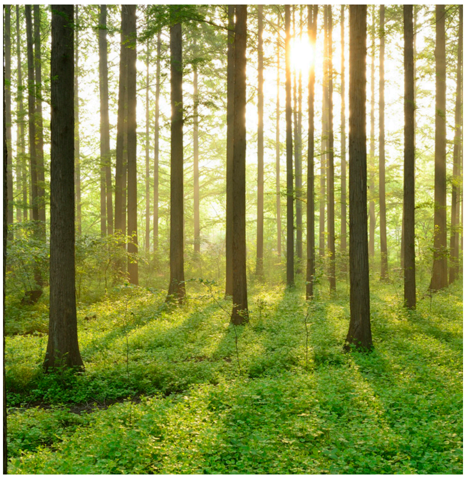
THE IMPACT OF CLIMATE CHANGE ON NUCLEAR POWER

REPORT 2021:744



KLIMATFÖRÄNDRINGARNAS
KONSEKVENSER

Energiforsk

The Impact of Climate Change on Nuclear Power

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ISBN 978-91-7673-744-6 | © Energiforsk April 2021
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Preface

The year 2020 was the warmest ever measured in Europe and the global average temperature was at the same high level as in 2016. Global greenhouse gas emissions continue to increase, and we are moving towards a global temperature rise of over 3 degrees compared to pre-industrial levels towards the end of the century. The impacts will be irreversible if we do not succeed in breaking the trend.

The temperature increase is much faster in Sweden and the rest of the Arctic region compared to the global average increase. Increased temperature affects both the natural environment and the society, and effects are already experienced in Sweden. The Swedish energy system is affected as well, with changes in the production conditions and various parts of the energy system becoming more vulnerable.

In this project – The impact of climate change on the energy system – Energiforsk has gathered about 15 researchers and analysts from Chalmers University of Technology, IVL Swedish Environmental Research Institute, Profu and SMHI to deepen the knowledge about the impact of climate change on the Swedish energy system and what measures are needed to reduce the negative effects.

This part of the project has been carried out by Thomas Unger and Jenny Gode from Profu and Erik Kjellström and Gustav Strandberg from SMHI in close collaboration with representatives from relevant parts of the energy sector, research organizations, authorities, insurance companies, and more.

Energiforsk would like to thank the researchers and participants in the project's steering group as well as working groups. In total, more than a hundred people from around 50 different organizations have contributed to the project. Energiforsk would also like to thank the project's financiers (C4 Energi, the Swedish Energy Agency, E.ON Sverige, Fortum Sverige, Göteborg Energi, If, Jämtkraft, Karlstads Energi, Skellefteå Kraft, the IVL Foundation, Svenska kraftnät, Söderenergi, Tekniska verken i Linköping, TVO, Uniper, Vattenfall, ÅForsk).

Sammanfattning

I allt väsentligt bedöms den nordiska kärnkraften vara väl rustad mot konsekvenser av den pågående klimatförändringen, åtminstone under vad som kan betecknas som en mycket lång men ändå överblickbar tid. Väderrelaterade händelser som påverkar driften har dock förekommit och väntas inträffa även i framtiden. Klimatförändringen kan komma att bidra till ett ökat antal sådana händelser. Detta bedöms inte äventyra säkerheten över lag utan är väsentligen en fråga för driftsekonomi och leveranssäkerhet för elförsörjningen.

Ett klimatrobust kraftslag

Vår studie visar att den svenska och finska kärnkraften är väl rustade mot ett föränderligt klimat till följd av global uppvärmning. Det gäller i ett tidsperspektiv som spänner över de kommande decennierna och en bra bit bortom 2050-talet och det gäller givet de olika klimatscenarierna som vi analyserat här. Denna robusthet är en följd av den höga säkerhetsnivån som råder rent generellt inom kärnkraftsverksamheten och som också är anpassad för att möta extrema väderhändelser. Dessa säkerhetsmarginaler bedöms i allt väsentligt vara tillräckliga för att hantera även ett klimat i förändring. De nyligen genomförda investeringarna för oberoende härdkylning har ytterligare stärkt robustheten mot framtida extremväder. Klimateffekternas inverkan på extrema väderhändelser på mycket lång sikt är dock till stor del osäkra.

Tillståndshavarna, det vill säga de företag som har tillstånd att driva reaktorerna, är ålagda att ta hänsyn till ny kunskap inom bland annat klimatforskningen i de återkommande helhetsbedömningarna (”Periodic Safety Reviews”; PSR) som görs i enlighet med kärntekniklagen och Strålsäkerhetsmyndighetens föreskrifter. I det arbetet ska kärnkraftverken värdera hur säkerheten på anläggningen kan upprätthållas under en kommande 10-årsperiod.

Påverkan på driften

Även om kärnkraften är genomgående robust mot konsekvenser av klimatförändringen så är det inte detsamma som att den är helt opåverkad. Väderhändelser har tidigare påverkat driften och tillgängligheten negativt även om det historiskt har varit i en mycket liten omfattning. Det finns dock indikationer på att klimatförändringen leder till att antalet väderrelaterade driftstörningar kan komma att öka i framtiden. Det gäller bland annat blixtnedslag som kan störa både det externa och det interna nätet, och ett varmare hav som dels i extrema fall kan leda till effektreducering (eller till och med tillfällig nedstängning), dels kan ge upphov till fler incidenter med marina organismer som i viss utsträckning kan sätta igen kylvattenintagen. När det gäller blixtnedslag så är det framför allt kraften (energin) i nedslagen som är relevant för driften i ett kärnkraftverk, och inte antalet nedslag. Ett varmare hav inverkar också menligt på

den termiska verkningsgraden och därmed på produktionen av el även om detta sett under ett helt år torde vara av relativt liten betydelse. Med tanke på att samtliga nordiska kärnkraftverk ligger vid kusterna så är även havsnivåökningen en faktor att beakta. Baserat på de studier vi har haft tillgång till här så ser detta inte ut att fordra några extra förebyggande åtgärder fram till slutet av detta århundrade. Först då, och med utgångspunkt från ett klimatscenario med omfattande temperaturökning, kan det möjligen bli en fråga för de sydligare belägna reaktorerna om man vill ta höjd för extremväder med återkomsttider på i storleksordningen 10 000 år. Det blir då också en fråga om vilka säkerhetsmarginaler som är rimliga att utgå från. För de nordligare belägna kärnkraftverken (Forsmark och de finska verken) medför landhöjningen inte bara en motriktad utan även en starkare effekt än havsnivåökningen under lång tid. Den resulterande effekten på dessa breddgrader blir därmed en landhöjning under de närmaste decennierna.

Framför allt en ekonomisk fråga

Att hantera eventuella följder av ett klimat i förändring är för kärnkraftsägarna i mångt och mycket en ekonomisk fråga och för det omgivande elsystemet en fråga om leveranssäkerheten för el. Det handlar om att väga de negativa konsekvenserna av vissa driftstörningar eller effektreduceringar och de uteblivna intäkterna från elförsäljningen mot investeringar i åtgärder för att minimera sådana effekter. Ett exempel är försämrad kylning till följd av varmare hav som kan åtgärdas med investeringar i ökad värmeväxlarkapacitet eller en omlokalisering av kylvattenintagen på djupare vatten. Detta är exempel på åtgärder förknippade med relativt höga kostnader. Ett annat exempel är blixtnedslag som kan sätta såväl det externa nätet som det interna nätet ur funktion. Här har en rad skyddsåtgärder genomförts under årens lopp och man bedömer att ytterligare åtgärder finns att tillgå om det skulle visa sig att klimatförändringar leder till exempelvis kraftfullare blixtnedslag. I detta fall bedöms paletten av tillgängliga åtgärder som relativt billiga. Åtgärder riktade mot det externa nätet ligger dock utanför reaktorägarens kontroll.

Ytterligare ett sätt att hantera eventuella effekter av klimatförändringen på den framtida driften i kärnkraftverken är genom en översyn av drifttillstånden. Det gäller till exempel miljötillstånd som kan begränsa driften, av just miljöskäl, vid perioder då temperaturen vid kylvattenutsläppet överskrider en viss nivå under sommaren. Men det kan också gälla en anpassning och uppdatering av säkerhetsmarginalerna för driften.

Summary

In general, nuclear power in the Nordic countries is found to be well prepared against impacts of climate change, at least under what reasonably may be regarded as a very long but still foreseeable time to come. However, weather-related events that affect the operation of a nuclear power plant have occurred historically and are expected to occur in the future as well. Climate change may contribute to an increased number of such events. This is not considered to jeopardize safety in general but is essentially a matter of operating economy and security of electricity supply.

A climate robust energy source

Our study shows that Swedish and Finnish nuclear power plants are well prepared for a changing climate as a result of global warming. This applies in a time perspective that spans the coming decades and well beyond the 2050s, and in all climate scenarios analysed in this project. This robustness is a consequence of the high level of safety in the nuclear power sector which is adapted to meet extreme events including also extreme weather events. These safety margins are considered to be essentially sufficient to handle also a changing climate. The recent investments in independent core cooling have further strengthened the resilience to future extreme weather events. However, the impact of climate effects on extreme weather events in the very long term is largely uncertain.

The companies that are licensed to operate the reactors are required to take into account new knowledge in, among other things, climate research in the recurring Periodic Safety Reviews (PSR) which are made in accordance with regulations and law. These reviews stipulate the licensees to evaluate how the safety of the plant can be maintained over a coming 10-year period.

Impacts on the operation

Although nuclear power is consistently robust to the consequences of climate change, this is not the same as being completely unaffected. Weather events have historically and occasionally had a negative effect on operations and availability, even though to a very small extent. However, there are indications that climate change may increase the number of weather-related operational disturbances. These include lightning strikes that may impact the external and internal grids, and a warmer sea that in extreme cases may lead to power reduction (or even temporary shutdown), as well as more incidents with marine organisms clogging the cooling water intakes. It is primarily the intensity of the lightning strikes (not the number of strikes) that is relevant for the operation of a nuclear power plant. A warmer sea also has a negative effect on the thermal efficiency and thus on the electricity production, although probably of relatively little importance for the yearly production. Since all Nordic nuclear power plants are located on the coasts,

sea-level rise is also a factor to consider. However, sea level rise does not seem to require any extra preventive measures until the end of this century. After that, in a climate scenario with extensive global temperature increase and taking into account extreme weather events with a return time in the order of 10,000 years, sea-level rise may become a question for the reactors localized in the southern parts. For the more northern nuclear power plants (Forsmark and the Finnish plants), the land uplift entails not only a reverse but also a stronger effect than the sea level rise for a long time to come. The resulting effect on these latitudes will thus be a land uplift in the coming decades.

An economic issue

Dealing with the possible consequences of a changing climate is for the nuclear power owners in many ways an economic issue and for the surrounding electricity system a matter of security of electricity supply. It is a matter of weighing the negative consequences of certain operational disruptions or power reductions and the lost revenue from electricity sales against investments in measures to minimize such effects. An example is reduced cooling due to increased sea temperature, which can be remedied by investing in increased heat exchanger capacity or relocating cooling water intakes to deeper water. These are examples of measures associated with relatively high costs. Another example is lightning strikes that can disable both the external and the internal electricity grid. Here, a number of protection measures have been implemented over the years and it is estimated that additional measures are available if it turns out that climate change leads to, for example, more powerful lightning strikes. In this case, the range of available measures is judged to be relatively inexpensive. Measures aimed at the external grid are, on the other hand, beyond the control of the reactor owner.

Another way of dealing with the possible effects of climate change on future operations at nuclear power plants is through a review of operating permits. This applies, for example, to environmental permits that can limit operations, for environmental reasons in particular, during periods when the temperature at the cooling water discharge exceeds a certain level during the summer. But it can also be about adapting and updating the safety margins for operations.

Innehåll

Sökord

Klimatförändring, påverkan, risk, sårbarhet, kärnkraft

Climate change, impacts, risk, vulnerability, nuclear power

1 Introduction

Global warming affects the earth's climate to varying degrees in different places. Climate change constitutes both opportunities and challenges for the energy system. This study aims to describe and analyze the most important consequences for nuclear power.

1.1 BACKGROUND

The goal of the Paris Agreement is to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. However, the temperature has already risen by more than one degree. On northern latitudes climate change is accelerating faster and temperature rises are stronger than the global average. Rising temperatures are driving other climate changes such as changing precipitation, wind and cloudiness. Climate change will affect the energy sector in different ways. The vulnerability of the energy system is likely to increase, and the production potential changes. The electricity grid is affected, and the energy demand changes.

In the Energiforsk project "Climate-change impact on the energy system", Profu, SMHI, IVL Swedish Environmental Institute and Chalmers University of Technology have together analysed how a changed climate can affect the energy sector. The project has included impacts on hydropower, wind power, nuclear power, bioenergy, electricity networks as well as energy use, district heating and district cooling. Limited analyzes have also been made of the impact on solar energy and dam safety. The analyzes have been based on climate scenarios and energy system scenarios to take into account the expected development of both the energy system and the climate. SMHI has produced a number of climate indices to describe how weather and climate-related factors can change at temperature levels of +1.5°C, +2.0°C, +3.0°C and +4.0°C above pre-industrial levels. These are summarized in Kjellström et al. (2021).[1]

This report focuses on how climate change can affect nuclear power in the Nordic countries with a certain attention to Swedish conditions. Other reports from the project can be downloaded from Energiforsk's website.

1.2 METHOD

Figure 1 summarizes at an overall level the methodology used in the project. The methodology has been inspired by a risk and vulnerability methodology that VTT in Finland developed in 2008 within the framework of a Nordic research project on the consequences for the energy system of climate change. This methodology has since been further developed during the project and a number of tools and templates have been developed and adapted to the project's various sub-studies.

[1] Kjellström, E., Strandberg, G and Lin, C, 2021. Förändringar i klimatet som påverkar energisektorn i Sverige. Energiforsk, rapport 2021-745.

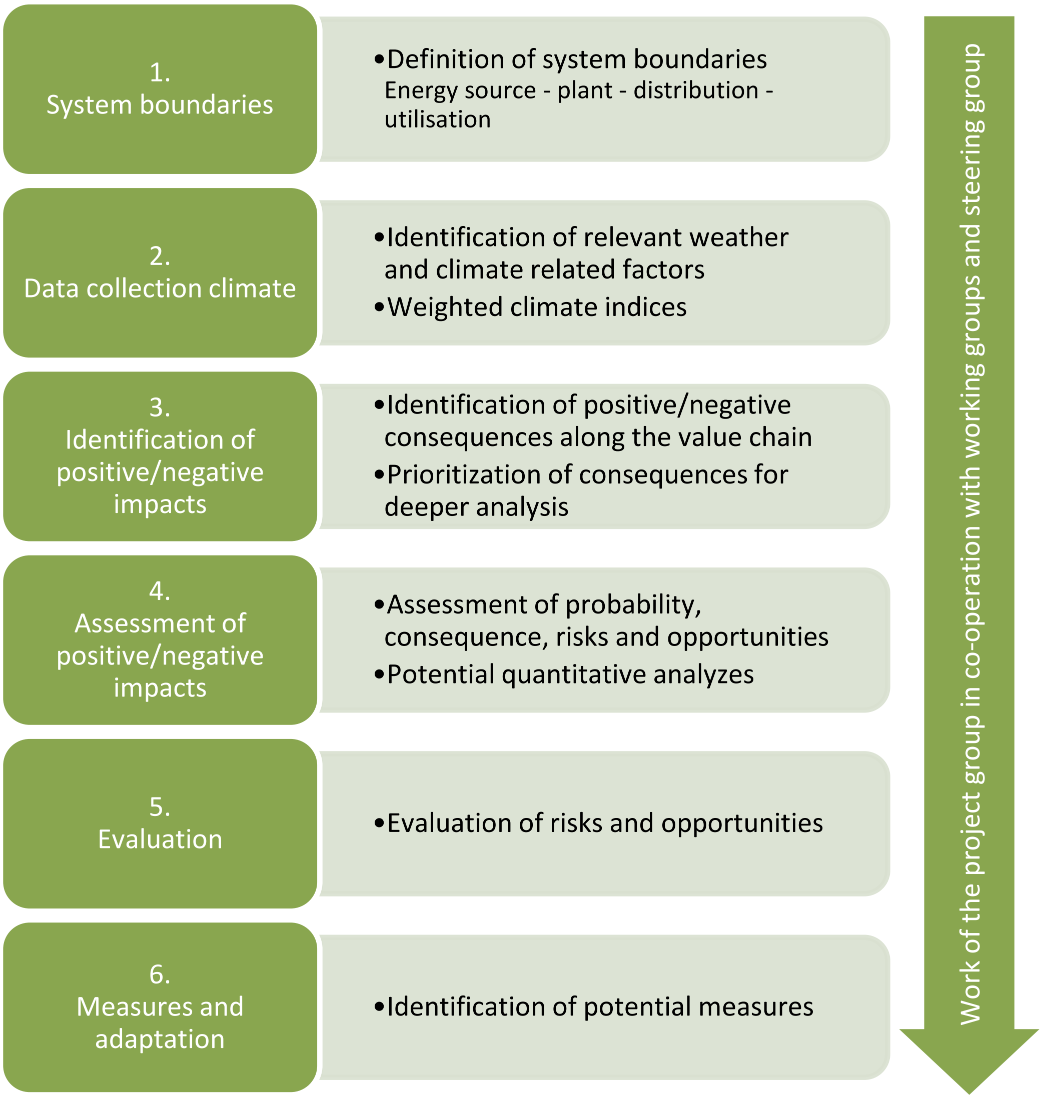


Figure 1. Overall methodology for the project. Some iteration has taken place between the various sub-steps during the project. The methodology is a further developed version of a risk and vulnerability analysis developed by VTT in Finland (Molarius et al., 2008).[2] Molarius et al. also included as an additional step in its methodology implementation of adaptation plan, which has not been included in our project.

The analyzes of consequences, risks, vulnerability and measures have been carried out by the project group in close collaboration with six working groups (hydropower, wind power, nuclear power, bioenergy, electricity grids and energy use, district heating and district cooling). These groups have met three times. At the end of the project, a working group on dam safety was also established, which met once. In each working group, about 10-15 people from energy companies, authorities, industry organizations, researchers and more participated. The discussions with the working groups have been very valuable for the project.

[2] Molarius R., Wessberg N., Keränen J. and Schabel J, 2008, "Creating a climate change risk assessment procedure – Hydropower plant case, Finland", XXV Nordic Hydrological Conference – Northern Hydrology and its Global Role (NHC-2008), Reykjavík, Iceland. 11-13 August 2008

Depending on important differences between the energy sources investigated in this study, the assessment approach has also been somewhat different.

1.2.1 System boundary and scope

The system boundary that defines the impact assessment of the "Nuclear power" part of the Energiforsk project "Climate-change impact on the energy system" is shown in Figure 2. Hence, it is the energy conversion, that is the power plant, that is in focus here.

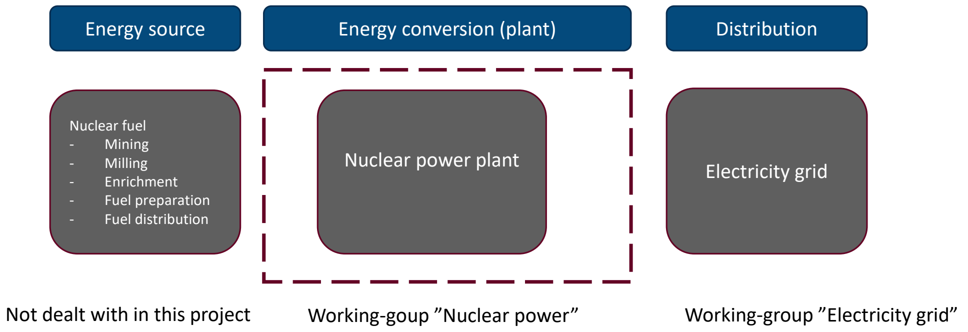


Figure 2: Simplified system boundary of the work conducted within the working group "Nuclear power" of the Energiforsk project "Climate-change impact on the energy system".

The system boundary includes the power-plant site itself with the reactor building and other complementary and ancillary buildings as well as the cooling water intake. Thus, we exclude fuel delivery, external grid and waste disposal from our climate change impact assessment. Nevertheless, the proper functioning of the external grid is crucial for the normal operation of a nuclear power plant (NPP) which we will get back to in the forthcoming sections of this report.

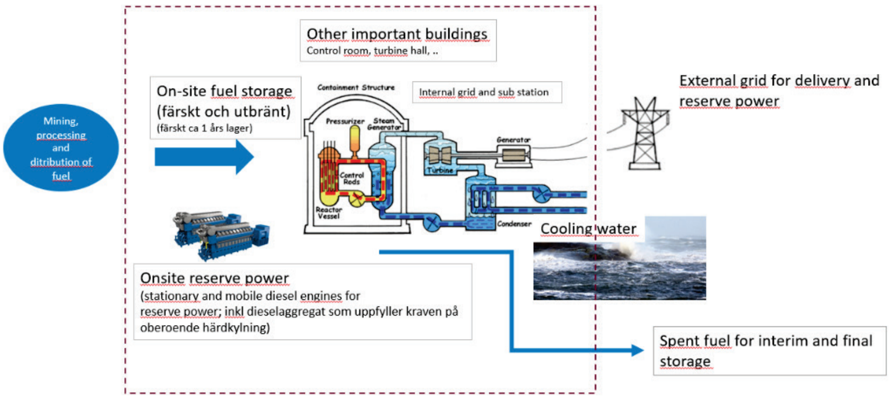


Figure 3: Key components within the system boundary "Nuclear power plant"

NPPs are designed and constructed to withstand very extreme events including weather-related events. It is our ambition with this report to qualitatively assess if climate change in any way may alter the view on these very high safety margins and whether climate change may impact the normal operation of a NPP in the Nordic countries. Critical components of a NPP that potentially may be impacted in a negative way by weather events include cooling-water intakes, air inlets for onsite reserve power generation (diesel engines), the internal electricity grid and, as mentioned, access to the external grid.

1.3 SOME INITIAL REMARKS ON NUCLEAR SAFETY

The three cornerstones of nuclear safety are:

- Keeping the core stable, including sub-critical operation if desired, during operation
- Keeping the core cooled at all times (also after shutdowns or incidents)
- Containing radioactive releases also during/after an accident

Nuclear safety requirements are designed to meet extreme events of various kinds including also extreme weather events with an estimated probability that is extremely low. For normal safety functions, the Swedish NPPs are designed to handle events with return periods of 100 000 years, that is an event frequency of once in 100 000 years. For very extreme events, with more severe safety implications, the Swedish NPPs are designed to withstand events with return periods of a million years. This corresponds to the safety requirement of the independent core cooling system which is mandatory at Swedish units since the end of 2020 as a response to the Fukushima accident in 2011 (we will elaborate somewhat more on the independent core cooling in the chapter on "Measures"). Also in Finland, additional safety measures were implemented in the wake of the Fukushima accident.[3] This accident spurred the EU to initiate comprehensive assessments of risk and safety, the so-called "stress tests", of the NPPs across the EU. In Sweden, the work was ordered by the Swedish Radiation Safety Authority (SSM) and reported in December 2011. The stress tests showed that Swedish facilities are robust, but the tests also identified a number of opportunities to further strengthen the facilities' robustness (SSM, 2011).[4] One such outcome to further strengthen robustness is the independent core cooling system mentioned above.

Safety issues are constantly being monitored and necessary measures are, consequently, taken to guarantee safety. The mandatory periodic safety reviews (PSRs) conducted at the NPPs reflect the current state of research and knowledge also within the science of climate change. Thus, the outcomes from the present study may also support the safety work done by the NPP operators.

In this project, we will assess several climate-change and weather-related events that may affect the operation of a NPP. Generally, this is a matter primarily of securing a stable generation of electricity to the public electricity grid. Ultimately, however, it may also be considered as a matter of keeping the safety level at the highest possible standard also in a future where climate most likely has changed.

[3] STUK 2019, "Finnish report on nuclear safety: Finnish 8th national report as referred to in Article 5 of the Convention on Nuclear Safety".
[4] SSM 2011, "European stress tests for nuclear power plants – The Swedich national report".

1.4 THE ROLE OF NUCLEAR POWER IN THE NORDIC COUNTRIES – STATUS AND OUTLOOK

One important dimension in the overall assessment, within a system context, of the climate change impact on nuclear power is to elaborate on the future role of nuclear power in the Nordic energy system. By this we mean analysing a future energy and electricity system where the effects of climate change are likely to be more tangible than today. Whether nuclear power plays a vital role in the future electricity system or if it only contributes marginally (or not at all) to the electricity supply determines the relevance of climate-change robustness of nuclear power in a system context. This is also valid for other energy sources or means of electricity generation. Such an overall system assessment is reported in the final report of this project.

1.4.1 Existing sites

In Figure 4, we present the existing sites of NPPs in the Nordic electricity system, in Sweden and Finland. We may already here conclude that the relatively outspread localization of single NPPs across the Nordic region is beneficial both from an electricity-grid perspective and from a weather-impact perspective. Extreme weather phenomena, potentially further amplified by climate change, are generally spatially limited implying that not all NPP sites are affected simultaneously. This advocates for robustness if we consider nuclear power as an entity in the Nordic electricity system.

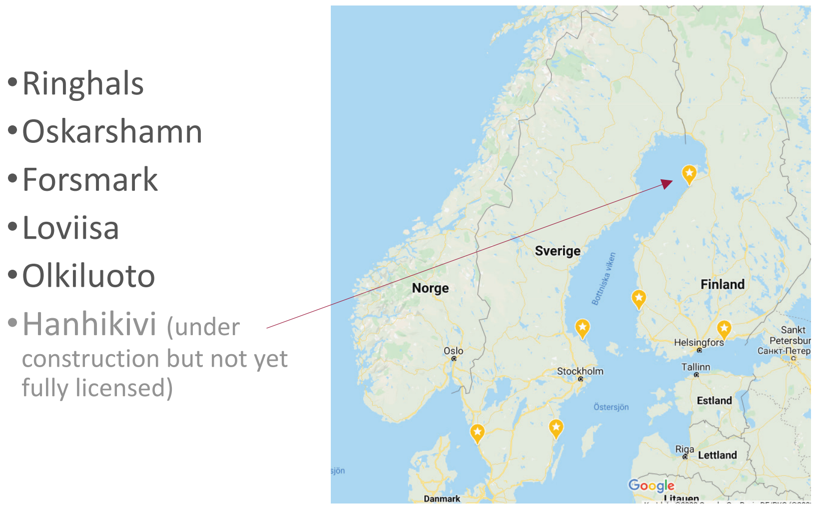


Figure 4: Existing nuclear-power sites in the Nordic countries

In time of writing (Feb 2021), the Hanhikivi NPP is still without a formal construction license but is pending approval by the involved authorities. Nevertheless, initial construction work has already begun at the site.

1.4.2 Prospects to 2050

In the shift from 2020 to 2021, Sweden closed the reactor, Ringhals 1, i.e. the last of the four decided reactor closures since 2015. Currently, no plans to close any additional reactor exist. Thus, the Swedish installed nuclear capacity currently amounts to somewhat less than 7 GW electricity. In Finland, the fifth reactor, Olkiluoto 3, is expected to be grid-connected during the second half of 2021 and subject to regular operation in February 2022.[5] Together with the decided investment of the Hanhikivi plant, which we here assume is ready for operation by 2030, the installed capacity of nuclear power in the Nordic countries is likely to follow the trajectory depicted in Figure 5 if we assume a total operational lifetime for all existing reactors of 60 and 80 years, respectively. This gives an idea of the future installed capacity of nuclear power in the Nordic countries and its dependence on assumptions on remaining operational lifetimes. If we, for instance assume 60 years of total operational lifetime for each single reactor in Sweden and Finland, the available capacity in 2045 would be roughly half of the currently existing capacity. If we on the other hand assume 80 years of total operational lifetime, all the currently existing reactors would still be available in 2050. The actual operational lifetime is plant specific and depends on the technical status and economic performance over time but may also be affected by policy. Operational lifetimes of a specific NPP can be prolonged through investments in lifetime extensions if considered profitable. Furthermore, installed capacity of nuclear power may be increased through investments in new reactors.

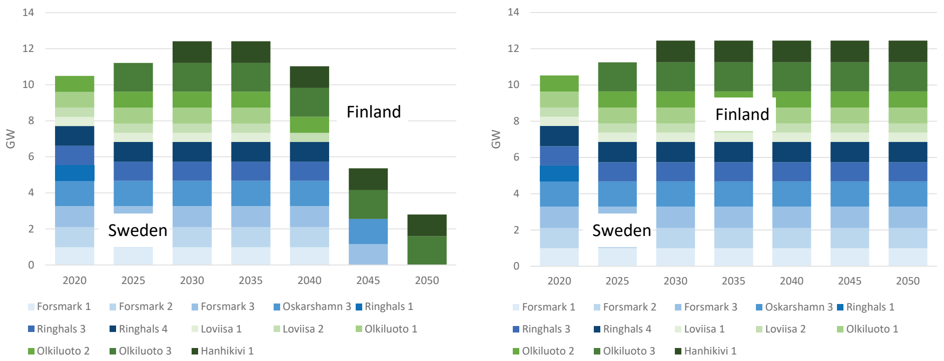


Figure 5: Ageing of existing and decided nuclear power capacity in Sweden (blue bars) and Finland (green bars) assuming 60 years of operational lifetime (left) and 80 years of operational lifetime (right). Source: IAEA/PRIS and own assumptions.

1.4.3 Scenarios for the future electricity system

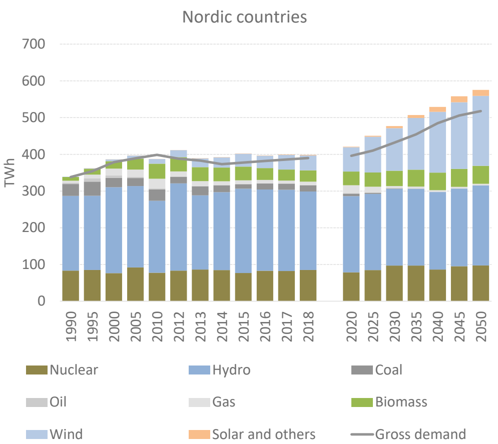
In the project "Climate-change impacts on the energy system", we also assess possible future scenarios for the electricity system to estimate the overall system effect, including all investigated energy sources, of climate change. These electricity-system scenarios are taken from the interdisciplinary research project NEPP.[6] As mentioned earlier, this is further discussed in the final report of the project but also in an additional sub report on climate and energy scenarios.[7] In this section, we will merely give a brief summary of these outlooks for the electricity system and with special attention to nuclear power. We use two

[5] Montel Power News, 2020 (August), https://www.montelnews.com/en/story/tvo-delays-olkiluoto-3-16-gw-start-to-october-2021/1142940.
[6] NEPP, https://www.nepp.se/.
[7] Energiforsk 2021, "Scenarios for energy and climate" (in Swedish), to be published.

different scenarios with different external key conditions that have decisive impact on the development of the electricity system. The time horizon spans from today to 2050. In our climate change impact assessment, the analysed time horizon may, however, stretch beyond 2050.

The first scenario, the "Climate Policy" scenario (Figure 6) assumes a stringent climate policy meeting the European climate-policy goals expressed by the EU. A consequence of that is a significant increase in electrification in transportation and industry. This, in turn, leads to an increase in North European electricity consumption and, consequently, an increase in long-term wholesale electricity prices. Existing NPPs are subject to lifetime extensions, which generally is profitable given our cost assumptions. Thereby, existing plants may operate well beyond the 60 years of operation that we here assume are feasible prior to significant re-investments for such lifetime extensions. Furthermore, investments in new capacity post 2040 are profitable under two important conditions in this scenario: 1) costs for new NPP are significantly lower in the long term than what is currently indicated by the ongoing projects in Europe and North America; 2) policy making and market-based investments consider *emission-free* generation rather than an electricity-generation system that is based entirely on renewables. Thus, the generation mix also contains fossil-based power plants with carbon dioxide capture and storage and nuclear power among other generation technologies. A system entirely based on renewable electricity generation is likely to entail electricity prices with a higher degree of variability, that is periods with very low wholesale prices as well as periods with very high prices. Such variability is likely to affect investment incentives in capital-intensive technologies, such as nuclear power, in a negative way unless they become equipped with increased flexibility.

By 2045, the total installed electricity-generation capacity in the Nordic countries amounts to around 190 GW according to this scenario (some 110 GW today). Nuclear power contributes with roughly 7% of that capacity. However, even though the capacity contribution of nuclear power is small in that context, it concerns capacity with a high availability in contrast to e.g. wind and solar power that dominates the installed capacity.

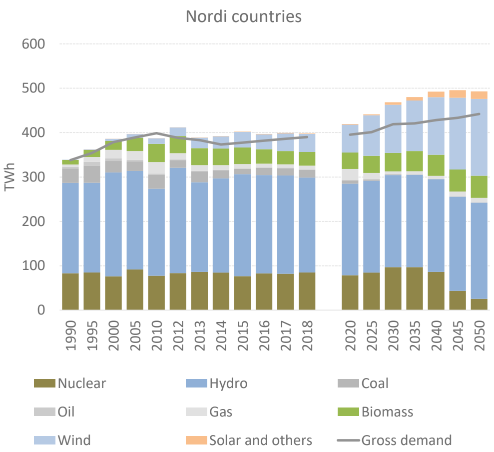


Scenario features

- Stringent climate policy in EU and globally
- EU meets its 2050 targets
- (Very) high prices on CO_2 post 2030 (typically 100 EUR/t post 2035)
- Extensive electrification in transportation and industry ("Hybrit" and others)
- Massive expansion of renewables
- Lifetime extensions and new investments in NP
- Increased recirculation of materials leading to reduced (increase of) waste streams
- Relatively fast phase-out of coal-fired generation in Germany
- Based largely on the Roadmap scenario by Swedeenergy in 2019

Figure 6: Electricity production in the Nordic countries in the "Climate-policy" scenario.

In the second scenario, our “Base” scenario, we instead analyse possible consequences of *existing* policy instruments. This also results in significant emission reductions but is not sufficient to meet the long-term goals. Furthermore, electrification within industry and transportation proceeds in a significantly lower pace and extension compared to the “Climate-policy” scenario. Consequently, wholesale electricity prices are lower throughout the modelling period making new investments in nuclear power unprofitable. Furthermore, in this scenario we assume that lifetime extensions of existing capacity beyond 60 years is not an option.[8] Thus, the Nordic electricity-generation mix is almost completely dominated by renewables.



Scenario features

- Existing policies; EU 2030-target met but not 2050 goals
- Policy mix of climate, renewables and end-use efficieny measures
- Increasing prices on CO_2 (”moderate” levels, typically around 50 EUR/t)
- Electricity use increases slowly; no extensive electrification
- Slow growth in electric vehicles
- Continued growth of renewables
- No new nuclear power in Swe/Fin besides decided projects (liftetime extensions not considered)
- Relatively slow phase-out of coal-fired generation in Germany
- Based largely on the reference case of the Swedish energy agency in 2019

Figure 7: Electricity production in the Nordic countries in the “Base” scenario.

Hence, our two scenarios describe a future to 2050 where nuclear power either supplies somewhat more electricity than today or where nuclear power supplies significantly less than today. In relative terms the contribution of nuclear power is smaller than today in both scenarios. Thus, based on these scenario projections we might conclude that from a climate change point of view there are other electricity-generating sources, especially wind power, that are more relevant to discuss in terms of robustness towards climate change. However, nuclear power supplies capacity with high availability and ancillary services in the electricity market, especially at times where the electricity system might be subject to stress, even if its relative role in terms of annual generation might be smaller than today. The value of such firm and dispatchable capacity is likely to increase in the future. The same goes for the ancillary services (frequency and voltage control) that are necessary to keep the electricity gid stable and operational and that is provided by, among others, NPPs. This fact together with an operator’s perspective on nuclear power

[8] To exclude lifetime extensions post 60 years of operation is a choice we made in this specific scenario. Additional sensitivity runs including lifetime extensions indicate that such investments generally are profitable under the given cost assumptions. However, technical and economical feasibility of lifetime extensions beyond 60 years are uncertain since there are no track records of any NPP across the world still in operation that, hitherto, has reached an operational lifetime beyond 55 years. Nevertheless, in the US, for instance, the NPP units Peach Bottom 2+3 and Turkey Point 3+4 have been granted extended operational licenses by the US Nuclear Regulatory Commission corresponding to a possible operational lifetime of 80 years.

makes it still highly relevant to assess the robustness of nuclear power in relation to a changing climate in the Nordic countries, even if the contribution in relative terms from nuclear power may decrease in the future Nordic electricity market.

2 Climate change

The Earth's climate is in rapid change. Consequences are seen globally, not least at high latitudes. Climate model projections show continued rapid future changes with strong impacts for Sweden. In this section we describe projected changes in various aspects of climate of relevance for the nuclear sector based on a wide range of high-resolution regional climate models.

2.1 OVERVIEW OF CLIMATE CHANGE AND CLIMATE SCENARIOS

The ongoing climate change has led to an increase of the global mean temperature that in 2020 reaches almost 1.2°C compared to preindustrial conditions (WMO, 2020[9]). Climate change is also noticed in Scandinavia with temperature increase substantially higher than the global mean. For the 30-year period 1991-2019 compared to 1861-1890 the average Swedish temperature has increased by 1.7°C. The corresponding number for the global mean is 0.8°C. The rate of global warming is now at 0.2°C per decade implying that global mean temperature will reach +1.5°C relative to preindustrial levels sometime between 2030 and 2052 and +2°C another 2-3 decades away (IPCC, 2018).

How large the warming will actually be, in a time perspective of more than 30 years depend strongly on future emissions of greenhouse gases and on the sensitivity of the climate system. Larger emissions lead to stronger warming implying that a certain warming level is reached earlier compared to a case with smaller emissions. Depending on the emissions global mean warming at the end of the century may become 1,5-5°C (IPCC, 2013[10]; IPCC, 2018[11]).

This report focusses on the 1.5°C and 2°C warming compared to preindustrial conditions. We have also analysed other warming levels: +2,5°C, +3°C, +3,5°C and +4°C. The results clearly show progressing climate change at higher warming levels. In general, this leads to stronger impacts. In some cases, the nature of the consequences may change with higher levels of warming.

2.1.1 Key aspects of climate change

Here we give a short introduction about climate change over the last century and what can be expected until 2100. For a more elaborate description see the report on

[9] WMO, 2020. WMO Provisional Report on the State of the Global Climate 2020. https://library.wmo.int/index.php?lvl=notice_display&id=21804#.YDY7v-hKiUl

[10] IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.A., Boschung, J., et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.

[11] IPCC, 2018. Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Cambridge & New York: Cambridge University Press.

climate change (Kjellström et al, 2021[12]). Results from this research project will be used for the new web-based climate service at SMHI starting in 2021. It is recommended to check to what degree indices and results from this project may have been updated with newer material.

Both observed and projected climate change for the future is generally larger over the continents than over the oceans. The strongest warming is projected for the Arctic where diminished sea-ice and snow cover amplifies the changes leading to even stronger temperature increase. The northerly position of Scandinavia, with snow and ice during winter makes climate change pronounced. Generally, we anticipate continued increased mean temperature, mostly for winter but also in summer. In particular, we expect the winter season to become shorter and summers to become longer which has already been observed,

Also precipitation changes with global warming. The water holding capacity of air increases with temperature implying that global warming leads to intensified evaporation from oceans, lakes and rivers but also from soil and vegetation. An amplification of the hydrological cycle leads to more precipitation, which, for Sweden and Scandinavia implies stronger precipitation especially during the winter half year. The type of precipitation is also projected to change with a larger fraction of rainfall at the expense of snow. Also in summer, precipitation is expected to increase but it is uncertain to what extent and in southern Scandinavia there may even be a decrease. The larger evaporation in a warmer climate leads to an increased risk of dry conditions, in particular in years with little precipitation.

The climate in Sweden and Scandinavia shows a very strong variability with large variations between warm and cold years and between wet and dry years. This type of variability is projected to be pronounced also in a future warmer climate with a shift towards warmer conditions and changes in precipitation as described above. Many of the projected changes are not just involving long-term averages like annual, seasonal or months but also shorter time scales as changes in short-term events on hourly and sub hourly time scales. This is a result of many weather-related extremes being expected to change in a warmer climate. For instance, there is an increased risk of high-intensity rainfall associated both with intensifying cloud bursts and with large-scale low-pressure systems and associated fronts. In additions, there is an increased risk of heat waves and higher temperatures and a decreases risk of cold snaps and low temperatures.

2.1.2 Climate scenarios

The climate information in this report is based on results from simulations with a large number of regional climate models from EURO-CORDEX (Jacob et al., 2014[13]) where the simulations have been made at a computational grid with 12,5 x 12,5 km horizontal resolution covering Europe and large parts of the North Atlantic. The regional models are taking boundary conditions from a number of global climate

[12] Kjellström, E., Strandberg, G and Lin, C, 2021. Förändringar i klimatet som påverkar energisektorn i Sverige. Energiforsk, rapport 2021-745.

[13] Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O. B., Bouwer, L. M., et al. (2014b). EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Chang. 14, 563–578. doi:10.1007/s10113-013-0499-2.

models from CMIP5 (fifth phase of the Coupled Model Intercomparison Project) that is behind many results assessed in the fifth assessment report by the international panel on climate change (IPCC, 2013[14]). In total, an ensemble of 65 regional climate simulations has been used for the analysis. For some climate change indices, the material has been reduced to about 10 simulations as data are not available for all models. The purpose of including as many models and simulations as possible is to be able to systematically describe robust features of future climate change as well as the main sources of uncertainty.

To identify at what time different warming levels are reached we have used the global mean temperature as simulated by the global climate models. We first calculate running 30-year averages, for each model, and then identify the first 30-year period when temperature reaches a certain warming level compared to 1861-1890. In this way we can compare material corresponding to the same global warming taken from partly different time periods in different models as the exact rate of change may differ between them. In the project we have used 1971-2000 as our reference period against which we can compare the different warming levels. As we are already, in 2020, on our way to +1,5C and, later, +2C some of the climate change signal compared to 1971-2000 that we present has already occurred. For +1,5C this amounts to slightly more than 70% and for +2C about 50%. These numbers can be seen as a crude representation of how large fraction of the expected climate change signal that we have already seen. The global mean temperature differs between start and end of the 30-year periods for +1.5°C and +2°C as a result of the analysed periods not being descriptions of a stationary climate.

In this work we have extracted information on different weather and climate related factors. As these are more or less complex the model's ability to simulate them in detail varies. Therefore, we have used daily data for a number of different model variables including temperature, precipitation amount or atmospheric humidity to calculate a number of different climate indices. These indices can be simple averages or maximum or minimum values for the variable. They could also be more complex indices like how many days in row temperature has exceeded a certain level or how many days in a year there is snow on the ground. The climate indices are described in detail in (Kjellström et al., 2021[15]). For some weather and climate related factors there are no single indices that can be used to answer questions on what the consequences of climate change is on the energy system. In those cases, we have made assessments based on joint consideration of several indices. For example, the combination of climate indices for “effective precipitation” (e.g., precipitation minus evaporation), “longest dry period” (e.g., period without any precipitation) and “heat wave” (e.g., number of warm days in

[14] IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.A., Boschung, J., et al. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1535.
[15] Kjellström, E., Strandberg, G and Lin, C, 2021. Förändringar i klimatet med påverkan för energisektorn i Sverige. Energiforsk, rapport 2021-745.

a row) have been used to give an indication of changing conditions for drought and thereby forest fires.

In forthcoming chapters, the climate indices are presented in maps for Scandinavia where changes are shown for each model grid point (at 12.5 x 12.5 km). The maps show simulated climate conditions at the +2°C global warming level compared to the reference period 1971-2000

When we summarize the results, we have used the following terminology:

- "most likely" meaning that there is an unambiguous signal and that the assessment is made based on a large material with many simulations.
- "likely" meaning that we see a relatively unambiguous signal and that the assessment is made based on a large material with relatively many simulations.
- ″less likely″ meaning that we see only a small change based on many simulations.
- ″uncertain″ meaning that we either see different signals from different models or that we only have a small number of simulations to base the analysis upon.

In all four cases, the assessments may be partly made on additional information outside of the EURO-CORDEX simulations that are described in more detail.

2.2 CLIMATE CHANGE AND WEATHER EVENTS RELEVANT TO NUCLEAR POWER

In this section, we report and discuss a number of weather events (or phenomena) of relevance to the operation of nuclear power, and to what extent climate change is expected to change conditions for such weather events. We summarize these weather and climate related phenomena in Table 1 (these were the weather events that we discussed in our working-group sessions). Also included in the table are very brief descriptions of the potential impacts on the operation of a NPP localized in the Nordic countries. The significance of these potential impacts on the operation of a NPP is assessed in the next chapter on "Impacts". As the name suggests, that chapter deals primarily with impacts on the NPP site and NPP operation while we in the present chapter focus solely on weather events and to what extent climate change may impact such weather events or phenomena.

Table 1: Summary of weather events and climate-change related phenomena of relevance to the operation of nuclear power.

Weather event/ climate change	Potential impact on NPP operation
1 Windstorms and hurricanes	Flooding of NPP site, damage to some structures and components
2 Sea-level rise	Flooding of NPP site
3 Heavy rainfall	Flooding of NPP site
4 Thunderstorms	Damage to key components (electricity grid)
5 Heat waves	Damage to key components, impeding working conditions
6 Increased sea-water temperatures	Reduced cooling efficiency, formation of marine organisms → risk of clogging cooling-water inlets
7 Ice formation at sea	Risk of clogging cooling-water inlets
8 Very low air temperatures	Ice formation clogging air intakes of onsite reserve-power generators
9 Sub-cooled rain	Damage to key components (electricity grid, switchyards), clogging air intakes of onsite reserve-power generators
10 Heavy snowfall	Clogging air intakes of onsite reserve-power generators, impeding logistics to/from NPP site
11 Forest fires	Risk of clogging air intakes of onsite reserve-power generators, impeding logistics to/from NPP site

2.2.1 Windstorms and hurricanes

It is not expected that there will be any significant changes in maximum wind speed. The estimate is, however, highly uncertain as results from climate models differ and as they have problems in representing storm tracks. It is uncertain whether windstorms in Sweden will change in a future warmer climate and according to the EURO-CORDEX regional climate models it is not expected that maximum wind speeds will become larger. It is likely that the risk of strong local winds associated with cloudburst will increase as a result of a more energetic atmosphere and vigorous convection.

2.2.2 Sea-level rise

Sea-level rise will lead to more pronounced high sea-water level events even if windstorms or other low-pressure weather conditions do not change. Thus, the high sea levels become even higher and, correspondingly, the frequency of high sea-level events increases.

As mentioned earlier, increased global temperature due to climate change will affect sea level and sea temperatures across the world. Large geographical variations occur for a number of reasons including changes in winds and ocean currents, sea water density and gravitational effects. In our parts of the world, especially further up north, land uplift exerts, to a certain extent, a counteracting force that further complicates the issue (see Figure 8). The net effect on local sea level in Sweden and the Nordic countries is, thus, very dependent on location, time frame and future climate (RCP) scenario. Thus, it is very likely with increasing mean sea level at NPP sites in the south while in the northern parts of the Baltic sea area (see Figure 8), land uplift will reduce or even completely counteract increases spurred by climate change at least over the next 200 years for the scenario with strongest greenhouse gas emissions. For mitigation scenarios land uplift may continue to counteract sea level rise also in a longer time perspective of centuries and millennia.

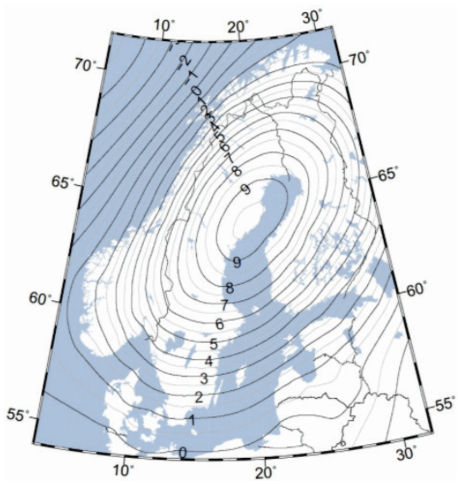


Figure 8: Model-calculated land-up lifting in mm/year, independent from climate change impact on sea level (Source: Lantmäteriet[16])

As a whole, large uncertainties are associated to the estimates of sea-level rise due to climate change especially concerning ice losses at Antarctica and Greenland.

The most recent estimate for sea level rise in Sweden taking also land uplift in consideration is found in Hieronymus and Kalén (2020)[17]. Compared to earlier studies it includes improved regional estimates from the IPCC special report on ocean and the cryosphere (IPCC, 2019).[18] The improved modelling indicates larger ice losses in the Antarctic region, in high emissions scenarios, than previously reported. Table 2 gives estimated sea-level rise at the three Swedish NPP sites considering also land uplift that is especially pronounced for Forsmark.

[16] Lantmäteriet (the Swedish mapping, cadastral and land registration authority), https://www.lantmateriet.se/sv/Kartor-och-geografisk-information/gps-geodesi-och-swepos/Referenssystem/Landhojning/#entrance-wrapper

[17] Hieronymus, M., Kalén, O. Sea-level rise projections for Sweden based on the new IPCC special report: The ocean and cryosphere in a changing climate. *Ambio* **49,** 1587–1600 (2020). https://doi.org/10.1007/s13280-019-01313-8

[18] IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Table 2: Estimated sea-level relative to the mean sea level in the height system RH2000 during the period 1986-2005 for the municipalities where the three Swedish NPP sites are located at 2050 and 2100 due to climate change according to two emission scenarios. The numbers (in cm) are median and a likely range defined as lower and upper estimates (17th and 83rd percentiles from the uncertainty intervals given by IPCC, 2019). Data are taken from www.smhi.se, see Hieronymus och Kalén (2020)

	RCP2.6		RCP8.5	
	2050	**2100**	**2050**	**2100**
Ringhals (Varberg)	16 (3 to 30)	19 (-7 to 46)	21 (8 to 35)	63 (28 to 99)
Oskarshamn (Oskarshamn)	20 (5 to 36)	20 (-6 to 46)	25 (11 to 39)	64 (30 to 99)
Forsmark (Östhammar)	3 (-11 to 18)	-17 (-36 to 3)	8 (-3 to 19)	29 (-4 to 63)

Closely linked to weather events with very strong winds are powerful waves and extreme sea-levels that may pose a risk of wave splashing at the NPP site and, thus, increase the risk of flooding. Besides estimating mean sea-level rise due to climate change, Hieronymus och Kalén (2020)[19] have also estimated extreme sea levels based on observations from the Swedish coasts. The estimates have been made by applying extreme value theory. These estimates are summarized in Table 3 below. We emphasize here that these return levels are estimated from only around 50 years of data. Return levels for 1000 or 10000 events inferred from such limited amounts of data are extremely uncertain. In fact, they could often be biased low since very extreme events are often missing from such short records. An example given in Hieronymus and Kalén (2020) of including a single yearly maximum resulted in changing the 200-year return level by several decimetres. Bearing this caveat in mind these figures could be added to the estimates in Table 2 in order to include the effect of increasing mean sea level on extreme sea levels due to climate change.

Table 3: Estimated extreme sea-level rise and corresponding return periods based on hourly observations at the three Swedish NPP sites. Numbers are given in meters above average sea level (Hieronymus och Kalén, 2020). The length of the observational series is indicated in the rightmost column.[20]

	100 yrs	200 yrs	1000 yrs	10000 yrs	No of years
Ringhals	1,60	1.67	1,82	2,0	46
Oskarshamn	1,02	1.05	1,10	1,14	55
Forsmark	1,39	1.45	1,56	1,67	40

[19] Hieronymus, M., Kalén, O. Sea-level rise projections for Sweden based on the new IPCC special report: The ocean and cryosphere in a changing climate. *Ambio* **49,** 1587–1600 (2020). https://doi.org/10.1007/s13280-019-01313-8

[20] As mentioned in the introduction, events with return periods of 100 000 years are of relevance to normal safety functions at a NPP. The analysis reported in Table 3 does, however, not cover that time interval.

Estimates resulting from combining information from Tables 2 and 3 do not include potential changes in the windstorm climate or other regional factors influencing extreme sea level height along the Scandinavian coasts. High-resolution regional climate models could be of use here but as concluded by Hieronymous and Kalén (2020) more research is needed in order to evaluate the ability of such models to simulate conditions favourable of extreme sea-level heights and further to assess corresponding information on climate change from large ensembles of simulations.

2.2.3 Heavy rainfall

Climate-change modelling suggests that it is very likely with stronger precipitation extremes on all time scales. Indices assessed in this project indicate stronger precipitation on annual and seasonal time scales as well as on weekly and daily time scales. Climate scenarios generated by very high-resolution regional climate models at a few km grid spacing are still lacking for Scandinavia. This means that confidence in statement on high-intensity short-term duration cloud bursts is low. These models are not only better at representing such events but have also resulted in stronger increase in rainfall intensities for short-term cloudbursts compared to existing scenarios with more coarse-scale models. Consequently, there is a risk that this intensification is underestimated.

A specific problem related to flooding relates to *compound events* where several phenomena occur at the same time. Intense precipitation in a river runoff catchment or locally can, in combination with high sea level events lead to severe flooding. Potentially, impacts of such compound events can be relatively dramatic on some man-made constructions and infrastructures. As this relates to two, or more, rare events occurring more or less at the same time the return period is much longer than those for the individual events. This makes it even more difficult to assess as the observational record is relatively short. Potentially, large climate model ensembles could be used here to expand the sample size (van den Hurk et al., 2015[21]) but such studies are essentially lacking for Scandinavia.

2.2.4 Thunderstorms

It is likely that the number of days with risk of thunderstorms increases and that the thunderstorm season gets longer.

Warmer and more moist conditions in the future will favour more lightning-related events. On the other hand, a warmer climate may increase cloud water content at the expense of cloud ice content, where the latter is a prerequisite for lightning. Taken together, it nevertheless seems likely that the number of days with risk of thunderstorms increases and that the thunderstorm season becomes longer in duration.

[21] van den Hurk, B., van Meijgaard, E., de Valk, P., van Heeringen, K.-J. & Gooijer, J. Analysis of a compounding surge and precipitation event in the Netherlands. Environ. Res. Lett. 10, 035001 (2015)

2.2.5 Heat waves

It is highly likely with higher maximum temperatures, more warm days and more prolonged periods with warm days. Figure 9 (see below at 2.2.7) shows clearly that maximum temperatures in summer increases the most over the Baltic Sea with impacts on the coastal areas. It is also clear that heat waves get longer and more intense as also the number of tropical nights increase substantially which implies that the relief of cooler conditions in night time gets less pronounced. As a consequence of this it is expected that the need for cooling will increase.

2.2.6 Increased sea-water temperatures

There is a large uncertainty related to details in future change in the Baltic Sea and the North Sea as global climate models are coarse and thereby have a crude representation of these oceanic areas. In this report we have not assessed detailed scenarios of sea surface temperatures from high-resolution regional climate ocean models. Instead, we look at air temperatures in the atmospheric regional models that are forced by global model sea surface conditions (see 2.2.5 above). Considering this caveat, the models indicate a strong increase in sea surface temperatures in the future. Figure 9 indicates that maximum air temperatures in summer increase the most over sea and that extended warm periods and the number of tropical nights increase substantially in southern Scandinavia and over large parts of the Baltic Sea and the North Sea. We conclude that it is very likely with higher mean sea surface temperatures. It is also very likely with more frequent and intense marine heat waves. This may affect both the power output from a NPP and seawater cooling through clogging of cooling-water inlets by marine organisms (more on that in the next chapter).

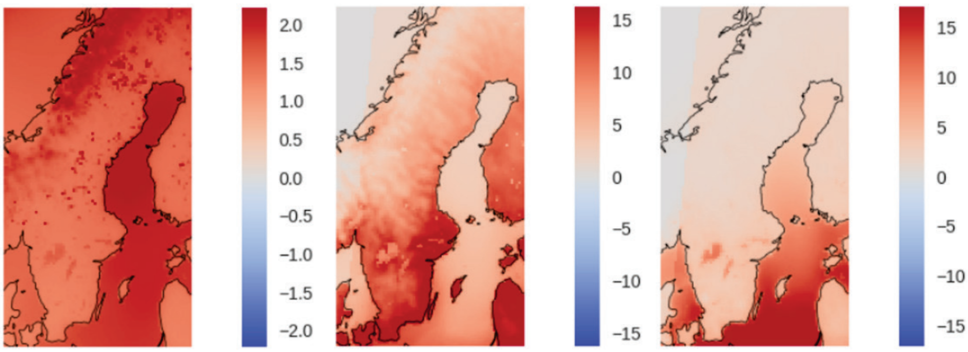


Figure 9: Projected changes in climate indices of relevance for high sea-water temperatures at +2°C global warming compared to pre-industrial conditions. From left to right changes in: maximum temperature (°C), consecutive warm days in June-August (days), tropical nights (i.e. days when night-time temperatures stay above 20°C)

2.2.7 Ice formation at sea

It is very likely with a decrease in the length of the ice season in all areas. In addition to a shorter ice season, also the extent of sea ice is projected to decrease due to warmer conditions during winter inhibiting ice formation and growth.

On the "positive" side is that potential problems associated with ice formation at sea are, accordingly, reduced since both the length and intensity of the ice season at sea is decreased in all regions across the Nordic countries. Some of the ice-related problems that may affect the operation of a NPP are discussed in the next chapter on "Impacts".

2.2.8 Very low air temperatures (enabling on-land ice formation)

It is very likely that problems related to very low air temperatures will decrease. The number of days when the temperature is below 0°C decreases everywhere and amounts to about a month at the +2°C level. In northern Scandinavia there may be an increase in the winter months when conditions go from way below 0°C to close to 0°C. This is shown in Figure 10 for number of days with zerocrossings, i.e. days when the temperature is both above and below 0°C. Also the number of occasions with precipitation close to 0°C increases, both for rainfall below plus two degrees as indicated in Figure 10 and for snowfall above minus two degrees in Figure 11 (below).

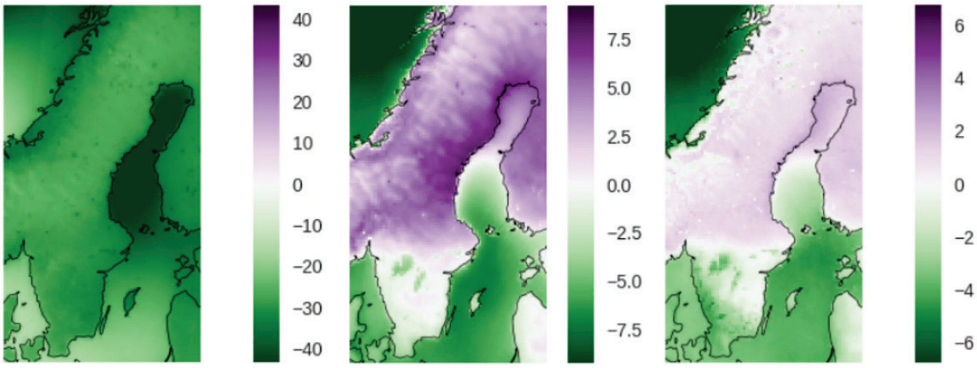


Figure 10: Projected changes in climate indices of relevance for snow and heavy snowfall at +2°C global warming compared to pre-industrial conditions. From left to right changes in the number of days with: frost on annual basis (i.e. the temperature is below 0°C at some time), zerocrossings in December-February (days), rainfall when the air temperature is below plus two degrees on an annual basis (days).

2.2.9 Sub-cooled rain

It is very likely with reduced number of days with risk of sub-cooled rain and/or days with rain in combination with temperatures close to 0°C in the south (Ringhals, Oskarshamn, Forsmark). In the north, there may be an increase in days with such conditions in winter.

Special weather phenomena combining subcooled rain and windstorms are so called ice storms. This is an extremely rare phenomena in our parts of the world but more common in North America[22]. In a warmer climate with more water vapour being evaporated from the North Atlantic precipitation is projected to increase over Scandinavia in winter. Potentially, if temperatures are still low enough, this could increase the risk of ice storms. Even though ice storms may be a potential threat to electricity supply, we have omitted any further analysis of these events as these are currently not occurring in northern Europe and today's climate models can not represent them adequately. Consequently, there is also limited scientific literature on such events for Scandinavia.

2.2.10 Heavy snowfall

Snowfall will be reduced in all of Scandinavia on an annual mean basis. Heavy snowfall is also projected to decrease in most areas. However, in colder climates such as in northern Sweden, heavy snowfall events are not projected to decrease

[22] For an example see e.g. Gyakum, J. R., , and P. J. Roebber, 2001: The 1998 ice storm—Analysis of a planetary-scale event. *Mon. Wea. Rev.*, **129** , 2983–2997.

and may even increase particularly in the mountains. As a result, heavy snowfall events will still exist. In northern Scandinavia the higher temperatures result in an increase in the number of days with snowfall at high air temperatures when humidity can be higher. This is also indicative of potential heavy snowfall.

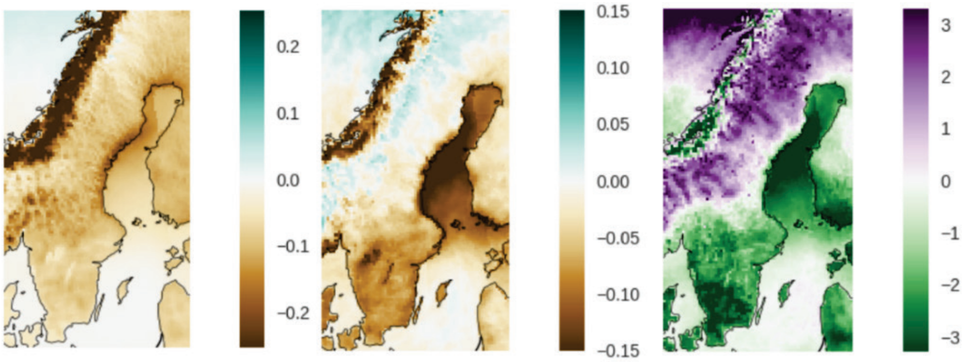


Figure 11: Projected changes in climate indices of relevance for snow and heavy snowfall at +2°C global warming compared to pre-industrial conditions. From left to right: Annual snowfall amount (mm/day), maximum snowfall intensity (mm/hour), number of days with snowfall when the air temperature is above minus two degrees.

2.2.11 Forest fires

It is likely that the risk of forest fires in dry years will increase in a future warmer climate despite a general increase in precipitation. This assessment builds on the fact that i) temperatures increase, ii) evaporation increases, iii) the fire season gets longer, iv) the interannual variability in some of these aspects increases. Figure 12 shows only small changes in effective precipitation in southern Sweden, local areas with longer dry periods and a clear picture of longer periods with heat waves. These changes get more pronounced at higher warming levels indicating that the risk of forest fires accelerates at higher degrees of global warming.

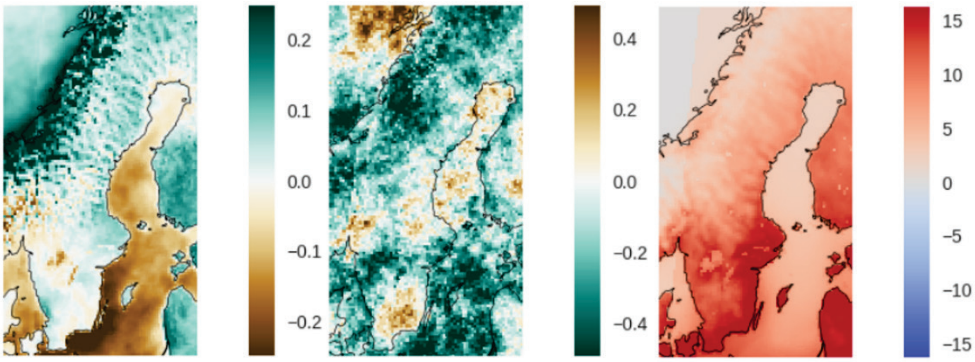


Figure 12: Projected changes in climate indices of relevance for forest fires at +2°C global warming compared to pre-industrial conditions. From left to right: effective precipitation in June-August (precipitation minus evaporation in mm/day), longest consecutive dry period in June-August (days), consecutive warm days (days).

3 Potential impacts on the operation of a nuclear power plant

There is an important distinction between potential impacts that may lead to safety concerns and impacts that may affect the (normal) operation of a NPP. We will find in this chapter that the potential impacts of climate-change induced weather events first and foremost are related to operation. Therefore, impacts of climate change is primarily a question of economics for the power plant owner and a question of security-of supply for the electricity system.

In this chapter, we focus on important *potential* impacts on the NPP site and on the safe operation of a NPP, resulting from the different weather events (or phenomena) that were described in the previous chapter. As we also reported in the previous chapter, conditions for these weather events may change due to climate change which is essential in this impact assessment.

3.1 SOME REMARKS ON EXTREME EVENTS

As we have mentioned, safety and operational standards at a NPP rest, among other things, on detailed assessments of more or less extreme events with specified return periods or probabilities of down to less than once in a million years. When it comes to extreme weather events, the return periods of such occurrences are generally calculated by applying extreme-value distribution functions to historically observed weather events. For very extreme events, the observation data, of course, spans a time period that is far shorter than what is estimated in the return period. Thus, uncertainties in such analyses may be large.

In this study, the data from the climate modelling has generally not made it possible to estimate return periods of extreme weather events or to what extent these values may be impacted by climate change. The data material has in several aspects made it possible to quantify the amplitude of different weather events, as for example significant draughts, heat waves, cloudbursts etc. For other weather events such as very powerful thunderstorms or temporarily high sea-levels, we have relied on qualitative estimates. However, we have not had access to material that enables estimates on the impact of climate change on return periods for very extreme weather events, neither in a qualitative nor in a quantitative way (with a certain exception for extreme sea levels in the previous chapter). Thus, we cannot quantify our findings in terms of probabilities or return periods for (extreme) weather events in a way that is normally done in the nuclear-power sector, so-called event classification according to the requirements defined in SSMFS 2008:17 by the Swedish Radiation Safety Authority. Such an event classification allocates events that range from various operational situations to highly improbable events into different event classes each defined by a frequency range or return period (SSM, 2015).[23] The event classification defines the appropriate operational and

[23] SSM 2015, "Design Guide for Nuclear Civil Structures (DNB)", Report no 2015:25.

safety requirements at a NPP depending on return period and severity of the event. A possible consequence of reflecting the latest findings within climate-change research is that some weather events may be subject to re-classification in these event-classifications if there are indications that climate change sufficiently impacts the frequency of occurrence of that specific weather event. As mentioned, however, this has not been investigated further in our study.

3.2 METHOD OF ASSESSMENT

The starting point of our assessment here is to map *potential and relevant weather-related impacts* on the operation of a NPP, such as flooding, reduced electric efficiency, damage to buildings and components and so forth, and to link these impacts to corresponding *weather events.* These weather events were identified and discussed in the previous chapter. Furthermore, we qualitatively assess the *significance* of the impact of a given weather phenomena on the operation of a typical NPP. This is done by gathering inputs from the working group that consisted of experts within the nuclear industry. The outcomes of these inputs are reported in the present chapter. In a final step, we assess the measures that need to be undertaken, or already have been undertaken, to handle the impacts that were identified during this work. We also elaborate whether these measures already are sufficiently in place or not, and whether they are expensive or relatively easy to install or to implement. This assessment was also done in a qualitative way with the helpful input from the working group. The results of that assessment are presented in the next chapter on "Measures and adaptive strategies".

Knowledge of climate change impact on some of the relevant weather phenomena presented here is sparser, or more uncertain, than for other assessed weather phenomena. Thus, we have made a more detailed assessment of certain weather phenomena than for others, even if they are considered as relevant to the nuclear industry. Thunderstorms is one such example that is highly relevant for the nuclear industry but where we still need to gather further knowledge on the impact of climate change on conditions forming thunderstorms in the future.

The identified relevant impacts and related weather events were ordered according to priority suggested by the working group.

Before we describe in detail our impact assessment, we start by looking at some actual experiences, based on available reports, of weather-related incidents and their impact on the operation of NPPs in the Nordic countries.

3.3 RECENT OPERATIONAL EXPERIENCES OF WEATHER EVENTS

Based on experiences and the incident reporting to the IAEA, NPPs in Sweden and Finland have, hitherto, experienced weather-related incidents or disturbances only on (very) rare occasions, see examples reported in Figure 13 - Figure 15.[24] In these three figures weather-related incidents are included in the category "Environmental conditions". On average, such incidents result in either a shut-down or in a temporal reduction in power output of a NPP in the Nordic countries

[24] IAEA (2019), "Operating Experience with Nuclear Power Stations in Member States, 2019 edition".

during only very few hours per year (<5 hrs; averaged over some 40 years and concerning, in this case, two blocks at Ringhals and one block at Olkiluoto). This means, however, that for certain years the duration of the incident can stretch over several hours (or days) while for other years, there are no reported (weather-related) incidents at all. In the case of Ringhals 2, for example (Figure 13), the heat wave during 2018 caused the unit to reduce its power output and, ultimately, to shut down completely since the upper sea-temperature operational limit was exceeded (depending on heat-exchanger configuration). Thus, the number of reported hours with weather-related incidents became relatively large during that specific year. Measures to deal with such events are discussed in the forthcoming chapter on "Measures and adaptive strategies".

The marine heat wave in the summer of 2018 also affected the electricity generation at the Loviisa NPP where the production at both blocks was temporarily reduced due to seawater temperatures approaching the upper limits as given by environmental regulation.[25]

Outage includes power reduction or complete shutdown

Full Outages, Analysis by Cause

Outage Cause	2018 Hours Lost			1975 to 2018 Average hours lost per reactor-year		
	Planned	Unplanned	External	Planned	Unplanned	External
A. Plant equipment problem/failure		79			1034	
C. Inspection, maintenance or repair combined with refuelling	680			1028	1	
D. Inspection, maintenance or repair without refuelling	49			65		
E. Testing of plant systems or components				2	0	
F. Major backfitting, refurbishment or upgrading activities with refuelling				75	47	
H. Nuclear regulatory requirements					3	
J. Grid limitation, failure or grid unavailability						10
K. Load-following (frequency control, reserve shutdown due to reduced energy demand, reactive power)						5
L. Human factor related					2	
N. Environmental conditions (lack of cooling water due to dry weather, cooling water temperature limits, flood, storm, lightning, etc.)			117			4
P. Fire					68	
R. External restrictions on supply and services (lack of funds due to delayed payments from customers, disputes in fuel industries, fuel-rationing, labour strike outside the plant , spare part delivery problems etc.)						1
Z. Other					1	
Subtotal	729	79	117	1170	1156	20
Total	925			2346		

On average, hitherto single hours each year

Partly due to high sea-water temperatures during summer leading temporarily to shut-down

Source: IAEA, "Operating Experience with Nuclear Power Stations in Member States ,2019 edition"

Figure 13: Reported outages at Ringhals 2 in 2018 and during the entire operational time horizon of the unit (weather-induced outages included in "environmental conditions").

Ringhals 2 was permanently shut down in the end of 2019 due to previous decisions (based, in turn, on market outlooks) by the owners. In the end of 2020, also Ringhals 1 was permanently taken out of operation due to the same reasons. The sea-water temperature limits that apply to the two remaining units, 3 and 4, are higher than the corresponding limit for Ringhals 2. Based on the incident reporting for Ringhals 3, we may conclude that the heat wave of 2018 did not affect the operation of that unit (zero "environmental conditions" according to the incident reporting for 2018, see Figure 14).

[25] Fortum (2018), https://www.fortum.com/media/2018/07/temporary-reduction-power-loviisa-power-plant-units-1-and-2-due-high-sea-water-temperature

Outage includes power reduction or complete shutdown

Full Outages, Analysis by Cause

Outage Cause	2018 Hours Lost			1981 to 2018 Average hours lost per reactor-year		
	Planned	Unplanned	External	Planned	Unplanned	External
A. Plant equipment problem/failure					306	
C. Inspection, maintenance or repair combined with refuelling	938			754	17	
D. Inspection, maintenance or repair without refuelling				203		
E. Testing of plant systems or components				5	1	
J. Grid limitation, failure or grid unavailability						2
K. Load-following (frequency control, reserve shutdown due to reduced energy demand, reactive power)						4
L. Human factor related					4	
N. Environmental conditions (lack of cooling water due to dry weather, cooling water temperature limits, flood, storm, lightning, etc.)						1
Z. Other					2	
Subtotal	938			962	330	7
Total		938			1299	

On average, hitherto a single hour each year

R3+R4 were not affected by the high sea-water temperatures during summer 2018
since higher sea-water temperature limits apply to R3+R4 compared to R2 (R1 was subject to planned outage)

Source: IAEA, "Operating Experience with Nuclear Power Stations in Member States ,2019 edition"

Figure 14: Reported outages at Ringhals 3 in 2018 and during the entire operational time horizon of the unit (weather-induced outages included in "environmental conditions").

Finally, in Figure 15 we present the IEAE incident report for Olkiluoto 2 in 2018 and the period preceding 2018. It is clear, that this unit has been virtually unaffected (close to zero hours of outage) by weather conditions during its entire operational lifetime so far.

Outage includes power reduction or complete shutdown

Full Outages, Analysis by Cause

Outage Cause	2018 Hours Lost			1982 to 2018 Average hours lost per reactor-year		
	Planned	Unplanned	External	Planned	Unplanned	External
A. Plant equipment problem/failure		93			318	
B. Refuelling without maintenance				37		
C. Inspection, maintenance or repair combined with refuelling	257			355		
D. Inspection, maintenance or repair without refuelling				9		
E. Testing of plant systems or components				19	1	
F. Major backfitting, refurbishment or upgrading activities with refuelling				27		
J. Grid limitation, failure or grid unavailability			60			4
K. Load-following (frequency control, reserve shutdown due to reduced energy demand, reactive power)						12
L. Human factor related					8	
N. Environmental conditions (lack of cooling water due to dry weather, cooling water temperature limits, flood, storm, lightning, etc.)						0
P. Fire					0	
Z. Other					1	0
Subtotal	257	93	60	447	328	16
Total		410			791	

On average, close to 0 hrs (single incidents during single years have, however, occured)

Source: IAEA, "Operating Experience with Nuclear Power Stations in Member States ,2019 edition"

Figure 15: Reported outages at Olkiluoto 2 in 2018 and during the entire operational time horizon of the unit (weather-induced outages included in "environmental conditions").

However, some of the incidents reported in Finland, as equipment failure, may in fact have been indirectly caused by prevailing weather conditions (e.g. component failure due to extreme heat), which was pointed out by Finnish representatives during the working-group sessions of this study.

Other weather-related incidents affecting the operation of the Nordic NPPs include jellyfish clogging of cooling-water inlets at the Oskarshamn 3 unit in 2013 leading to grid disconnection of that unit in order to meet safety regulations. Jellyfish incidents are likely to increase with increasing sea-water temperatures as a consequence of global warming. In Finland, at least three incidents have been reported concerning so-called "frazil ice", which lead to turbine trips.[26] As we will see in the next chapter on "Measures and adaptive strategies", there are available measures to deal with both intruding marine organisms and ice-related problems.

It is likely, as we have seen in previous sections, that climate change increases weather-related incidents of relevance to nuclear power. As mentioned in the introduction, the nuclear industry regularly undertakes PSRs (periodic safety reviews) where the ability to maintain safety is assessed during the coming decade considering also new knowledge within science and technology. New findings on climate-change impacts may, thus, support that work.[27]

3.4 ASSESSMENT OF IMPACTS ON NUCLEAR POWER RELATED TO WEATHER EVENTS AND CLIMATE CHANGE

In this section we assess relevant, and weather-related, potential impacts on the NPP site and to what extent climate change may increase concern for future potential impacts of such weather events. As a result of the working-group sessions, we have identified 17 relevant combinations of potential NPP impacts and weather events, see Table 4. This overview was reported in a more simplified way in the previous chapter (see Table 1). We have grouped the combinations into five main groups that each define a specific potential site impact that is considered as important to the secure generation of electricity at the NPP and, ultimately, with respect to safety. The five main groups concern flooding of the power-plant site, damage on key facilities or components, impact on cooling performance, impact on-site reserve power (air intakes) and impeding logistics to and from the power-plant site. Each of these five groups are further divided according to weather phenomena, the second column in the table. Thus, concern for flooding for example can be caused by different weather or climate phenomena (sea-level rise or heavy rainfall). However, the table should *not* be read in a way that gives the reader the impression that heavy rain or sea-level rise is destined to lead to flooding of the nuclear power plant. Instead, the table links *potential* impacts (flooding in this case) that the NPP needs to consider for operational and safety reasons, with weather events that *may* contribute to a certain risk of facing such an impact. As we have mentioned and also will find in the next section, existing measures and safety margins are designed to handle also extreme weather events. In the third column of the table, we briefly summarize, if possible, the estimated impact of climate change on the frequency, duration and amplitude of each weather event. There we find, for instance, that climate change is very likely to

[26] Frazil ice is a type of frozen water that has been observed to form in subcooled moving water, can form very quickly and may block cooling-water intakes. More on the incidents related to frazil ice can be found in Männistö 2016, "Frequency of Frazil Ice and Algae Threats to Ultimate Heat Sink for Hanhikivi-1 NPP ", 13th International Conference on Probabilistic Safety Assessment and Management (PSAM 13).

[27] The licensees of a nuclear power station are required to submit a PSR of each reactor unit at least every ten years. The review must verify that the plant complies with the current safety requirements and has the prerequisites for safe operation until the next PSR, taking into account advances in science and technology. The analyses, assessments and proposed measures shall be reported to the Swedish Radiation Safety Authority (Ministry of Environment, 2019, "Sweden's Eighth National Report under the Convention on Nuclear Safety").

increase the sea-level as we have reported earlier. This in turn, *may* have an impact on the overall estimate of the risk of flooding.

To relate each main impact (flooding in this example) to different weather phenomena is also meaningful when assessing corresponding measures. The risk of flooding involves a different set of measures if we are talking about concern for sea-level rise due to global warming or if we are talking about heavy rainfall. Furthermore, localization of NPPs also determine the relevance of impacts and appropriate measures. The relatively few NPPs in the Nordic countries are distributed over a relatively wide area with different conditions concerning weather seasons, salt-content of water (affecting ice conditions) and land topography.

From a NPP point of view, the progress rate of a specific incident or event is also a relevant parameter. In case of fast-progress events, such as heavy rain or lightning, necessary preparations or measures must be in place in advance. Such events can also lead to sudden outages affecting security of supply of the electricity system. In contrast, slow-progress events, increase in sea level or sea-water temperature due to global warming, may give (plenty of) time for additional preparations in case they are considered as needed. Such events can have a more long-term impact on investment incentives in electricity generation based on nuclear power (as well as other power sources).

Table 4: Overview of weather-related impacts on the NPP site, corresponding weather events and estimated contributions from climate change.

Potential **impact on NPP operation**	**Related weather event**	**Estimated contribution from climate change**
Flooding of NPP site	Sea-level rise	Very likely with increasing mean sea level in the southern parts of Sweden, and counteracting land-uplift in the northern parts of Sweden
	Windstorms and hurricanes	Significant changes in maximum wind speed are not expected. The estimate is, however, highly uncertain
	Heavy rainfall	Very likely with stronger precipitation extremes on all time scales.
Damage on key facilities, components and ancillary buildings ***(not associated with flooding)***	Thunderstorms	It is likely that the number of days with risk of thunderstorms increases and that the thunderstorm season gets longer.
	Windstorms and hurricanes	Significant changes in maximum wind speed are not expected. The estimate is, however, highly uncertain
	Extreme heat waves	Highly likely with higher maximum temperatures, more warm days and more prolonged periods with warm days.

<u>Damage</u> on… *(contd.)*	Subcooled rain	Very likely with reduced number of days with risk of sub-cooled rain.
Reduced or failed <u>cooling</u>	Increased sea-water temperature	Very likely with higher mean sea temperatures.
	Marine organisms (spurred by increased sea-water temperature)	Very likely with higher mean sea temperatures and, furthermore, very likely with more frequent and intense marine heat waves
	Ice formation	Very likely with a decrease in the length of the ice season in all areas and decreased extent of sea ice.
Jeopardize on-site reserve power through clogging of <u>air intakes</u>	Ice formation though low temperatures	It is very likely that problems related to very low air temperatures will decrease.
	Ice formation through subcooled rain	Very likely with reduced number of days with risk of sub-cooled rain and/or days with rain in combination with temperatures close to 0C in the south (Ringhals, Oskarshamn, Forsmark). In the north, there may be an increase in days with such conditions in winter.
	Heavy snowfall	It is likely that the snow season becomes shorter but heavy snowfall events may still exist.
	Debris and soot through forest fires	It is likely that the risk of forest fires will increase in a future warmer climate despite a general increase in precipitation.
Impeding <u>logistics</u> to and from the NPP site	Heavy snowfall	It is likely that the snow season becomes shorter but heavy snowfall events may still exist.
	Heat waves	It is very likely that heat waves become more intense and frequent and that maximum temperatures get higher.
	Forest fires	It is likely that there will be an increasing risk of forest fires mostly due to warmer summers and longer heat waves.

Due to lack of resources and time during our working-group sessions, we had to prioritize among the NPP impacts listed in the table above according to an order that was given by the working group prior to the last working-group meeting. Based on the prioritization, the risk of flooding due to sea-level rise, potential damage on key facilities through thunderstorms, reduced cooling performance through increased sea-water temperatures and marine organisms, and the risk of flooding due to windstorms and heavy rain were considered as especially relevant. However, almost all the 17 identified combinations of impacts and weather events were considered relevant to some extent by the working group. Nevertheless, not all 17 combinations were discussed and scrutinized but are still to some extent included in the following sections. We present the assessment in the following section according to the main impact groups in Table 4 and not according to chosen priority.

3.5 FLOODING

Flooding may in extreme cases be a result of different, or combined, weather conditions and could lead to penetration and infiltration of water at the NPP site. This, in turn, presents a risk to the proper functioning of reserve power facilities, electric switchyards and substations, thus, affecting the internal grid or jeopardizing the external grid connection. Furthermore, flooding may potentially lead to structural stress on ancillary buildings or other constructions at the site through water pressure. Erosion is another possible effect of flooding. Finally, flooding may also affect logistics such as transportation networks around the NPP site. Very high (temporary) sea-levels may also impact the cooling capabilities due to increased water pressure on the cooling-water outlets which may lead to decreased power output.

The risk of flooding is primarily associated with extreme weather events such as heavy rainfall and/or windstorms or hurricanes. The question is to what extent sea-level rise due to climate change may increase risks of flooding at the NPP sites in the Nordic countries. Alternatively, the return period of a given extreme event affecting the sea-level may decrease as a consequence of climate change (e.g. an extreme event with an occurrence of once in 10000 years might in the future receive a return period of, say, 5000 years instead). We reported findings on extreme sea-levels in the previous chapter on "Climate change and weather events relevant to nuclear power" for the three Swedish NPP sites.

3.5.1 Impact of sea-level rise

Based on the findings as regards risk of flooding and climate-change impact on sea-level rise, the working group found the possible impact on the NPP operation to be limited or insignificant and not affect safety. It was mentioned during the discussions, however, that sea-water flooding could present a potential safety concern but given the estimated relatively small effect caused by climate change in our parts of the world and under a foreseeable future, this is not likely to currently initiate any reconsidering of onsite safety.

3.5.2 Impact of windstorms and hurricanes

As mentioned, it is not sea-level rise itself that leads to concern for flooding but rather sea-level rise *in combination* with extreme weather events such as windstorms and hurricanes. Even though powerful windstorms were considered as potentially challenging to onsite operation and safety, the working-group panel agreed upon that the overall impact on the NPP operation is limited or negligible based on the findings and knowledge presented as regards climate-change impact on future windstorms and hurricanes.

3.5.3 Impacts of heavy rainfall

Heavy rainfall is a third factor that must be considered when assessing the risks of flooding at a NPP site. As such, heavy rainfall also presents a potential challenge to the operation of a NPP. Similar to the discussions on the impact of climate change on sea-level rise and windstorms, the estimated impact of climate change on heavy rainfall was considered, by the working group, to be limited or even negligible as regards impact on NPP operation.

3.5.4 Remarks on combined effects

When discussing the risk of flooding, the combined effect of a future sea-level rise due to global warming in combination with extreme weather events occurring at the same time including powerful windstorms and heavy rain is, of course, extra interesting. Finnish experiences mentioned during working-group sessions indicated that such combined effects of extreme weather, hitherto, have been seen at very rare occasions. However, climate research indicates that some combined effects will become more frequent in the future, even though uncertainties are especially large out of reasons that we mentioned in Chapter 2.

3.6 DAMAGE ON KEY FACILITIES, COMPONENTS AND ANCILLARY BUILDINGDS

Even though flooding may, as we have discussed, imply damage on structures and essential facilities, we have in this section chosen to focus on potential damages caused more directly by weather events such as thunderstorms, powerful windstorms, heat waves and subcooled rain, rather than the infiltration of water through flooding.

3.6.1 Thunderstorms

As is reported in the supplementary report on the electricity grid (Energiforsk, 2021)[28], thunderstorms present a significant challenge to the electricity grid and its components such as substations. From a NPP point of view access to a stable external grid is essential for feeding electricity into the grid and to rely on a stable (external) grid for reserve-power requirements. Loss of offsite power was considered, by the working group, to be a more apparent risk to the safe operation of a NPP than the risk of onsite damage caused by thunderstorms and lightning. It was mentioned during the working-group sessions that without a proper functioning external electricity grid, a NPP is generally not operated beyond typically three days due to safety reasons.[29] Such long outage times for the electricity gid are, however, relatively unlikely in the Nordic electricity system.

[28] Energiforsk 2021, "Climate-change impact on the electricity grid" (in Swedish), Report 2021:740.

[29] This time limit is an approximation and is likely to differ between different NPPs and depending on the status of the external electricity grid. During the time when the external grid is inaccessible, a NPP normally reduces its power output and proceeds with so-called house load operation, i.e. onsite internal electricity use is supplied by the reactor. Such a "stand-by" mode of operation enables a relatively swift re-connection to the grid once the external grid is up and running again.

Lightning strikes on switchyards, substations or power lines may cause loss of external (and internal) grids. Thunderstorms may also lead to damage or disruption of other electronic key devices through direct lightning strikes, electrostatic discharges or magnetic pulses. Lighting strikes may also result in fires at the plant or in close vicinity to the plant. Finally, new digital equipment may be significantly more sensitive to the negative effects of thunderstorms compared to older and analogue systems.

Climate change may affect lightning both in terms of frequency and amplitude (energy release). From a NPP point of view, the amplitude is more relevant.

As regards lightning, the working-group found climate-change impact to be of somewhat more negative significance than in relation to the risk of flooding, (although the majority of the working-group members that participated cast their vote on "limited or no impact"). This view might, of course, also embody the potential severity of lightning, regardless of climate change, on the electricity system. As mentioned, the impact of climate change on thunderstorms and lightning is still somewhat unclear and subject to continued research. Therefore, when asking the working group for their view, we assumed that the future climate entails thunderstorms with higher frequency (which actually is very likely) *and* with higher amplitude (which actually is uncertain). The views by the working-group participants that cast their vote on "significant negative impact" were motivated by the view that sudden and unforeseen incidents (as lightning strikes) are always negative and could result in significant impact.

As mentioned, the working group considered the risk of losing offsite power (external grid) to be the most relevant negative impact due to thunderstorms and lightning and, therefore, it is potentially a matter of operational disturbance. In terms of economic performance, the impact was considered as relatively small which also applies to safety. However, if such lightning impact occurs simultaneously with a major storm, safety concerns may increase since also other safety-related onsite systems may be affected (involving control systems or onsite reserve power).

3.6.2 Windstorms and hurricanes

Damage to ancillary buildings or key facilities at a NPP can also be caused by very powerful winds. Safety regulations require the operators of NPPs to consider very extreme wind events potentially causing damage from flying objects, so-called "tornado missiles", such as steel bullets, spears and even cars. The lion share of the onsite buildings is constructed to withstand extremely powerful tornado-like winds with wind speeds of 72 m/s (with an estimated return period of more than a million years).

Another potential outcome of powerful winds are so-called salt storms that have occurred at times along the west coast of Sweden. Such salt storms can, in turn, lead to salt coating of key facilities at the NPP site, especially electric switchyards which may cause short circuits and discharges. This happened in 2005 at Ringhals and eventually led to shutdown of some of the units.[30] In situations where weather conditions could increase the risk of salt coating, the switchyards are rinsed with freshwater for precaution. Salt storms are considered not to present any threat to safety (SSM, 2011).[31]

The possible impacts of windstorms and hurricanes in terms of onsite damage was not further discussed within the working group due to priority.

3.6.3 Heat waves and sub-cooled rain

Heat waves and sub-cooled rain were also mentioned as weather events that potentially may have an impact on the NPP operation, let alone with a low priority given by the working group. Heat waves might for instance cause component failure through thermal stress or fatigue and sub-cooled rain could lead to ice formation that, in turn, may affect the internal grid and switchyards.

3.7 REDUCED OR LOSS OF COOLING CAPABILITIES

The next group of our identified five main groups of NPP impacts concerns seawater cooling capability. Cooling of the reactor core is essential to plant safety as well during normal operation as after reactor shutdowns due to significant generation of decay heat. Normally, cooling is supplied through cooling-water inlets at site-specific inlet depths at sea. If sea-water temperatures rise significantly, during heat waves in summer or, in a more long-term perspective, as a slowly progressing result of global warming, the electric (or turbine) efficiency is reduced, and, consequently, power output for a given thermal output (and for a given heat-exchange configuration). Hence, electric efficiency is somewhat higher during winter than during summer.

In a situation when the sea-water temperature is at a relatively high level, there might be a risk that cooling capabilities are insufficient to handle decay heat removal in case the reactor needs to be stopped for whatever reason. At such a point, the thermal power of the reactor is gradually reduced in order to decrease the decay heat or, alternatively, to match the cooling capabilities with the prevailing decay heat. If the sea-water temperature exceeds a certain reactor-specific temperature level defined by safety assessments, the reactor is finally shut down. As mentioned in a previous section, this happened to Ringhals 2 during the heat wave in 2018, while units 3 and 4 continued normal operation (due to higher design temperatures; Unit 1 was out of operation from other reasons during that period).

Another possible negative effect from increased sea-water temperatures that also potentially may jeopardize cooling performance is the presence of marine organisms such as jellyfish and algae. These organisms thrive in warmer temperatures and may clog, either partially or completely, cooling-water inlets (this has been experienced by Oskarshamn NPP as mentioned before). Other

[30] Sveriges Radio 2005, "Stormen stoppade fyra kärnreaktorer", https://sverigesradio.se/artikel/535802
[31] SSM (2011), "European stress tests - The Swedish National Report for nuclear power plants"

possible reasons for clogging cooling-water inlets include driftwood and debris originating from e.g. windstorms or forest fires.

3.7.1 Increased sea-water temperatures

A majority of the working group agreed that, based on the presentations and findings from climate-change research, there is only limited or no impact from climate change on the cooling capabilities determined by sea-water temperatures. Such impact was found to be primarily a matter of economics rather than safety. Higher sea-water temperatures lead to reduced electricity generation, all else equal, and, thus reduced economic revenues. This must be weighed against possibilities to enhance cooling capabilities though additional investments in heat exchangers as an optional response to increasing sea-water temperatures (more on this topic in the upcoming chapter on “Measures”).

3.7.2 Marine organisms

As was discussed in Chapter 2, it is very likely with higher sea mean temperatures and more intense marine heat waves as a result of climate change. These are conditions that are beneficial for the formation of marine organisms such as jellyfish and algae, which are events that often occur very suddenly and, thus, present a challenge to the NPP operation.

The view of the working group on the impact of climate change on the presence of marine organisms at the vicinity of the cooling-water inlets and, thus, on cooling capability was somewhat diverse. A majority of the participating working-group members voting for “limited or no impact” while “significant negative impact” received nearly the same share of votes. It was also mentioned that the presence of marine organisms is especially difficult to predict since it also involves the potential transportation of species from far away through sea currents.

3.7.3 Ice formation

In general, ice formation and the potential impact on cooling has not been an issue at the NPPs in Sweden but has, historically, caused some incidents at the Finnish NPPs (see previous chapter on historical experiences). A sea with ice cover does not present a problem in itself. Instead, potential problems are primarily associated with the formation of so-called “frazil ice” which according to the Finnish Radiation and Nuclear Safety Authority (STUK) can be considered as a sudden event.[32] Such frazil ice may cause blocking of the cooling-water intakes. Changes in ice formation due to climate change may also affect periods with frazil ice formation. The Finnish representatives in the working group pointed out that several measures have been implemented in recent years which have reduced the problems associated with ice formation significantly. One such measure includes the circulation of warmer outlet cooling water into the (colder) cooling-water intake channel. This is also possible at the Swedish units. As mentioned, climate change will reduce the length of periods with ice formation at sea, especially in the

[32] STUK, 2019, “The Radiation and Nuclear Safety Authority’s safety assessment of the operating licence application for the Olkiluoto 3 nuclear power plant unit”.

southern and middle parts of the Baltic Sea. To what extent this also may affect and dampen the potential problems related to frazil-ice formation is according to Finnish experiences still unclear.

3.8 AIR-INTAKE CLOGGING OF ON-SITE RESERVE POWER

The fourth group of our main impact groups concerns securing onsite reserve power. Onsite reserve power facilities, typically diesel generators, are essential in the safe operation of nuclear power and serve as reserve power facility for cooling purposes in case of an incident involving loss of the external grid. Since these facilities require combustion air, the air intakes are potentially a weak spot being exposed to the risk of clogging and, thus, jeopardizing the proper functioning of the onsite reserve power units in case they are needed. As such, clogging of air intakes may present a potential safety issue. Air-intake clogging may be induced by sub-cooled rain, ice formation, heavy snowfall or debris/soot from near-by forest fires.

In the wake of the Fukushima accident in 2011, the European Council decided that stress tests had to be undertaken at all nuclear power stations across the EU. As a result, the Swedish Radiation Safety Authority decided that independent core cooling systems had to be implemented at all nuclear power stations in operation in Sweden by December 2020. As a result, onsite reserve power capability was significantly increased with respect to robustness and design to withstand extreme external events (including extreme weather and sea levels) and extended beyond the requirements of the incumbent safety systems (more on independent core cooling systems in the next chapter on "Measures").[33]

Finally, clogging of air intakes serving ventilation systems in ancillary buildings (such as office buildings) may also potentially impact the normal operation of a nuclear power plant but is not related to the same concern as in relation to onsite reserve power facilities.

3.8.1 Winter and low-temperature conditions: heavy snowfall, sub-cooled rain and ice formation

As regards potential clogging of air intakes, in particular heavy snowfall in combination with strong winds are of special interest. Such events usually occur suddenly. Based on the findings on climate change reported in Chapter 2, these problems associated with winter conditions are likely to decrease in the future, especially for NPPs localized in the more southern parts of the Nordic countries.

During the working-group sessions we considered winter and low-temperature conditions (heavy snowfall, sub-cooled rain and ice formation) as a whole with respect to the risk of clogging air intakes at onsite reserve power facilities. In general, the working group believed climate change to have a limited or insignificant impact on the NPP operation as regards clogging of air intakes.

[33] SSM (2020), https://www.stralsakerhetsmyndigheten.se/press/nyheter/2020/forsmark-ringhals-och-okg-uppfyller-kraven-pa-oberoende-hardkylning/

3.8.2 Forest fires and the potential impact of debris and soot

Debris and soot from nearby forest fires may also potentially impact air intakes at onsite reserve power facilities or at ventilation intakes at other buildings at the power plant site. This issue was raised during working-group sessions but was, however, considered to be of minor relevance.

3.9 IMPEDING LOGISTICS AND WORKING CONDITIONS

The last group of potential weather (and climate-change) related challenges to the normal operation of a NPP involves logistics and transportation to and from the NPP site itself and onsite working conditions. This is probably foremost an issue related to the safe transportation of working force while logistics related to key materials or components necessary for the power plant operation are challenged at weather events subject to significantly longer duration times (due to abundant onsite supply and storage). For instance, fresh nuclear fuel corresponding to typically one year's consumption is stored at the power plant site.

Heavy snowfall could be one potential reason that safe transportation to and from the NPP site is jeopardized. From our reporting in previous sections, we have found that the patterns of snowfall due to climate change are likely to change rather significantly. Climate modelling shows that there will be a decrease in heavy snowfall in the south. Also, in the north the season with snowfall will become shorter but heavy snowfall events may still exist making it uncertain whether there will be any changes or not. However, the provision of key materials and components for a NPP used during operation is, generally, done during revision of the units, typically during summer months.

Moreover, forest fires represent a potential threat to logistics to and from a NPP site. As mentioned earlier it is likely that there will be an increasing risk of forest fires mostly due to warmer summers and longer heat waves. Changes in precipitation and soil moisture are more uncertain but also have significance to the occurrence of forest fires. Likely, there will be more pronounced differences between dry and wet summers.

Furthermore, working conditions at the site may be challenging during periods with extreme heat waves. We have earlier concluded that heat waves are very likely to become more intense and frequent and that maximum temperatures get higher. It is also very likely that the number of tropical nights increases, implying a reduction in relief from cool conditions during night. This is not likely to jeopardize NPP safety but must be taken into consideration in order to ensure proper future working conditions.

No further discussions or analyses were carried out concerning the impacts of impeding logistics or compromise working conditions due to weather phenomena and climate change. In the working group, this was believed to have minor relevance or concern.

4 Adaptive strategies and measures

Measures and investments at NPPs are spurred by either lifetime extensions, repowering (increasing output power) or by safety requirements. Such investments have regularly been undertaken at the NPPs in Sweden and in Finland over the past years, which also has been proven to be beneficial from a climate-change adaptation perspective.

During the working-group sessions key measures and adaptive strategies were identified as responses to the potential impacts identified and discussed in the previous chapter. In the present chapter, we give an overview of the key measures that were discussed during working-group sessions. These include measures for handling the risk of flooding, lightning strikes, reduced sea-water cooling capability and the risk of air-intake clogging at onsite reserve power facilities. Some of the measures were also discussed in terms of whether they already are available of whether additional investments are needed.

As we have mentioned, the operation of nuclear power is subject to extreme safety standards and measures. These standards have been further amplified through the implementation of independent core cooling systems at the Swedish nuclear power facilities since the end of 2020. This system is designed to supply the reactor with sufficient core cooling under very extreme events, including extreme weather, with a return period of more than a million years *at the same time* as both the main coolant, seawater, is lost (LUHS; Loss of Ultimate Heat Sink) and the external electricity gird is inaccessible (ELAP; Extended Loss of AC Power). The detailed technical implementation of the independent core cooling systems may differ somewhat between the NPPs but it basically consists of diesel engines completely sealed, lightning-secured and isolated, also electrically, from the surroundings, and with access to separate cooling-water reservoirs (or tanks) sufficient for maintaining necessary cooling of the reactor core during at least 72 hours. This state of operation can be further extended in time if fuel and cooling water can be re-filled. The independent core cooling system supplements the conventional onsite reserve-power facilities that also consist of diesel engines. Thus, the implementation of the independent core cooling is beneficial for the robustness also against the potential negative amplification of climate change on extreme weather events.

4.1 MEASURES FOR HANDLING FLOODING

Sea-level rise due to an increasingly warmer climate is a change in external conditions with a (very) slow pace in progression. A slow pace is, of course, beneficial in terms of adaptation including preparatory work and protective measures in case they are considered necessary in a long-term perspective. Protective measures against flooding have in the past been implemented across the Nordic NPPs to various extent. This involves structures or shields to protect onsite buildings and pumps. At the Loviisa NPP, critical buildings and pumps are completely sealed and protected to a sea-level of +4.6 m above normal sea level. This is expected to be sufficient to withstand extreme weather events. Furthermore, constructing protective walls has also been a matter of interest. Such plans were, however, opted out at Loviisa since protective walls do not exclude the possibility of flooding caused by heavy rain. In fact, a protective wall could in that case even have a negative effect unless proper drainage is maintained. All Swedish NPPs are constructed to withstand an external seawater level of at least 3.0 m above normal sea level without facing the risk of fuel damage (SSM, 2011).[34] Moreover, all Swedish units are designed to handle flooding through high ground water levels and all units are equipped with drainage systems to remove ground water from the area between the rock and the buildings.

Even if climate-change gradually may reduce the safety margins with respect to events with extreme sea levels, it was concluded that the margins are sufficient given a relevant time frame. Let us take a closer look at a specific example, namely the Ringhals NPP. The plant is situated around 3 m above the (normal) sea level and the independent core cooling system an additional 0.5 m above sea level. Based on the climate modelling made available to this project and following the quantitative estimates on sea-level rise due to global warming and extreme weather that are reported in Chapter 2, a "worst case" estimate on extreme high sea-water level events at Ringhals combines the upper end of the likely range[35] of sea-level rise of the RCP8.5 scenario with the highest estimated sea-level event due to extreme weather (i.e. combining Table 2 and Table 3). This would lead to around 3 meters above normal sea level in 2100, at the same level as the Ringhals power plant ground level, and 2,35 meters in 2050, respectively. Here, we note that the RCP8.5 scenario is a scenario involving very large increases in future carbon emissions that sometimes has been contested as unrealistic and it should be considered a worst-case scenario[36]. At the same time, however, there are many projections of global mean sea-level rise that are higher than the 83rd percentile of the likely range given by the IPCC implying that the risk of seeing such high sea levels is not negligible. Even though these figures may be considered as very high-end estimates, they nevertheless form a base for discussions on acceptable uncertainties and tolerances which, of course, is constantly present in nuclear safety. The relevance of such long-term impacts may also be viewed against the projections of remaining operational lifetimes of, in this case, NPPs. It is not unlikely that Ringhals NPP is still in operation in 2050 while the situation in 2100 is a completely different one considering that, by then, the Ringhals site itself would be around 130 years old.

Contrary to sea-level rise due to climate change, sea-level rise due to extreme weather conditions such as significant low-pressure events including windstorms and hurricanes or heavy rainfall are fast-progress events and require sufficient protective measures to be ready and available at the site, primarily protecting and shielding pumps and seal buildings.

One essential viewpoint that was mentioned during the working-group sessions was that it is probably not realistic to protect the site against flooding under all possible conditions. Instead, measures must guarantee the safe shut-down of the

[34] SSM 2011, "European stress tests for nuclear power plants: The Swedish National Report"
[35] See Table 2
[36] https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario

plant, in case of flooding, and the sufficient maintaining of cooling also after the shut down even though the plant site itself would be virtually inaccessible due to flooding.

In summary, existing measures to handle flooding were considered sufficient also in a climate-change context, at least given the time frame and climate scenarios discussed here. Time frames stretching beyond, say, 2070 in combination with climate scenarios following a global temperature trajectory that significantly surpasses the ones investigated in this project (or, alternatively, considering the high-end level estimated long-term sea-level rise) could, however, give reason to reconsider the effects of sea-level rise at least in the southernmost localizations Ringhals and Oskarshamn.

4.2 MEASURES FOR HANDLING THUNDERSTORMS AND LIGHTNING

As mentioned, thunderstorms and lightning were identified by the working group as one of the more relevant weather events that potentially may cause operational malfunctions of an NPP especially related to the availability of the external grid and the risk of losing offsite power. Thus, some of the adaptive strategies and measures lie beyond the reach of the power plant owner. The possible effects of lightning strikes may both entail an economic (temporarily affecting the power output from the plant) and a safety-related dimension.

At the power plant site, existing measures for reducing negative impacts of lightning strikes include various lightning-protection systems both for onsite purposes and for reducing negative effects from lightning strikes on the external grid. Separating key buildings by a certain distance is one very apparent onsite measure. Moreover, ”shadow effects” of taller, less important, structures such as the ventilation stack to protect lower situated and more important buildings such as onsite reserve power facilities, is also utilized in the design of a NPP site. Lightning protection systems also depend on the type of thunderstorms and possible lightning strikes (amplitude and frequency). Some of the measures that have been carried out in order to further protect the internal grid from lightning impacts are a result of the Forsmark incident in 2006.[37]

For future purposes, the working group identified knowledge on the intensity of lightning to be essential and to what extent climate change may affect lightning intensity. In case intensity increases this may call for additional measures. Such measures are, however, considered to be relatively inexpensive.

4.3 MEASURES FOR SECURING SUFFICIENT SEAWATER COOLING

Measures to ensure sufficient seawater cooling of a NPP depend, of course, on what aspect of seawater cooling that is affected. In this section, we consider measures to handle increasing sea-water temperatures due to global warming,

[37] The Forsmark incident was a result of a short circuit in a switchyard outside the power plant which led to significant voltage variations that propagated into the internal grid of the Forsmark power plant. The chain of events affected unit 1 and eventually led to equipment failure in the control-room and malfunction of two of the four onsite reserve-power (diesel engines) units.

which reduces electric efficiency for a given thermal output, and measures to reduce the risk of clogging cooling-water inlets due to marine organisms or ice formation. Driftwood or debris from powerful winds or nearby forest fires were also mentioned during working-group sessions as potential causes for clogging but were, nevertheless, considered relatively irrelevant.

4.3.1 Increasing seawater temperatures

Increasing seawater temperatures due to global warming is a slow-progress phenomenon which, thus, enables sufficient time to adapt. However, during summer global warming may amplify periodic marine heat waves, which in temperature may progress relatively fast even though it is not a sudden event. As we have mentioned, marine heat waves affected the operation of both Swedish and Finnish NPPs in the summer of 2018.

Adapting to increasing seawater temperatures concerns first and foremost economy and not safety. The economic loss of generating a somewhat lower electricity output for a given thermal power output must be weighed against investments in additional heat-exchanger capacity or modified turbine configurations, which are relatively expensive measures (see discussion by Analysgruppen, 2018)[38]. Furthermore, environmental regulation stipulates upper temperature limits on cooling-water outlets in order to minimize impact on marine life. Such regulation, which does not concern safety, may also be subject to revision in the future given that average seawater mean temperatures increase. At the Loviisa power plant, for instance, the environmental regulation defines two temperature limits on the cooling-water outlet, one of 34 °C that must not be exceeded and one limit of 32 °C that can be exceeded but needs to be reported if exceeded more than 24 hours. In addition, there exist relative temperature limits, the temperature increase from intake to outlet.

And finally, safety margins for the operation of NPPs may also be revised in the future allowing higher cooling-water temperature at the outlet side of the reactor core. Most likely, however, measures reducing the cooling-water temperature at the intake are closer in order of priority. Such measures include the placement of water intakes at deeper water depths where the water is cooler or dredging or reducing the influence of (warmer) surface water at the intakes. Such measures are currently subject to ongoing research in Finland. The cost-benefit balance of such measures is yet to be determined. Most likely, relocating cooling-water intakes at significantly deeper depths, which probably would eliminate the problem of increasing sea-water temperatures, is a highly costly measure.

4.3.2 Marine organisms

The intrusion or clogging of marine organisms at cooling-water intakes may, in fact, present a potential safety concern. In Finland, TVO mentioned problems with organisms growing in the tunnel structures of the cooling-water intakes. The intrusion of marine organism can be a relative fast-progress event creating large

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[38] Analysgruppen (2018), ”Kärnkraft och värmeböljor”, https://www.analys.se/wp-content/uploads/2018/08/karnkraft-varmeboljor-rapport2018.pdf

populations of marine organisms as a result of marine heat waves, sea currents or powerful storms. If these populations clog or block cooling-water intakes, the primary source of cooling is affected and might even face the risk of a complete malfunction which, ultimately, leads to fast shut-down of the plant.

Several measures against the risk of clogging cooling-water intakes have been undertaken during past years. This includes relatively inexpensive measures such as improved screening systems that remove organisms and debris at the water intakes. These screening systems may, however, be insufficient in case populations of intruding marine organism become very large. If the clogging of seawater intakes is only partial, there still exist a critical level of cooling capability, supplementary measures may be used such as air cooling and the option to reverse cooling flows. The latter implies using the cooling-water outlet as inlet instead. Such additional measures are most likely plant specific. The addition of certain agents, such as sodium hypochlorite to reduce problems with intruding marine organisms was also mentioned by the working group. In that case, the addition of such agents needs to be done in a way that the chemical substance does not affect sealife or seawater quality.

As mentioned, independent core cooling systems introduced after the Fukushima accident have increased the robustness against events that could jeopardize the provision of seawater cooling, at least during a limited amount of time. In Sweden, the independent core cooling systems are designed to handle a complete loss of the primary heat sink (seawater) during 72 hours using e.g. external water tanks and artificial lakes. This is considered to be well enough in time in order to regain access to proper seawater cooling capabilities for normal operation. Depending on the size of these water reservoirs or possibilities to refill water and to refuel onsite reserve power generators, decay-heat removal may function properly even up to weeks without access to seawater.

In general, the working group argued that sufficient measures were in place to handle also extreme events concerning marine organisms from a safety point of view. Nevertheless, the risk of clogging cooling-water intakes by marine organisms is considered as highly relevant and may increase unplanned outages at NPPs in Sweden and Finland in the future.

4.3.3 Ice formation

During the working-group sessions, ice formation was mentioned as a potential difficulty related to cooling-water intakes and some historic experiences have proven that (in Finland, see Chapter 3). However, ice-related problems were considered to be of minor relevance in a future perspective, both since protective and sufficient measures have been undertaken in the past (concerning e.g. “frazil ice” in Finland) and since ice formation and growth in itself decreases in a warmer climate.

4.4 MEASURES TO SECURE AIR INTAKES FOR ONSITE RESERVE POWER

The risk of clogging air intakes at onsite reserve power facilities, diesel engines, has been significantly reduced due to the introduction of independent core cooling systems. As mentioned, independent core cooling systems involve several measures but also include safety upgrades with respect to air intakes at onsite reserve power generators. Consequently, improved filters, screens and strengthened constructions have been among these measures. Furthermore, the degree of redundancy of such air-intakes has increased through back-up air intakes.

Finally, instructions and routines to act in case air intakes risk clogging due to weather events have been improved. This concerns removal of ice and snow. During these weather events, onsite staff is frequently sent out for adequate inspections.

The measures concerning securing air intakes at onsite reserve power facilities are generally associated with relatively low costs.

5 Discussions and conclusions

In general, nuclear power is due to its prominent safety standards concerning, among others, extreme weather events, very robust against climate change. This is valid under a foreseeable future and given the climate scenarios that have been assessed here. Additional measures carried out as a response to the Fukushima accident further amplifies this. Nevertheless, continued and close monitoring of the progress of climate change is recommended since a number of identified weather-related events may have an increasing impact on the operation of NPPs in Sweden and Finland. Thus, climate change is primarily a concern for the normal operation of a NPP and not for safety.

We have found during this project, that climate-change does not seem to present any direct risk to safety among the NPPs in Sweden and Finland. Existing safety standards and measures are likely to be sufficient for decades to come also in climate scenarios depicting a more significant global warming. Mandatory safety measures and investments that have been carried out in the wake of the Fukushima accident, independent core cooling systems, have further strengthened safety standards which has been beneficial for handling, and preparing for, also extreme weather events. This especially concerns onsite reserve power generators and an independence of seawater cooling for at least 72 hours in case of a very severe disturbance.

5.1 IMPORTANT IMPACTS TO MONITOR

Even though nuclear power stands robust against climate change, we have found indications that climate change may increase the frequency of unplanned outages, operational disturbances, at a NPP which in that case primarily is a matter of economic loss and a matter of security of supply of the electricity system. For future monitoring, special attention should be given to:

- the impact of lightning strikes and the climate-change impact on both lightning frequency (likely to increase) and lightning amplitude (uncertain impact). It is primarily the amplitude (energy release) that is of relevance to the operation of a NPP. Protective onsite (internal grid) measures are believed to be sufficient but damage to the external grid, which is beyond control of the NPP operator, may also affect the operation at the site.
- increased sea-water temperatures and marine heat waves increase the risk of (partly) clogging cooling-water intakes through marine organisms (jellyfish and algea). These events may progress relatively fast and have historically caused some operational disturbances leading to reductions in power output. Filters are examples of measures that have been implemented.
- increased seawater temperature due to global warming and reduced cooling capability and, consequently, reduced thermal efficiency is first and foremost a question of economic optimization where loss in income (determined by electricity price and loss in generation) must be weighed against costs.

Measures include investments in increased heat-exchanger capacity, relocation of cooling-water intakes to deeper depths, revised safety margins and revised environmental permits limiting cooling-water outlet temperatures.

Besides these three factors, also sea-level rise due to global warming in combination with extreme weather (powerful winds and heavy rain) presents reason for concern, more specifically related to the possibility of flooding of the NPP site. Even though sea-level rise will certainly be an issue to consider in e.g. urban planning and in other areas, it was, however, found that there are currently no signs of any significant challenges in relation to the localizations of NPPs in Sweden and Finland in, say, a 2060-2070 perspective. This also includes extreme weather events that temporarily may lead to substantially higher sea levels, in the order of typically up to 2 meters above normal (future) sea-level. However, in a 2100 perspective, the uncertainty interval of continued sea-level rise is significantly stretched and may present reason for caution, especially when considering climate scenarios that assume a high degree of global warming, and especially for NPP localizations in the southern half of the Nordic countries.

5.2 EXTREME WEATHER EVENTS AND COMPOUND EFFECTS ARE SUBJECTS OF FURTHER RESEARCH

Climate-change modelling and research remains a field associated with significant uncertainties. Some of the knowledge is more robust such as the strong warming seen for all seasons while other findings are subject to large uncertainties. The latter includes for instance changes in the wind climate, changes in summertime precipitation and soil moisture conditions and changes in extreme events. Parts of these uncertainties are related to limitations in the climate models due to coarse resolution and insufficient knowledge of relevant processes. An example relates to summertime heavy precipitation in connection to heavy rain showers and thunderclouds. Such clouds are not adequately resolved in most climate models and are thereby not well represented. First results with very high-resolution models indicate that these events can be simulated in a better way (e.g. Belušić et al. 2020).[39] In addition, climate-model simulations indicate stronger climate change signals related to extreme precipitation in such models but this is so far not shown for the Nordic region. Part of the uncertainties, for instance those related to extreme events, are due to insufficient amounts of data where observational time series are too short. A particular example pertains to so called compound events, i.e. when two or more events occur at the same time thereby reinforcing each other implying that impacts are more pronounced. Research on such events requires long observational time series from many sites in combination with large ensemble of simulations with climate models.

[39] Belušić, D., de Vries, H., Dobler, A., Landgren, O., Lind, P., Lindstedt, D., Pedersen, R.A., Sánchez-Perrino, J.C., Toivonen, E., van Ulft, B., Wang, F., Andrae, U., Batrak, Y., Kjellström, E., Lenderink, G., Nikulin, G., Pietikäinen, J.-P., Rodríguez-Camino, E., Samuelsson, P., van Meijgaard, E. and Wu, M., 2020. HCLIM38: A flexible regional climate model applicable for different climate zones from coarse to convection-permitting scales. Geosci. Model Dev., 13, 1311–1333, DOI: 10.5194/gmd-13-1311-2020.

5.3 ANY POSITIVE SIDE EFFECTS?

In general, climate change does not carry any "benefits" if we strictly consider the future operation of nuclear power. However, three possible exceptions, let alone with uncertain relevance, can be mentioned. The first exception concerns ice formation at sea. In general, potential problems with ice formation are likely to decrease in a warmer climate even though there may be exceptions depending on geographical location. The second possible exception concerns potential problems with heavy snowfall (clogging air intakes or impeding logistics) which also are likely to decrease. A third potential exception was mentioned during the working-group sessions and it involves sea-level rise and whether cooling capabilities, in fact, might improve somewhat since cooling-water intakes will gradually, and automatically, relocate to deeper (and, thus, colder) water depths. However, based on later remarks given by oceanographic expertise at SMHI this is highly likely to have a negligible effect. Furthermore, for localizations in more northernly parts land uplifting may, in fact, completely counteract and even outweigh sea-level rise for many years to come. It is only at the strongest forcing and at the end of the century and beyond that sea level rise may grow into a significant problem.

5.4 FINAL REMARKS

In conclusion, based on the climate research reported in this study the impact of climate change on the future operation of nuclear power was generally considered as limited or insignificant by the working group. In general, existing safety measures seem to be unchallenged by what we today know about the effects of climate change, at least during a relatively long time to come. However, we have also found that climate change may lead to an increase in operational disturbances which, therefore, may impact power-plant economics and security of supply in the electricity system.

Continued monitoring of climate-change research is wise especially when considering new nuclear reactors, such as the planned Hanhikivi plant in northern Finland. For new units, the choice of a feasible site must be viewed against the prospect of hosting industrial activity during a time span of maybe in the order of a century. During such as time span, impacts of climate change will grow in relevance.

The NPPs in Sweden and Finland are widely, and evenly, distributed across a widespread geographical area. This is beneficial from an electricity-grid perspective but also from a viewpoint related to extreme weather. Extreme weather events progressing fast are much less likely to affect more than a single NPP localization at the same time. Furthermore, local conditions differ between the NPPs in the Nordic countries implying that the conditions forming a specific weather event or phenomena are different as well as the impact of a certain weather event. Ice formation might, for example, still be an issue of interest to NPPs situated further up north than for plants located in the south. Moreover, weather-related issues differ between localizations at the West Coast and along the Baltic Sea.

THE IMPACT OF CLIMATE CHANGE ON NUCLEAR POWER

Nuclear power is a source of electricity that generally is robust to climate change. Weather-related events have, however, occasionally caused some disturbances in the normal operation of nuclear power plants both in Sweden and in Finland.

Even though this is primarily not a question for safety, climate change may lead to an increase in operational disturbances in the future with a possible economic aspect. There are, however, additional measures available for dealing with such disturbances. The deployment of these measures is ultimately a question of weighting additional costs against a potential reduction in income from selling electricity.

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