south of 34th Street. The substation is adjacent to the 14th Street cogeneration plant, which has been a major power source for Manhattan for several decades. The substation was built for a 3.8 m storm surge, but the surge in Hurricane Sandy was 4.3 m. In New York City and Westchester, 900 000 ConEd customers were without power, 250 000 of them because of the failure of the 13th Street substation. Other substations in Brooklyn, Long Island also failed due to flooding and driven spray. System-wide projects are now under way to raise equipment and install waterproof walls at substations.

Backup generators failed at the New York University Langone Medical Center at 33rd Street and FDR, also facing the East River. The failure required 215 patients to be moved to other facilities in the middle of the storm. There were some islands of power, especially in groups of buildings served by co-generation systems. Distribution lines and substations were the primary failure points in the system, leaving 7.4 million without power across the path of the storm.

Impacts on New York City subways

The Metropolitan Transit Authority (MTA) is the largest in the United States, carrying some 10 million passengers daily. Since much of the trackage is below grade and often below sea level, the MTA uses some 700 pumps spread throughout the system to remove 49 000 m^3 of water that leaks daily into the tunnels under normal conditions. The system can withstand rainfall at the rate of 38 mm/hour.

The MTA learnt lessons from the heavy rainfall in 2007 and from Hurricane Irene (August 2011) and took a number of precautions in the face of impending storms. These include moving buses and trains to higher ground, covering subway entrances and ventilation grates with tarps and sandbags and clearing debris from all pumps and drains in subways, tunnels and on bridges. In addition, all pump trains (diesel-powered trains fitted to remove water from tunnels), portable pumps and emergency response vehicles were readied. The Incident Command Center in Manhattan was activated and staffed well before the storm's arrival.

Service on the subways was stopped at 19h00 on 28 October and for the buses at 21h00, to allow their movement away from threatened areas. Finally, a number of temporary, water-proof walls were built across tunnel entrances to prevent flooding from heavy rainfall. Bus service resumed at 17h00 on 30 October and subway service on 1 November, though some lines were closed for as long as a year because of track and bridge damage.

Unexpected challenges emerged with the flooding of the Brooklyn-Battery and Queens-Midtown tunnels and to the damage to tracks and bridges in Far Rockaway, on the Long Island Railroad and on the Metro-North system, north of New York City.

Impacts on nuclear power plants

Oyster Creek, a 636 MW_e BWR located 90 km south of New York City along the New Jersey shore, was shut down for refuelling on 21 October. In the course of the storm, it lost its connection to the grid on 29 October. Operators declared an alert and turned to backup generators to maintain cooling. On 30 October, its cooling water intake structure was flooded with 2 m of water due to the storm surge. No damaged was sustained. The plant restarted on 30 November.

The Indian Point Energy Center, along the Hudson River 55 km north of Manhattan, contains two PWRs, units 2 and 3, which produce 1 020 and 1 025 MWe, respectively. Unit 3 scrammed on 29 October as the result of an upstate electrical grid disturbance and restarted on 2 November. Unit 2 continued to operate at full power throughout the storm.

Seabrook Station, 64 km north of Boston and set back 1.5 km from the shore along the New Hampshire coast, is a 1 244 MWe PWR. Commissioned in 1990, it was shut down for refuelling during the hurricane, but restarted on 30 October.

Salem nuclear power plant, along the Delaware River estuary about 30 km south of Wilmington, Delaware, consists of two PWRs rated at 1 174 MWe and 1 130 MWe. Unit 1 was manually shut down from 100% power on 30 October because of the high water level at water intake. Unit 2 was down for maintenance during the storm. Hope Creek 1, a 1 268 MWe BWR, is located adjacent to the Salem site and continued operating at 100% power during the storm.

Limerick Generating Station, south-eastern Pennsylvania, has two 1 134 MWe BWRs. The reactors reduced power from 100% to 50% and 22% respectively on 30 October because of the storm effects and at the request of the regional electric grid operator.

Nine Mile Point nuclear station, on the New York shore of Lake Ontario, has two BWRs of 609 MWe and 1 140 MWe. The reactors are about 375 km from New York City and not within the hurricane. However, unit 1 was manually shut down from full power on 29 October owing to an electric grid disruption caused by the storm. Unit 2 continued to operate at full power.

Overall, 34 nuclear power reactors from South Carolina to Vermont were in Hurricane Sandy's path. Of that total, 24 reactors continued to generate electricity throughout the storm, though some, as noted above, operated at reduced power. Of the ten remaining reactors, seven were already shut down for refuelling or inspection and three (Indian Point 3, Salem 1 and Nine Mile Point 1) safely shut down, as designed, because of storm conditions or grid disturbances (NEI, 2012).

Conclusions

These three events suggest several conclusions about the vulnerability of nuclear power facilities to flooding, drought and severe storms that may be exacerbated through climate change and a gradual rise in sea level. The experiences at Cooper during the 2011 flooding and in the New York subway system and local nuclear plants demonstrate that planning, preparation and pre-placement of equipment and supplies are critical.

The 2011 Missouri River flooding demonstrated that site differences and secondary accidents can impose unforeseen difficulties. The 2011 floods also dramatically showed that the overall event can be mitigated but prolonged by river management decisions.

The plants that endured the 2012 drought were required to make partial though long-lasting reductions in power. Shortages of water for cooling are chronic and widespread rather than short-term and localised problems.

The experience during Hurricane Sandy indicates that the power reactors are generally less vulnerable than other components of the infrastructure, particularly the electrical grid and substations, to the impact of severe hurricanes and a sustained rise in sea level. The need for robust systems not dependent on external power was demonstrated by such diverse events as the station blackout and meltdowns after the tsunami that hit the Fukushima Daiichi plant and the inability to pump gasoline after Hurricane Sandy. This type of event shows that resilience and adaptation to climate change need to be addressed both at the level of the generation and at the system level, including grids, cooling bodies, and other infrastructures.

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Chapter 11. **Regulations, standards and policies**

In the previous chapters, examples of extreme weather events from the last 25 years were described. The case studies show how such events can have an impact on the operation of nuclear power plants. In many cases, the experience and lessons learnt from these events have led utilities to develop engineering or other measures to improve the robustness and resilience of nuclear power plants and their surrounding environment, as well as the efficiency of the plants. In some cases, improvements were required by the nuclear safety regulators to ensure that the nuclear power plants meet stronger safety requirements. Environmental regulations, industry standards and policies are other drivers for adaptation. In many cases, these regulations, standards and policies are themselves based on past events, as well as more pressing demands from the general public to develop climate adaptation measures. This chapter will give some examples of such regulations, standards and policies developed in the European Union. Examples of changes proposed in US regulations are also described in this chapter, though some of these are being reconsidered today. The chapter also describes a particular case study, the flooding of le Blayais nuclear power plant in 1999 in France, which led to changes in risk assessment methodologies, flood protection measures and requirements. Finally, this chapter also describes recent changes in safety regulations related to climate change issues.

Environmental regulations

EU environmental regulations

The following issues have being identified[1] (see Table 11.1) as the main effects that climate change may have on nuclear power plants:

- increase in water temperature and a decrease in cooling water availability;
- ambient air temperature increase;
- flooding risks from increased precipitation.

According to the study (EC, 2011a), floods are seen by operators of nuclear power plants (as well as operators of other thermal power plants and hydro-electric dams) in Europe as having the highest impact on their installations. In general, until now, nuclear utilities had not considered the effects of climate change as a separate issue, since these effects were in most cases already addressed in the framework of safety reviews, which are part of the licensing regime and carried out every ten years in most European countries.

However, adaptation to climate change has now been introduced in all environmental and sectoral legislation in the EU as an essential factor to be considered in the medium and long term. The existing EU environmental legislation approaches the issue of adaptation by ensuring that climate change considerations are taken into account at EU, national and sectoral levels and by providing mechanisms to regularly update the information.

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[1] Questionnaires sent to nuclear power plants operators in Europe carried out as an initiative of the European Commission (EC, 2011a).

Table 11.1. **Qualitative link between technologies and climate change effect**

Technology	Δ air temp.	Δ water temp.	Δ precip.	Δ wind speeds	Δ sea level	Flood	Heat waves	Storms
Nuclear	1	2		-	-	3	1	-
Hydro	-	-	2	-		3	-	1
Wind (onshore)	-	-	-	1	-	-	-	1
Wind (offshore)	-	-	-	1	3	-	-	1
Biomass	1	2	-	-	-	3	1	-
Photovoltaics	-	-	-	-	-		1	1
CSP	-	-	-	-	-	1	-	1
Geothermal	-	-	-	-	-	1	-	-
Natural gas	1	2	-	-	-	3	1	-
Coal	1	2	-	-	-	3	1	-
Oil	1	2	-	-	-	3	1	-
Grids	3	-	-	-		1	1	3

Note: 3 = severe impact; 2 = medium impact; 1 = small impact; - = no significant impact. CSP = concentrated solar power.

Source: EC, 2011a.

As part of the strategic objectives of the EU policy, adaptation is discussed in a number of key EU initiatives, such as:

- Europe 2020 – Europe's growth strategy, "Strategy for smart, sustainable and inclusive growth";
- resource efficiency flagship initiative;
- European Commission's proposal for a 7th Environment Action Programme to 2020.

The Europe 2020 strategy notes that "*We must strengthen our economies' resilience to climate risks, and our capacity for disaster prevention and response*".

Environmental policies have traditionally focused on single cause-and-effect relationships. With the incorporation of the concept of adaptation, more complex interrelations need to be taken into account.

Adaptation to climate change policy in the EU

In June 2007, the European Commission presented the *Green Paper on Adapting to The Impacts of Climate Change,* based on the conclusions reached by the European Climate Change Programme. It describes possible actions on adaptation at the EU level. After a public consultation process during 2007-2008, the Commission published the White Paper "Adapting to climate change: Towards a European framework for action" (COM/2009/147) in April 2009. The White Paper presents a framework for the development of the EU's and its member states' strategies to adapt to climate change. The EU strategy on adaptation to climate change was published in 2013 (EC, 2013a).

It is accompanied by an Impact Assessment focusing on economic, environmental and social impacts in key sectors: agriculture, forests, fisheries, energy, infrastructure/building, industry/services, tourism, health and cross-cutting issues (water, ecosystems/biodiversity and land use).

The objective is to identify actions at the EU level to increase resilience to climate change. The White Paper establishes a framework for action based on five key pillars:

- A tool (Climate-ADAPT[2]) implemented to improve knowledge about:
  - monitoring programmes and information;
  - climate change impact scenarios;

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[2] http://climate-adapt.eea.europa.eu.

  - socio-economic aspects;
  - costs and benefits of different adaptation options;
  - information on good practices.
- Climate-ADAPT contains information on adaptation policies and measures, and includes adaptation case studies across Europe. It is an information technology tool and database on climate change impacts, vulnerability and best practices.
- Considering climate change impacts in EU policies: Incorporating climate risk assessments and adaptation measures in sectoral policies at the European level to reduce, in the long term, the vulnerability of sectors such as agriculture, forests, biodiversity, fisheries, energy, transport, water and health.
- Financing: Climate change is one of the priorities for the EU.
- Supporting international efforts on adaptation as part of the EU international co-operation policy, particularly in neighbouring countries.

The EU strategy states that "Whatever the warming scenarios, and however successful mitigation efforts prove to be, the impact of climate change will increase in the coming decades because of the delayed impacts of past and current greenhouse gas emissions. We therefore have no choice but to take adaptation measures to deal with the unavoidable climate impacts and their economic, environmental and social costs. By prioritising coherent, flexible and participatory approaches, it is cheaper to take early, planned adaptation action than to pay the price of not adapting. In view of the specific and wide-ranging nature of climate change impacts on the EU territory, adaptation measures need to be taken at all levels, from local to regional and national levels."

The main objective of the EU Adaptation Strategy is therefore to contribute to a more climate-resilient Europe by promoting action by member states, better informing the decision-making process, and promoting adaptation in key vulnerable sectors.

The strategy promotes the incorporation of low-cost and no-regret adaptation options regardless of the existing uncertainties related to the future impacts of climate change.

Adaptation has already become mainstream in EU legislation in sectors such as marine waters, forestry and transport; and in policy instruments such as inland water, biodiversity, and migration and mobility. The EU Commission has tabled legislative proposals on integrating adaptation in agriculture and forestry, maritime spatial planning and integrated coastal management, energy (EC, 2011b), disaster risk prevention and management, transport, research, health, and the environment. Mainstreaming climate change adaptation into EU policies will continue to be a priority in the energy and transport sectors. Also, adaptation action is being considered in the disaster risk management policies that the EU and the member states are developing.

The Adaptation Strategy contains eight actions:

- **Action 1**: Encourage all member states to adopt adaptation strategies and facilitate their implementation by providing guidelines.
- **Action 2**: Provide funding from LIFE, the EU fund for climate action, to support capacity building and foster adaptation, particularly in vulnerable areas such as cross-border management of floods, transboundary coastal management, urban land-use planning, natural resources management, desertification and forest fires.
- **Action 3**: Introduce adaptation in the Covenant of Mayors framework.
- **Action 4**: Bridge the knowledge gaps identified with information on damage and adaptation costs and benefits, regional and local analyses and risk assessment frameworks, models and tools. This will support decision making and help assess the effectiveness of past and current adaptation measures. The Commission is trying to identify relevant tools and methodologies to address these knowledge gaps. The findings are used to improve the information available on Climate-ADAPT.
- **Action 5**: Further develop Climate-ADAPT by improving access to information and by developing interaction between Climate-ADAPT and other relevant platforms.

- **Action 6**: Facilitate the climate-proofing of the Common Agricultural Policy.
- **Action 7**: Ensuring more resilient infrastructure. European standardisation organisations are starting to map industry-relevant standards in the area of energy, transport and buildings, identifying standards to be revised so as to better include adaptation considerations.
- **Action 8**: Promote insurance and other financial products for resilient investment and business decisions. Accompanying the Adaptation Strategy, the Commission published the Green Paper on the insurance of natural and man-made disasters, with the objective of encouraging insurers to improve their management of climate change risks. The Commission intends to improve the market penetration of natural disaster insurance and to unleash the full potential of insurance pricing and other financial products for risk prevention and mitigation and for long-term resilience in investment and business decisions.

In addition, the revision of the Monitoring Mechanism Decision/Regulation (EU, 2013) includes an article that requires member states to report every four years on their national adaptation planning and strategies, outlining their implemented or planned actions, the main objectives, and the category of climate change impact addressed.

At the end of 2018, 28 out of 33 members of the European Environment Agency (EEA) had already adopted national adaptation strategies.

Water policy and adaptation

The EU has developed a comprehensive water policy increasingly focused on environmental issues. Since 2000, with the adoption of the Water Framework Directive (WFD), water policy has taken an integrated approach to water management, on the basis of the concept of “river basin management” with the objective of achieving good status of all EU waters by 2015.

Several EU policies and initiatives include directly or indirectly adapting to climate change with regard to water issues. The most important ones are the EU Water Framework Directive (WFD) and its daughter directives, the EU Floods Directive, the EU Water Scarcity and Droughts Policy.

▪ Water Framework Directive

The Water Framework Directive 2000/60/EC (WFD) establishes a legal framework to protect and restore the water environment across Europe by 2015 and to ensure the long-term sustainable use of water. It replaced several directives on different issues like surface water, measurement methods and sampling frequencies, exchanges of information on freshwater quality, fish and shellfish water, groundwater, and discharges of dangerous substances. The directive addresses inland surface waters, transitional waters, coastal waters and groundwater. It obliges member states to assess the environmental pressures of human activities and their impact on waters, to set targets for improving the status of water bodies, implement the necessary measures and achieve “good status” for surface and ground water in 2015.

River basin management plans (RBMPs) containing concrete measures to be implemented have to be established with public participation and reviewed every six years to incorporate recent information.

Although climate change is not explicitly included in the text of the WFD, it has to be comprehensively considered in the different steps of its implementation and in the planning and implementation of the RBM. These steps include characterisation of the issues, analysis of pressures and impacts, economic analysis, monitoring, design of the programmes of measures and the default and waterbody objective-setting processes. The second RBM plans due in 2015 have to be designed to be climate-proof, ensuring that measures are flexible enough to be adjusted to changing climate conditions. In the case of fixed measures, they need to incorporate climate projections in their design.

Guidance on how climate change shall be taken into account in the RBMPs has been developed by the Common Implementation Strategy (CIS) of the WFD (EC, 2009b).

- Floods Directive

The so-called Floods Directive (EU, 2007a) provides a framework for adaptation with regard to water issues. It establishes a legal framework for the assessment and management of flood risks across member states, with the objective of reducing the adverse consequences of floods to human health, the environment, cultural heritage and economic activity.

The directive requires member states to produce the first flood risk management plans (FRMPs) in 2015 in those areas for which potential significant flood risk has been assessed. FRMPs have to provide adequate and co-ordinated measures to reduce this flood risk, taking into account the possible impact of climate change. Since climate change contributes to an increase in the likelihood and adverse impact of flood events, the expected impact of climate change on the occurrence of floods shall be taken into account at all required stages of implementing this directive.

The main elements of the flood risk management cycle are preliminary flood risk assessment, flood hazard and risk maps, and flood risk management plans. For each river basin district, or unit of management or portion of an international river basin district lying within their territory, member states have to undertake a preliminary flood risk assessment.

- Water scarcity and droughts policy

Further deterioration of the water situation in Europe is expected if temperatures keep rising as a result of climate change, in particular in southern countries in the EU. The European Commission adopted an official communication regarding water scarcity and droughts on 18 July 2007. The communication, “Addressing the challenge of water scarcity and droughts” (EC, 2007), is closely linked to climate change, having the objective to further develop adaptation measures to address the increasing impacts of water scarcity and droughts expected in the next decades.

The communication presents different options to manage the problems of water resource scarcity and drought, and presents good practices implemented in various countries. The main priority is on water saving to guarantee that all possibilities to improve water efficiency are fully explored. Member states are encouraged to draft drought management plans. It proposes to establish the European Drought Observatory EDO, developed by the Joint Research Centre (JRC), and introduces the possibility of using European funds for countries suffering prolonged droughts.

The accompanying technical report provides recommendations on how to develop drought plans with mitigation and prevention measures in order to minimise the environmental, economic and social damage caused by droughts.

Water quantity issues will increasingly be integrated into sectoral policies in the EU.

A Policy Review for Water Scarcity and Droughts was completed in November 2012, as part of the “Blue Print for Safeguarding European Waters” adopted by the European Commission on 14 November 2012.

- Blueprint to Safeguard European Waters

The Commission presented in November 2012 a “Blueprint to Safeguard European Waters”, with the objective of strengthening the enforcement of the Water Framework Directive. The “blueprint” outlines actions for better implementation of current water legislation, integration of water policy objectives into other policies, and filling the gaps in water quantity and efficiency. The water blueprint fits into the EU’s 2020 Strategy and more specifically the 2011 Resource Efficiency Roadmap.

Industrial Emissions Directive

The Commission adopted the Industrial Emissions Directive (IED) on 21 December 2007. It entered into force on 6 January 2011 and was transposed into national legislation by member states by 7 January 2013.

The IED is the successor of the Integrated Pollution Prevention and Control (IPPC) Directive. It tries to minimise pollution from various industrial sources across the European Union in particular through better application of best available techniques. Operators of industrial installations conducting activities covered by Annex I of the IED are required to obtain an integrated permit from the authorities in the EU countries.

The permit conditions, including emission limit values (ELVs), must be based on the best available techniques (BAT), as defined in the IPPC Directive. BAT conclusions (documents containing information on the emission levels associated with the best available techniques) are the reference for setting permit conditions. To assist the licensing authorities and companies in determining BAT, the Commission organises an exchange of information between experts from the EU member states, industry and environmental organisations co-ordinated by the European IPPC Bureau of the Institute for Prospective Technology Studies at the EU Joint Research Centre in Seville (Spain). This results in the adoption and publication by the Commission of the BAT conclusions and BAT Reference Documents (BREFs).

Although installations for the production of nuclear power are not part of the scope of Annex I of the IPPC Directive, the environmental techniques considered in the BREF "Industrial Cooling Systems" apply where they relate to the cooling systems of the conventional section of these installations. The scope of the BREF Industrial Cooling Systems, approved in 2001, is the following:

- once-through cooling systems (with or without cooling towers);
- open recirculating cooling systems (wet cooling towers);
- closed circuit cooling systems, air-cooled cooling systems;
- closed circuit wet cooling systems;
- combined wet/dry (hybrid) cooling systems;
- open hybrid cooling towers.

Its review started in 2015, and there is a proposal to merge the BREFs Energy Efficiency (ENE) and Industrial Cooling Systems (ICS) into a BREF "Resource Efficiency", though according to the JRC's website (JRC, 2019), this has not yet occurred. This may introduce new requirements for power plants. The environmental requirements associated with the design of cooling systems are:

- minimisation of energy use;
- minimisation of heat emissions;
- minimisation of large plume emissions;
- minimisation of emissions to water;
- minimisation of noise emissions;
- minimisation of emissions to soil and terrestrial habitats.

Adaptation to climate change will no doubt be a factor included in future documents and may pose new challenges for nuclear installations.

Environmental impact assessment and strategic environmental assessment

The EU legislation on environmental impact assessments and the Strategic Environmental Assessment Directive take into account, in their latest versions, the issue of adaptation to climate change at the stage of planning for new installations.

The strategic environmental assessment (SEA) helps to ensure that plans and programmes take full account of climate change issues. The SEA Directive (EU, 2001) requires identification and evaluation of planned impacts on a number of environmental issues, including climatic factors. Where appropriate, it requires putting measures in place so as to minimise and respond to significant impacts. The Commission identifies possible SEA climate change adaptation objectives such as:

- ensuring that drainage systems can cope with changing rainfall patterns/intensity;
- taking a precautionary and risk-based approach to developing in the floodplain;
- ensuring adequate future water supply and demand management;
- avoiding actions that limit future adaptation.

The Environmental Impact Assessment (EIA) Directive[3] was adopted in 1985 and later revised. In October 2012, the Commission adopted a proposal for a new directive aiming at simplifying the process and improving environmental protection. It incorporates new environmental challenges such as resource efficiency, climate change (including adaptation), biodiversity and disaster prevention. This amended directive (2014/52/EU) entered into force on 15 May 2014 and stipulates that EIAs must:

- detail the scope and control the quality of the information;
- assess reasonable alternatives, justify final decisions and monitor significant adverse effects post EIA;
- assess the needs to adapt to challenges like biodiversity loss, climate change, disaster risks, availability of natural resources.

These issues are becoming essential in policy making and constitute critical elements in assessment and decision-making processes, especially for infrastructure projects.

The EIAs have to identify, describe and assess the significant direct and indirect effects of each individual project on climate change and its exposure, vulnerability and resilience to natural and man-made disaster risks.

In assessing the characteristics of projects, particular consideration must be given to the impact on climate change in terms of greenhouse gas (GHG) emissions, including from land use, land use change and forestry, contribution of the project to an improved resilience, and the impact of climate change on the project (e.g. if the project is coherent with a changing climate).

Mandatory *ex post* monitoring is introduced only for projects that will have significant adverse environmental effects. This new obligation is found relevant for addressing impacts related to new challenges such as climate change and disaster risks.

All these new requirements may make the process more complicated and costly. There are imprecise and substantial new requirements that may exceed what can be assessed by a project developer, especially related to climate change considerations.

To facilitate the process, the Commission has issued guidelines on integrating climate change and biodiversity into environmental impact assessments.

US environmental regulations

In the United States there has been a significant movement towards requiring the installation of recirculating cooling systems and the construction of natural draft cooling towers at nuclear plants initially built with once-through cooling. The primary motivation for requiring recirculating cooling has been the impact of once-through cooling on aquatic life in the river or lake, either due to the temperature increase itself or to aquatic life passing through the screens, piping, pumps and valves of the plant.

The regulations on the handling and discharge of cooling water are derived from the Clean Water Act (CWA) of 1972 and enforced by the US Environmental Protection Agency (EPA). Two sections of the CWA are particularly relevant: Section 316(a) covers temperature limits on discharges and Section 316(b) covers the methods and technologies for reducing the impacts of impingement of aquatic life on the inlet structures and entrainment of aquatic life in the passage of cooling water through the generating plant.

Section 316(a) of the CWA provides that the EPA and delegated state agencies may authorise alternate thermal conditions in National Pollutant Discharge Elimination System (NPDES) permits where the effluent limitation is more stringent than necessary to assure the protection and propagation of a balanced, indigenous community of shellfish, fish, and wildlife in and on the body of water into which the thermal discharge is made. State regulations, in turn, provide for the granting of thermal variances and have the requisite authority to issue such variances. Variances are reviewed with each NPDES permit renewal.

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[3] Directive 85/337/EEC, amended by Directives 97/11/EC and 2003/35/EC.

The party seeking thermal variance has the burden of demonstrating that a variance is justified. In order for the permitting agency to determine whether a variance is warranted, the permit applicant typically must conduct scientific investigations to demonstrate, either through predictive or empirical means, that a balanced, indigenous aquatic community will be, or is currently, maintained and protected.

Notice that the regulation is not written in terms of a fixed temperature limit, but in terms of assuring the "propagation of a balanced, indigenous community …" The regulation also calls for co-operation between the EPA and state agencies.

Section 316(b) of the CWA regulates intake structures, particularly screens to prevent fish from being drawn into the plant and methods for reducing impingement mortality, where small fish become trapped on the inlet screens, and entrainment mortality, where larvae, eggs and other very small aquatic life pass through the plant and succumb to temperature changes, pressure variations or accelerations in their passage through the plant. A proposed rule for the enforcement of Section 316(b) was issued in April 2011 and then in 2015.

EPA enforcement of the CWA is on a site-specific basis, but the options considered must include closed-cycle cooling and fine mesh screens on the inlet structures. All facilities withdrawing at least 2 million gallons per day (MGD) from waters of the United States are within the scope of the rule, but the requirements to provide the EPA with justifying information apply only to facilities the use >125 MGD (>5.5 m^3/s). That justifying information includes:

- numbers and types of organisms entrained;
- entrainment impacts;
- social benefits and social costs;
- thermal discharge impacts;
- impacts on the reliability of energy delivery;
- impact of changes in particulate emissions or other pollutants;
- land availability;
- remaining useful plant life;
- impacts on water consumption.

Technical research in the United States focuses on quantification of the ecological and economic impacts of cooling water intakes, on evaluating performance, feasibility, impacts and cost of alternative fish protection technologies and impingement/entrainment sampling.

The Electric Power Research Institute (EPRI) carried out a study to estimate the national cost of retrofitting existing once-through cooled facilities with closed-cycle cooling systems at 428 power facilities potentially subject to a retrofit requirement (based on their use of over 50 MGD (2.2 m^3/s) of once-through cooling water. These facilities generate approximately 312 000 MW of electricity, including 60 000 MW from 39 nuclear facilities and 252 000 MW from 389 fossil facilities (EPRI, 2011). EPRI estimates a net present value of USD 62 billion (USD 19.6 billion and USD 42.4 billion for nuclear and fossil facilities, respectively) in capital costs to retrofit the 428 once-through cooled facilities.

Note that since 40% of the world's population lives within 100 km of a seacoast, one way of adapting to recurrent droughts would be to increase the use of seawater for cooling. All nuclear plants in Japan are located on the seacoast, in part because of their lack of any large rivers capable of supplying cooling water. As noted earlier, 15 of France's reactors are also located on the coasts. Coastal plants in the United States face the same regulations under the Clean Water Act. Mitigation of the thermal impact on marine life has been investigated by the Japanese (Kiyono et al., 2011). Earlier research by General Dynamics for the EPA investigated the use of subsurface horizontal injection of cooling water in deep water (>50 m) at considerable distances (~50 km) offshore to mitigate impacts on marine and coastal life (EPA, 1971). Technical research should focus on the areas of biofouling and corrosion of the heat transfer surfaces.

Safety regulations

IAEA regulations

The International Atomic Energy Agency (IAEA) provides guidance on the two main aspects of meteorological hazards: the hazard assessment and the protection against these hazards. The assessment for meteorological and hydrological hazards is dealt with in the Specific Safety Guide No. SSG-18 "Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations" and the protection against meteorological hazards is addressed in Safety Guide NS-G-1.5 "External Events Excluding Earthquakes in the Design of Nuclear Power Plants".

The general approach to hazard assessment according to SSG-18 consists in three steps: i) evaluation of the available data, ii) selection of an appropriate statistical distribution to fit the data, and iii) determination of the mean recurrence intervals based on the evaluation of the moments of the probability distribution. These analyses should be performed for air temperature, wind speed, precipitation and snowpack. For some rare meteorological phenomena such as lightning, tropical cyclones (typhoons, hurricanes), tornadoes and waterspouts, modified approaches are recommended because the standard methodology cannot easily be applied to these types of hazards. In addition, the systematic hazard assessment in SSG-18 recommends adding some margins onto the derived values to take account of potential future climate changes and to re-evaluate the design parameters periodically.

Compared to the comprehensive hazard assessment approach of SSG-18, the design requirements in NS-G-1.5 are rather generic. Whereas equipment qualification according to the safety and external event classification is required, structural design should follow the conventional building codes. With respect to the ultimate heat sink, the need to ensure its availability under drought conditions and other extreme meteorological situations is emphasised.

The requirements on probabilistic assessments for external hazards are described in the Specific Safety Guide No. SSG-3 "Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants". Starting from a comprehensive list of external hazards (including meteorological hazards), the relevant hazards and hazard combinations (i.e. those that should be analysed in detail) should be identified in a screening process and a subsequent bounding analysis. For those hazards that require a detailed assessment, the most important parameters relating to the damage potential should be defined. The estimation of the frequencies for various values of these parameters (i.e. the development of the hazard curve) should be based on a probabilistic evaluation that reflects recent available data, and on site-specific information. This analysis should also consider potential time trends in the data, which may be the most important part of the process addressing climate changes. To evaluate the capacity of the plant, fragility analysis of structures and components should be performed, including in particular plant-specific information available from the documentation and from walkdowns.

European developments (WENRA reference levels)

After the nuclear accident at the Japanese Fukushima Daiichi site, the Western European Nuclear Regulator Association (WENRA) initiated an amendment of its reference levels. This amendment also includes the development of the new Issue T on Natural Hazards (WENRA, 2016) that covers:

- the identification of natural hazards;
- the site-specific natural hazard screening and assessment;
- the definition of the design basis;
- the protection against design basis events;
- considerations for events exceeding the design basis.

Important aspects of these requirements are a common target frequency for design basis natural events of 10^{-4}/year and the requirement to perform a systematic assessment of beyond-design events to identify potential cliff-edge effects.

The frequency of external hazard occurrences is implicitly expected to be constant in the WENRA documents since no trend analysis possibly addressing the effects of climate changes is mentioned in them.

National regulatory requirements

As an example of the various regulations in the member states, Germany's regulatory requirements with respect to extreme meteorological conditions are the following:

Germany's nuclear regulations require extreme weather conditions to be considered in the design of nuclear power plants. The original requirements issued in 1977 as part of the Nuclear Power Plant Safety Criteria were quite general and in 2012 were replaced by the new Safety Requirements for Nuclear Power Plants). In this high-level regulatory document, various meteorological hazards are addressed explicitly. At the level below the Safety Requirements for Nuclear Power Plants, detailed nuclear safety standards are available only for flooding and lightning protection. For the design against other meteorological hazards, conventional civil engineering codes such as the DIN EN 1991 (based on Eurocode 1, EN 1991) are applied. In contrast to the requirements for earthquakes and flooding, the protection against meteorological hazards does not rely on site-specific hazard assessments and frequencies in the range of 10^{-4}/year to 10^{5}/year but on regional hazard maps and higher frequencies (in the order of 10^{-2}/year).

To verify the adequacy of the design, reassessment of the protection against external hazards is part of the periodic safety reviews of the German nuclear power plants which have to be performed every ten years. In general, these reviews consist of deterministic and probabilistic analyses. Whereas a probabilistic assessment for extreme external hazards (earthquake, flooding, aircraft crash, and explosions) is mandatory, this is not the case for meteorological hazards.

In the Czech Republic, the treatment of external hazards from a probabilistic point of view is described in the newly released Czech regulatory body's (SUJB) Decree, where the recommended scope and methodology of Level-1 probabilistic safety assessment for two Czech nuclear power plants – Dukovany and Temelin – are given. The external events/hazards analysis forms a significant point in the PSA-1 scope, as defined in this decree where, however, the new topic of climate change has not been addressed yet. A similar document has been developed for Level-2 PSA.

Example of risk-oriented treatment of external hazards – PSAs for Czech nuclear power plants

There are two main categories of negative impacts that climate change can bring, and that should be distinguished from a risk analysis point of view. The first category includes longer-term effects making the future operation of nuclear power plants more difficult, where risk analysis bears mainly on possible social and economic consequences of nuclear power plant operation (decreasing overall water resources because of higher temperature can lead to problems with cooling). The second category is related to the increasing frequency of "sudden" extreme natural events which may have a significant safety impact on plant operation. The comments made here will address the second category, where the progressive means of risk analysis using accident scenarios related to external events could be employed to determine the impact of climate changes if these means are further developed in the right way.

As current risk analyses can confirm, the relatively frequent natural events are usually of minor safety importance because nuclear power plants are constructed and operated to withstand their effects. Thus, most risk-related analyses are typically devoted to exceptionally intense natural events, most of which have not occurred up to now but could still occur with low probability but critical consequences. Since "direct" plant-specific data on such events are not available, special data treatment and extrapolation methods have to be used to estimate their frequency.

In the recent safety models for Czech nuclear power plants, analysis of external events has become an integral part of PSA and-risk-oriented decision-making efforts. This process started well before the Fukushima Daiichi accident and is continuing in parallel with stress tests and other activities, reflecting the impact and consequences of Japan's accident.

Risk-related analyses of selected external hazards will continue at both the Dukovany and Temelin plants. At Dukovany, the main goal is to address important changes in plant design and operation to protect against external events. In the case of Temelin, new risk analyses that are part of a broad PSA level-1 update are planned. The objective is to treat climate changes by improving the methodology for evaluating natural hazards.

The first part of each natural event analysis consists of identifying and selecting/screening external hazards. Some new approaches, for example the EPRI approach can be used here, although they have not taken into consideration climate changes experienced so far. The point is that the EPRI methodology is based on a long list of possible external hazards, only some of them natural, that are studied case by case and screened out or included into the detailed safety analysis for a given plant site on the basis of roughly estimated frequencies or safety impacts. Climate changes can be taken into account during the screening process such as the occurrence of various types of likely events in the area of the plant site being analysed. For example, whereas the category "tornado" could be definitely screened out of the analysis of Czech nuclear power plants during the previous thirty years since there was no record of tornadoes in the Czech Republic, several tornadoes have occurred since that time, and considering the plant risk-free would be questionable.

In general, the process of gradually screening out external hazards irrelevant from a risk point of view and developing a complete list of external events can be based on the answers to the following questions:

1. Is the given external hazard meaningful and real for the nuclear power plant and unit being considered?
2. Are the negative consequences of a given external event real enough to lead to some risk scenario?
3. Is the annual frequency of an external event occurrence high enough to predict a risk impact?
4. Does a given external event mean a real danger of over-reaching the vulnerability level of important safety components, systems and structures?
5. Is a given external event unique (not part of some other external event analysed in the external risk study concerned)?

In the example of tornadoes, a negative answer to questions 1, 2, 4, and 5 cannot be made whereas question 3 requires a further specific quantitative analysis.

The new aspect in the methodology is the emphasis on the analysis of combinations of external hazards. This aspect seems crucial for a probabilistic analysis of climate change impacts on safety, since the higher dynamics of natural (weather) processes can lead to more frequent occurrences not only of individual high-intensity events, but also of a combination of them.

The other part of external risk analysis looks at vulnerability, fragility and the consequences of external events and is usually carried out in three steps. Step 1 is focused on the selection of potentially risk-prone structures, components and systems. Step 2 is a fragility analysis. In step 3, an analysis of direct and induced consequences of external events (direct and major equipment failures) is carried out. From a detailed technical point of view, climate changes may not greatly influence this part of the risk-related analysis. However, it is quite possible that the assumptions and conclusions related to the methodology concerning the higher intensity of natural events will be relatively more important in the future since today very high-intensity scenarios are often simply screened out.

Since the weather events may become more frequent and intense, accident scenarios will also be more frequently modelling severe damages to plant equipment. From a risk point of view, it means that the spectrum of scenarios in the PSA model may need to be extended and new systems and human actions included in the model and analysis.

From a quantitative point of view, the key in risk analysis is an estimation of recurrences. For the relatively probable events, values derived from design applications can be used in the estimation of an event frequency in a very straightforward manner. The values of the parameter defining intensity of a given natural hazard (high wind speed) related to 100- and 10 000-year return period correspond to frequencies of 10-2 and 10-4 per year, respectively. For any other value of a (critical) load between these two values, frequency can be evaluated by using the selected probabilistic distribution and interpolation.

The problem is that the frequencies of some events still included in the PSA model (because the plant response may be quite unreliable and the conditional code damage probability very high) may be of the order of 10-5 to 10-6. In case of a similar low-frequency value for internal events (loss-of-coolant accident, LOCA, for example), generic frequency values may do the job. However, frequencies of natural events are highly site-specific and should not be estimated from generic data only. For such events, experience in terms of years maxima for the given parameter (wind speed, high/low temperature) covering 30 to 50 years of data collection may be available for typical cases and values of high-intensity parameters need to be estimated by extrapolation from plant-specific data (corresponding to 100 000 to 1 000 000 years of experience).

Ideally, data are recorded directly at plant site. However, the data are usually recorded at the site when the decision to build the plant is taken. Thus, for relatively new plants, only data collected over a period as short as a decade may be available. In this case, the data collected may be enriched by using the data collected in neighbouring locations, but the relevance of the data has to be verified carefully (correlation analysis is possible). There are typically several locations close enough to the plant where meteorological data produce several usable samples of data.

At the Dukovany nuclear power plant, for example, the data sample recorded directly at the site covers the last 30 years and is supplemented with data from five other locations close enough to the plant to obtain a sample covering 50 years, which is recommended as the minimum time for the application of statistical methods, including comprehensive correlation analyses of daily observations collected from the individual data sources. At Dukovany, the results of correlation analyses have shown a relatively high level of correlation between the values of the selected data sources and, in general, have supported the use of the data from weather forecasting stations near the plant. Since the Dukovany data were available for only a relatively short period, a non-parametric Spearman correlation coefficient was used for the selection of the best source of data.

The selection of probabilities that allow extrapolation is another key point. In the case of Dukovany, this matter was supported by a comprehensive comparison of the results obtained after using several distributions proposed in the methodologies. Although this was rather theoretical, it had a fairly big impact on the results of the data analysis and, consequently, on the results of an analysis of external risks to the plant. The Gumbell distribution recommended in the IAEA guide was confirmed as the best choice for all the external hazards specified as the most important for both the Dukovany and Temelin plants.

Several conclusions regarding the methodology of the analysis can be drawn from recent experience with the extrapolation of values based on the analysis of meteorological data records:

- The selection of probabilistic distribution has an essential impact on the results; that is why it is recommended to compare several proposed probabilities and to select one with i) the best references for the given type of analysis and ii) adjusting the data sample; the selection of Gumbell distributions is generally recommended.
- The selection of reference weather forecasting stations as the major data source should depend on having the same or similar meteorological conditions as the site considered, or the nearest station.
- The largest reliable dataset available is highly recommended:
  - The data sources from different weather forecasting stations should not be combined.
  - Lack of data (or too small a sample) should not be compensated by including maximum values of two, three or more previous years. The CSNI Working Group on Risk Assessment directed, in co-operation with the CSNI Working Group on Integrity and Ageing of Components and Structures, an international workshop on PSA of Natural External Hazards including Earthquakes, hosted by UJV Rez, on 17-19 June 2013, in Prague, Czech Republic (see Box 11.1).

Box 11.1. **The international workshop on PSA of natural external hazards, including earthquakes**

The CSNI Working Group on Risk Assessment (WGRISK) directed, in co-operation with the CSNI Working Group on Integrity and Ageing of Components and Structures (WGIAGE), a workshop entitled "International Workshop on PSA of Natural External Hazards Including Earthquakes", hosted by UJV Rez on 17-19 June 2013, in Prague, Czech Republic.

The focus of the workshop was on probabilistic safety analysis (PSA) of external events for nuclear power plants, including all modes of operation. The scope was generally limited to external, natural hazards, including those where the distinction between natural and man-made hazards is not sharp (such as external floods caused by dam failures). Participation was open to experts from regulatory authorities and technical support organisations, research centres, utilities, nuclear power plant designers and vendors, industry associations and observers from NEA member countries.

During its October 2006 annual meeting, the workshop held a formal technical discussion on the PSA treatment of external events other than seismic events. This discussion resulted in the need to review PSAs of external hazards for both existing and new reactors.

On the basis of the questionnaire responses and subsequent discussions, the project participants concluded that external events were playing an increasing role in PSAs and that there was a general trend in regulatory requirements towards consideration of all hazard categories (internal and external). Detailed analyses for some plants have shown that the contribution from non-seismic external events can be significant. The frequency and intensity of extreme weather events, and the significant risk they represent, may be affected by natural climate variability and by human-induced global warming.

The general report's recommendations were to pursue research on climate change and its effects (including potential effects on nuclear power plants, such as those being studied by the International Atomic Energy Agency), to re-evaluate the situation on external events in a few years' time and to encourage analysis of disruptions caused by external hazards.

The external hazards analysis methods have been used recently to evaluate operating nuclear power plant units and to identify the needs for modification of plant systems and procedures as well as to support the design of new plants. The major areas concerned in the external hazards studies, as identified before and during the workshop, are: i) the scope of the PSA for external events in terms of plant operation regimes; ii) the impact of a combination of external hazards; iii) the horizon for long duration scenarios; iv) multi-unit impacts; v) the establishment of screening procedure for site-specific hazards.

Furthermore, it was emphasised that addressing climate changes in probabilistic safety analyses of external events represents a major challenge for the process of deriving event frequencies. Addressing climate change means adding one or more parameters into the frequency model, and this parameter has to be estimated on the basis of available data.

Recognising the potential importance of climate change effects on some risk-informed decisions (e.g. those requiring consideration of risk projections for extended periods), the workshop suggested that WGRISK continue to monitor the state of the science, possibly addressing the topic through a technical discussion at a future meeting.

Stress test information on protection against extreme weather events

After the Fukushima Daiichi Nuclear Power Plant accident, the European Council requested that the safety of all EU nuclear plants be reviewed ("stress tests"). Stress tests were defined as targeted reassessments of the safety margins of nuclear power plants. The specifications of these tests were prepared by the Western European Nuclear Regulators Association (WENRA) (ENSREG, 2012).

The stress tests focus on extreme natural events that threaten the plant's safety and lead to severe accidents. Among the stress tests specifications, a special emphasis is given to earthquakes and floodings.

The licensees of EU nuclear power plants performed the stress tests, since they have the prime responsibility for the safety of the plants. The results are summarised in one report per site and are then published as licensee reports. All the individual licensee reports of one country are then summarised in a national report, and then in a final report summarising the national reports.

Stress test specifications focus on extreme natural events the frequency of which may change with climate change, and this in turn may have implications for the safety of current and future nuclear power plants, and their need to adapt to climate change.

Stress test specifications require a number of evaluations of climate change adaptation policies:

- extreme natural events challenging the plant safety:
  - floods, regardless of origin;
  - forest fires, airplane crashes;
  - large disturbances from breakdown of the electrical power grid impacting AC power distribution.
- presence storage of spent fuel to be considered;
- protective measures aimed at avoiding extreme scenarios;
- reassessment of safety systems to control such events;
- review of the design basis of the plant;
- loss of off-site power;
- a number of requirements directly related to the design basis flood (DBF):
  - level of the DBF;
  - methodology to evaluate the DBF;
  - provisions to protect the plant against DBF;
  - other effects other than those resulting from the flooding;
  - licensees' general process to ensure compliance;
  - the level of flooding that the plant can withstand without severe damage.

Since all licensees are working with the same specifications, their reports make it possible to check the current design basis against selected extreme weather events, as well as its rationale, the assessment methodology, and the measures taken to protect the plant against those events in a uniform way.

Table 11.2 summarises choices made by nuclear power plants in different European countries on the design basis for extreme weather events, why it is chosen (the rationale), and how it is evaluated taking account of the information provided in the licensees' stress test reports.

The table allows several conclusions. First, European nuclear power plants use different criteria to protect themselves against extreme weather events. For example, while Olkiluoto in Finland uses civil construction standards to protect against strong winds, Oskarshamn in Sweden defines a design basis event derived from frequency. Secondly, the design basis events that are defined for various nuclear power plants differ with respect to frequency. While German nuclear power plants use floods with a frequency of 10^{-4}/year as design basis event (based on KTA-standards), Oskarshamn protects itself against a flood with a frequency as low as 10^{-7}/year. Thirdly, in most cases where the design basis event is derived from frequency, historical data are used and extrapolated. Since it is expected that climate change will influence the frequency of extreme weather events, future evaluations (or re-evaluations) of the design basis event will have to take account of climate change when historical data are used.

Reassessment of design rules and adaptation measures against flooding: Le Blayais accident (1999)

Flooding is perceived as one of the most critical risks for the operation and safety of nuclear power plants, and climate projections described in Chapter 2 indicate increased risks of intense precipitation in many regions of the world, in particular Europe. A recent study that focused on hydro-meteorological hazards in Europe, the Rain Project, suggests that river floods will become more likely in central Europe and the United Kingdom, and that France, Germany, Hungary and Poland and are some of the countries that will have the largest increases in flood-prone areas (Rain, 2016). Therefore, it is worthwhile to look into an important case study for the impact of flooding events on nuclear power plants, Le Blayais accident (France, 1999), in addition to the flooding case studies in the United States reported in Chapter 10.

Le Blayais nuclear power plant, which consists of four 900 MW units, is the only nuclear power plant in France located in an estuary (4 nuclear power plants are located on the coast (English Channel) and the remaining 14 nuclear power plants are located along rivers), the so-called Gironde estuary, where the Garonne and Dordogne rivers meet. At this site, the effects of the sea are more important than those of the two rivers, hence the siting approach was based on data from high tides over several decades. The value on the basis of which the site protection system was designed was 5.02 m above the French national datum, corresponding to the level reached by the highest tide (coefficient 120) increased by a certain value to take into account local relief and meteorological conditions. The nuclear power plant site was therefore surrounded by a dyke of 5.2 m high along the estuary side, and 4.75 m along the sides. The operator Électricité de France (EDF) reassessed the flooding risks in the 1990s leading a new value of 5.46 m above the national datum, which would have implied raising the height of the dykes to 5.70 m.

On 27 December 1999 (Gorbatchev, 2000), a very severe flooding occurred at Le Blayais caused by a combination of factors: high tide, a storm surge that increased water levels by 2 m, and high waves generated by exceptionally high winds (200 km/h) in the estuary. The high winds also brought down the 225 kV supply lines to the four units, and one of the two 440 kV line (for units 2 and 4). These two units shut down automatically and emergency diesel generators started and operated until the line was brought back later that evening.

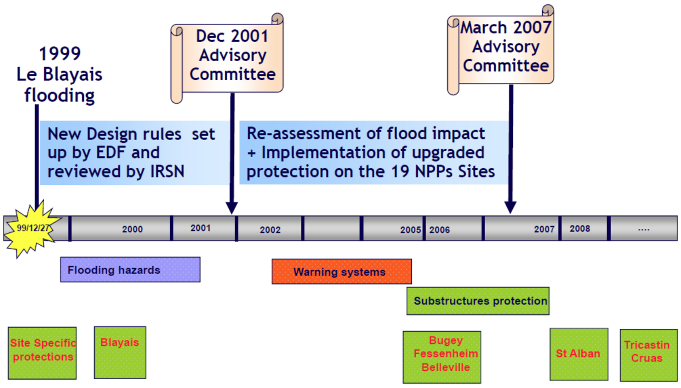
During that time, waves came over the dykes and water penetrated the site, with partial flooding of units 1 and 2, and to a lesser extent, units 3 and 4. An estimated 90 000 m^3 of water entered the site, with water penetrating parts of the building containing essential service water pumps (some of which became inoperable because of the immersion of their motors), electric equipment and other types of pumps. The on-site emergency plan was activated for 36 hours. Although safety was maintained at all times, the incident was rated 2 on the INES scale.

Following this incident, and after analysis by the TSO IRSN and the safety authority ASN (Autorité de sûreté nucléaire), EDF (de Fraguier, 2010) put in place a series of measures to improve the resilience of its nuclear power plants against the risk of flooding. The measures include new methodologies to assess risks as well as engineering upgrades to adapt to the revised risk framework:

- In addition to the basic safety rules in place, eight phenomena are to be taken into account, including wind-waves on sea, wind-waves in channels, swelling due to operation of pumps, deterioration of water-retaining structures such as dykes, rainfall (either brief and intense or regular and continuous), groundwater rise – and any realistic combination of the above.
- In terms of engineering measures, plugging of openings, reinforced water-tight doors, raised and reinforced dykes.
- A climate survey to reassess every ten years the risks and the need for additional measures.

The overall cost for the upgraded flooding protection of EDF's 19 sites, including site-specific protections for 7 most exposed sites, was evaluated at EUR 110 million.

Figure 11.1. **Flood-protection programme at EDF following le Blayais event**



Source: de Fraguier (2010).

Table 11.2. **Design basis for extreme weather events in European nuclear power plants**

Country	Nuclear power plant	EWE	Design basis	Rationale for design basis	Evaluation method	Evaluation report year
United Kingdom	Hunterston B	Floods	10^{-4} frequency		Wave overtopping – superposition of various events: mean high water spring, highest astronomical tide, wind – events from observations, extrapolated to the 10^-4 period	
Romania	Cernavoda	Floods	10^{-4} frequency		historical data and recent analyses	
Germany	Biblis A/B	Floods	10^{-4} frequency	KTA 2207	Study on the interim storage in the year 2003, confirmed by a study by Prof Jensen in 2011; model calculations	2003
Germany	Philipsburg 1/2	Floods	10^{-4} frequency	KTA 2207	130 years of historical data	1984, 2004 Review by *Institut für Wasserwirtschaft der Universität Karlsruhe* and confirmed
Germany	Gundremmingen	Floods	10^{-4} frequency	KTA 2207		1997
Spain	Almaraz	Floods	10^{-4} frequency	CTE (Documento Basico SE-HS)	Historical data	
Switzerland	Beznau	Floods	10^{-4} frequency		Historical data	2011
Finland	Olkiluoto	Floods		N 60	Average seawater level 1960	1960
Sweden	Oskarshamn	Floods	10^{-7} frequency			
Spain	Almaraz	High temperature	$2*10^{-3}$ frequency	ETF		
Romania	Cernavoda	High wind	10^{-4} frequency	STAS 10101/20-78	Statistical data	
Germany	Gundremmingen	High wind		DIN 1055		2005
Spain	Almaraz	High wind		CTE	Historical data	2006
Switzerland	Beznau	High wind		SIA Norm 160	Historical data	Rev. 2009
Finland	Olkiluoto	High wind		Finnish civil construction standards		
Sweden	Oskarshamn	High wind	10^{-2} frequency			
Germany	Gundremmingen	Snow		DIN 1055		
Spain	Almaraz	Snow		CTE (Documento Basico SE-AE)		

EWE: extreme weather events.

Source: Based on ENSREG reports, www.ensreg.eu.

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Chapter 12. **Vulnerability and adaptation of the nuclear power sector, R&D needs to improve its resilience and recommendations**

Vulnerability and adaptation of the nuclear sector

This study has shown that the nuclear power sector, as other types of infrastructure, can be vulnerable to some of the most extreme weather events, as well as to the effects of global warming. Learning from past experience, in particular the events highlighted in this report's case studies, as well as from periodic safety assessments, sometimes based on revised safety guidelines, has enabled the nuclear sector to improve its resilience against weather events. Specific adaptation measures have been designed to address, for example, high temperatures, lack of cooling water, frazil ice phenomena, or flooding risks.

Nuclear power plants are often described as being vulnerable to climate change because of their reliance on water – withdrawals of large amounts of water for cooling for nuclear power plants with once-through cooling systems. While nuclear power plants with such types of cooling system do require large amounts of water, one must keep in mind that most of that water is put back into the body of water, and the actual consumption is very low. Nuclear power plants with closed cooling systems or hybrid systems withdraw far less water, but consume more, for example with water converted into steam released through cooling towers. Data of partial or full shut downs of nuclear power plants due to lack of water or due to temperatures above regulatory limits show that the effect in terms of electricity production loss is very small, typically less than 0.2% of yearly production, with nuclear power plants having in general very high availability factors. Adaptation measures to address these issues include redesigning water intakes, increasing the performance and efficiency of heat exchangers, and replacing direct cooling with indirect or closed cooling systems.

The impact of thermal releases from power plants' cooling systems can be a concern for the ecosystem, and this needs to be assessed in a long-term analysis taking into account projected temperature increases in water bodies, irrespective of whether there are thermal power plants located near them. Two case studies are described in this report: one related to cooling from closed bodies of water (lakes), the other from rivers. Detailed studies have been performed in either case, concluding that in the former there could be a significant effect in the long-term but not in the near-term (several decades), while in the latter case no significant impact had been witnessed in a nearly 15-year study. Of course, in the long-term (end of century), if global warming exceeds 3-4°C, very significant impacts on the eco-systems will be observed. Energy infrastructures as well as urban systems will need to be designed with minimum requirements for withdrawing water or releasing into the environment.

While nuclear power plants can withstand intense storms without any problems due to the robustness of the building structures, the same cannot be said about the electricity grid. There are numerous examples of storms that bring down lines, depriving whole regions of electricity for hours or days. Ice storms, because of the weight on the lines, can be particularly destructive as shown by the 1998 Ice Storm event described in this report. Nuclear power plants can be affected in two ways: cutting the supply to the nuclear power plant, which can require emergency diesel generators to kick in and the units to be shut down, and preventing the electricity produced by the nuclear power plant to be distributed in the grid – which leads to the reactor scramming and being shut down. Adaptation measures to improve the robustness of the grid against storm include anti-collapsing pylons or underground transmission lines.

Storms can also affect the operation of nuclear power plants by impact the cooling sources. Debris blown into water bodies can pose a problem for the cooling of reactors, so water intakes need to be protected against the risk of clogging due to large amounts of debris.

Probably the most important type of event that nuclear power plants need to ensure resilience against is large scale flooding. Flooding has been flagged as a major risk to many infrastructures. In the case of nuclear power plants, as shown by Le Blayais incident, safety concerns may be raised if essential equipment becomes unusable because it is flooded. As was done in France, the utility Électricité de France (EDF), the technical safety organisation (IRSN) and the regulator (Autorité de sûreté nucléaire, ASN) developed a flood protection programme that involved the development of new risk assessment methodologies, as well as engineering measures to protect buildings and essential equipment from the risk of water penetration. Though not linked to climate change, the flooding of the Fukushima Daiichi nuclear power plant due to the tsunami generated by the Great East Japan earthquake of 2011 shows how important it is to ensure that nuclear power plants can be protected from any source of flooding.

Adaptation measures to improve the resilience of nuclear power plants against climate change are not all about re-engineering and adapting the designs. They can also be of organisational and planning nature. For example, better forecasting and preparedness, or optimised planning of outages to ensure that the overall electricity system is able to guarantee electricity supply to its customers even in critical weather conditions is of the upmost importance. And this can evolve in time as consumption patterns change. A few decades ago, in most developed countries, the peak consumption period of the year was winter, when "climate risks" were mostly related to storms. Today, with increased use of air conditioning, summers are becoming peak consumption period: there the most relevant climate risk may be that of a heat wave combined with a high-pressure system resulting in a "wind drought" that can represent a significant risk for systems with high shares of on-shore wind power. While river-based thermal power generation can also be curbed because of environmental reasons, coastal nuclear power plants can supply large amounts of electricity into the system without any problems.

Estimating the cost of adaptation (or the cost of inaction)

It is quite difficult to derive figures for the cost of adaptation (or the cost of inaction), since cost figures depend on the type of plant, the climate change issues it needs to address, and the local/national regulations and standards that apply. Addressing cooling issues may require the re-design of a water intake or a heat exchanger such as a condenser, the construction of a closed system with cooling towers, or the installation of air conditioning systems in buildings that house safety-graded equipment. Addressing the risk of flooding may require the elevation of existing dykes or flood-protection barriers, the installation of watertight openings and doors. These measures typically represent investment costs of several million euros to several hundred million euros. For example, EDF's programme to improve the flood-protection of its nuclear fleet (58 units, not all exposed to the same flooding risks) was estimated at EUR 110 million. EPRI's estimation for the closed cycle retrofit of the US nuclear fleet in compliance with the then-proposed Clean Water Act (USD 20 billion for 60 nuclear power plants) would have meant an investment of more than USD 300 million per plant. Unless forced by legislation or regulatory requirements, investments to adapt to climate change may not be made on economic grounds. It was reported for example in Chapter 7 (Finnish case study) that a redesigned water intake for the Loviisa nuclear power plant, aimed at pumping cooler water at a greater depth in summer – was not constructed in the end, as its costs would probably not have been covered by the sale of electricity generated by the improved thermal efficiency of the plant, in the current electricity market context.

If investments are not made, for whatever the reason, one has what is called the cost of "inaction". This can be differentiated in various categories:

- Direct impact:
  - loss of production due to partial or full outage because of:
    - compliance with environmental regulations (e.g. thermal releases), or safety regulations (e.g. maximum cooling water temperature for safety-related cooling systems) or
    - event affecting the operation of nuclear power plant (e.g. leading to the malfunction of the cooling system) or

    - event affecting the transmission grid.
  - loss of efficiency due to higher cooling temperature;
  - cost of repairs, refurbishment, safety upgrades.
- Indirect impact:
  - Purchase by the utility of power on the spot market to compensate for loss of production.
  - Compensation of customers (energy-intensive industry) required to reduce their electricity consumption (load shedding) during events where the generation mix is affected by extreme weather.

One question which remains unclear is who gets to pay for the costs of inaction: is it insurance companies, the operators of the plants that are not producing or producing less, or the end consumers?

R&D needs to improve the resilience of nuclear power plants

As was discussed in previous chapters, there are several ways in which climate change issues are addressed in the nuclear sector:

- guidelines (e.g. siting), safety standards and regulations;
- design stage (power plants or components) that takes into account climate change risks;
- technology: e.g. cooling technologies, reactor design, on-site water production;
- planning and plant management: e.g. based on demand forecast, outage planning;
- demand-side management.

Each of these areas are also the object of R&D programmes to improve the resilience of nuclear power generation.

For instance, R&D on technology is being pursued with the objective of reducing water usage, the impact of thermal releases and the costs of nuclear power generation. It is focused on:

- Cooling technologies:
  - closed cooling systems, hybrid systems;
  - low profile cooling towers (with better public acceptance);
  - dry cooling (not an option for large reactors but could be an option for small modular reactors in arid regions);
  - more efficient heat exchanger equipment (e.g. condensers).
- Modelling of cooling water intakes and thermal releases to reduce environmental impact and/or improve efficiency.
- Use of non-traditional water resources, such as treated waste water (in use in the Palo Alto nuclear power plant in the United States, and considered in some MENA countries).
- On-site production of “fresh water” through desalination, to reduce the need to resort to ground water pumping or extraction from rivers.
- Innovative reactor designs such as generation IV reactors, which have higher operating temperatures and efficiency than today’s light water reactors, possibly combined with advanced power conversion systems (supercritical CO_2).

R&D is also being carried out in areas of forecasting (of weather and electricity demand):

- Planning based on better assessment of demand:
  - Air temperature is one of the most important parameters driving electricity demand. In France, in winter, a drop of 1°C represents an increased electricity demand of about 2 400 MW.
  - Predicting consumption with one or two weeks lead time can help optimise the selection of generating units required to meet the demand.
- Better planning of outages:
  - Planning the refuelling and maintenance outages during peak heat periods in the sites that are the most vulnerable to heat waves (for example the river-based nuclear power plants) provided these outages can be balanced by increased production at other sites or by imports. As was mentioned in Chapter 8, EDF reviewed the maintenance planning of its fleet to ensure that all coastal units are in operation during summers.
- Improvements to the forecasting tools:
  - To select, size and design future plants, test their robustness against climate change events and extreme weather events.
  - Development of multi-scale approaches to combine long-term forecasts (several decades, which is the time scale of investments, and the time scale of the construction and operation of nuclear power plants) with short-term projections (for operational purposes and fleet management).

Conclusions and recommendations

The following conclusions and recommendations can be drawn from this study:

- For new plants, those that are typically designed for a 60-year lifetime and could still be in operation towards the end of the century, climate change is usually taken into account in both the design and the siting. Climate change-related risks (maximum sea level rise, maximum temperatures, wind speeds, etc.) are factored in the design and siting assessment.
- For existing plants, the safety case and the siting take into account risks known at the time of the design or construction. New knowledge about likely trends in external events needs to be taken into account in periodic safety reviews or licence extensions. Safety upgrades (such as those required following the Fukushima Daiichi accident) are mandatory, and are often the opportunity to improve the robustness and resilience of the nuclear power plant against the impact of climate events. Improvements in safety are often accompanied by improved resilience.
- For non-safety-related issues, for instance degraded thermal efficiency in the event of high cooling temperatures, or outages due to environmental regulations (low water levels in rivers for instance), the decision to adapt is an economic one. It balances the costs and benefits for the period over which the nuclear power plant is estimated to operate:
  - Factors that weigh against making adaptation improvements include: the cost of the adaptation with respect to the electricity market economics (at what level should the price of electricity be profitable for the utility to invest in measures that improve the power output of the plant); the concern that while the adaptation work is ongoing (for instance the replacement of a once-through cooling system with a closed-cycle cooling system with cooling towers), the plant may not be able to operate, so that the cost of adaptation is increased by the loss of revenue from the outage; the fact that an operator may be a single plant operator, and therefore no economies of scale can be gained from performing adaptation improvements; the remaining lifetime of the plant (whether it is 10 or 20 years or more); and, of course, the actual number of climate-related events that can affect the plant: the lower the number, the less convinced the operator will be to improve the resilience of the plant.

  - Factors that will encourage a utility to invest in adaptation include: safety requirements (always a driver for change); the fact that the utility may operate a fleet; the remaining lifetime (the longer, the more chance the utility will recover the costs of the investments), the high number of events that affect the operation of the plant, and finally security of energy supply issues (though this is often a governmental responsibility).

- It is important but not sufficient to address the issue of the resilience of any particular type of generating technology. The resilience of the whole system (generation + grid + consumers) needs to be addressed.

- Short-term economics is often not enough to drive changes and adaptation measures. These are viewed as costs. It is particularly true in liberalised electricity markets. In many of these markets (for instance in Europe), wholesale prices have decreased thanks to the introduction of large amounts of renewables that have priority access to the grid, making the profitability of any investments in dispatchable power generation a real issue. Thus, it is up to governments to put in place the appropriate investment framework to build and improve long-term resilience of energy systems as well as security of energy supply.

- Regulations, whether safety or environmental, and technological standards also have a clear role in adaptation. However, apart from safety regulations for which there can be no exception, there needs to be some flexibility in the way environmental regulations and technological standards (for instance “best available technology”) are applied, so as not to compromise the financial situation of operators or, more seriously, the global security of energy supply of a given country. Flexibility may mean for instance giving operators a reasonable time to switch from one technology to another.

- Governments have a responsibility to better co-ordinate policies (water, environment, energy) to ensure that they all pursue the objective of improving the resilience of the energy system, lowering the impact on the environment, and guaranteeing the security of energy supply of the country. Mitigation should not be overlooked, and low-carbon technologies should be favoured in a cost-effective manner in current and future energy systems.

- International collaboration and knowledge sharing are necessary to improve on learning from experience as well as on innovative adaptation measures. There needs to be more transparent information and data (for instance through “climate services”) to understand the uncertainties in risks related to future climate events.

- In terms of research and development needs, there needs to be more work on:
  - Cooling and other technologies to reduce water dependence.
  - Forecasting methods to improve plant and fleet management, and balance between supply and demand.
  - Safety assessment methods to address future climate change events in design and safety cases; pragmatic solutions need to be developed that can be accepted by regulators.
  - Economic assessment methodologies to make a better case for adaptation.
  - Advanced nuclear energy systems which could be more resilient against climate change, including generation IV systems (which have higher efficiencies), small modular reactors (which have lesser cooling requirements than larger plants), and submerged or floating reactors.

Most importantly, the study, which focussed to a large extent on the nuclear power sector, shows that the analysis of the vulnerability and resilience of a given technology needs to be made at the level of the system – including the electricity grid but also the environment (water in particular). Nuclear power plants, with their robust designs, long-lasting fuel, and a high availability factor that is to a large extent independent of weather conditions, can significantly enhance the security of supply and resilience of energy systems.

Appendix 1. **List of participants of the expert group**

This study has been carried out by the Ad hoc Expert Group Cost of Adaptation to Climate Change of the NEA Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle.

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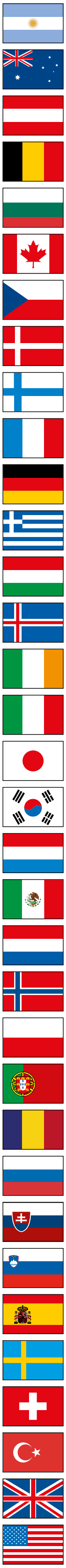

Climate Change: Assessment of the Vulnerability of Nuclear Power Plants and Approaches for their Adaptation

Climate change will create specific risks and challenges for nuclear power plants and the electricity system as a whole. Extreme weather events caused by climate change – such as floods, storms, heat waves and droughts – have already affected the operation of nuclear power plants. Any increase in the temperature of the water used to cool nuclear power plants can also lead to reductions in their power output due to decreasing thermal efficiency.

This report sets out the adaptation strategies that can be effectively implemented to improve the resilience of existing plants as well as any new installations. The costs of adaptation to climate change can vary significantly depending on the type of reactor, the climate change issues affecting them, as well as the applicable regulations and standards. However, while these adaptation costs can, in some cases, be significant, the costs of inaction – both directly at the plant level and indirectly for the electricity system – are likely to be even higher.

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