„The impacts of climate change on nuclear risk and supply security" Working Paper

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In the Joint Project, European NGOs and research institutions cooperate since 2003 on safe and sustainable energy issues with a focus on anti-nuclear activities in Central and Eastern Europe.
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1 Extended Summary

Should nuclear energy receive support because it might contribute to a CO_2-free energy supply? On the contrary – nuclear energy is highly unfit to withstand the effects of climate change, thus leading to increased nuclear risk rather than being part of supply security.

To substantiate this argument, the Joint Project – Nuclear Risk & Public Control has produced this working paper. Oda Becker, Eszter Mátyás and Patricia Lorenz examined existing and potential impacts of climate change phenomena on operating and on future NPP.

The impacts of these climate change phenomena on nuclear risk and on supply security are discussed on a general level. Case studies of nuclear facilities highlight the fact, that nuclear power plants are already severely impacted by climate crisis impacts, in particular increased water temperature, less water leading to cooling problems and ultimate problems of running those plants at all.

The aim of the working paper is to inform NGOs and the interested public about the impacts of climate change on the generation of nuclear power now and in future.

The first part of the working paper evaluates the contribution of nuclear power on energy supply security. To answer this question, also the main risks associated with nuclear power plants have to be examined. Thus, the second part deals with the changes in risks due to operation of nuclear power plants in times of climate changes.

The contribution of new nuclear power plants (NPP) to energy supply security is very limited. Nuclear new-build has significant delays between planning and operation, resulting in **increasing construction times**. According to the World Nuclear Industry Status Report (WNISR 2019), the mean construction time for the nine reactors started up in 2018 was 10.9 years. New nuclear plants take 5–17 years longer to build than utility-scale solar or onshore wind power, so existing fossil-fueled plants emit far more CO_2 while awaiting substitution by the nuclear option.

An economic history and financial analyses from done by the German Institute for Economic Research (DIW 2019) showed that **nuclear energy has always been unprofitable under liberalized market conditions; currently there is a clear understanding, that nuclear power cannot be built without strong state support (See Paks II, HPC and now Dukovany V).** None of the 674 nuclear reactors built from 1951 to 2017 was financed with private capital under competitive conditions.

Costs of NPPs have increased by 90-500% from project agreement to completion. All European & US NPP projects have been built on the basis of sovereign loan guarantees and/or promises of full cost recovery from consumers. Losses essentially bankrupted the world’s largest reactor vendors, Areva & Westinghouse. Hinkley Power contracted on a 35-year contract at £92.5/MWh, latest UK off-shore wind prices, <£40/MWh (both 2012 money). (THOMAS 2019)

Furthermore, the nuclear power production is not CO_2-free. According to Jacobsen (2019), the overall emissions from new nuclear are 78 to 178 gCO_2/kWh compared to 4.8-8.6 g CO_2/kWh for wind energy production (onshore).

The contribution of the ageing nuclear power plants to energy supply security is limited due to ageing effects which pose additional threats to the safety of old nuclear power plants. Furthermore, unexpected combinations of various adverse effects and undetected failures of old NPP may result in the failure of technical equipment, leading to the loss of required safety functions For example, due to continuous technical issues and extended outages, the average load factor of the Belgian fleet plunged to 48.6 percent in 2018. The average age of the seven reactors in Belgium is about 40 years.

The safety design of NPPs is very important to prevent as well as to deal with accidents. Concerns are growing due to the Fukushima accident, as it revealed that there could be basic safety problems with all operating units, especially with the older ones, whose design was prepared back in the sixties or seventies. Their safety design is outdated and showing deficiencies, which cannot be resolved by performing back-fitting measures.

With our climate-impacted world now highly prone to fires, extreme storms and sea-level rise, nuclear energy is touted as a possible replacement for the burning of fossil fuels for energy. Yet scientific evidence and recent catastrophes call into question whether nuclear power could function safely in our warming world. Extreme weather events, fires, rising sea levels and warming water temperatures all increase the risk of nuclear accidents, while the lack of safe, long-term storage for radioactive waste and proliferation remain persistent issues.

Global warming can contribute to the intensity of heat waves by increasing the number of very hot days and nights. Increasingly hot air also boosts evaporation, which can worsen drought. More droughts lead to dry fields and forests that are prone to catching fire, and increasing temperatures mean longer wildfire seasons.

Global warming also increases water vapor in the atmosphere, which can lead to more frequent heavy rain and snowstorms. A warmer and moister atmosphere over the oceans makes it likely that the strongest hurricanes will be more intense, produce more rainfall, and possibly be larger. A scientist warned 2019 about super-storms and related giant waves, able to push 2300-ton boulders along the ocean floor, far more numerous and higher than the one that damaged the Fukushima power plant.

The climate change affects nuclear energy production in several ways, including

- The efficiency of nuclear power plants decreases with increasing temperature.
- Some sites may lose safety, with sea-level rise being of particular importance.
- Extreme weather events threaten the safety of NPPs additionally.

The IAEA grouped climate change related phenomena into Gradual Climate Changes (GCC) and Extreme Weather Events (EWE). While safety issues are rather linked to extreme events, efficiency loss of nuclear power plants and location issues are primarily associated with gradual climate changes. However, gradual climate change and extreme weather events influence each other – rising sea levels, for example, also lead to extreme water levels during storms.

A global mean temperature rise of 0.4°C in 20 years means that a 1 GW(e) NPP will lose generation owing to **reduced thermal efficiency valued** at approximately €4–21 million net present value over the next 20 years. The cost of rising temperatures is in the order of €1–6 billion when calculating the amount of power generated by all currently operating NPP in the next 20 years worldwide.

The climate change induced increasing risk of flooding is another serious effect which can lead to nuclear disaster. Many nuclear plants are built on coastlines where seawater is easily available for cooling. Sea-level rise, shoreline erosion, coastal storms and heat waves – all potentially catastrophic phenomena associated with climate change – are expected to get more frequent as the Earth continues to warm, threatening greater damage to coastal nuclear power plants.

We are now observing persistent weather patterns more and more frequently during the summer half-year in the northern hemisphere. Their long duration can result in extreme outcomes. The summer of 2016 demonstrated that a single weather pattern can trigger both localized intense precipitation with flash floods and large-scale precipitation with river floods. Following the events of 2016 in Europe, it should be clear that extreme amounts of precipitation within a very short time are possible almost anywhere.

While it is undisputed that extreme weather events will become more frequent due to climate change, it is difficult to quantify these changes. The probabilities of occurrence to base licenses on are usually derived from past data series using statistical methods. In a phase of climate change, however, these data series are no longer reliable, and the derivation procedures are no longer valid. Science is right now not in a position to deliver precise data on the probability of occurrence of rare events. For flood protection sometimes safety factors are added which have only insufficient scientific validation. Taking this route is not recommended for nuclear energy, because the risk is too high in the case of under-dimensioning.

With a continuously evolving situation data recently acquired may be outdated by the time evaluation was concluded. The time lag is still more drastic for the drafting of new rules and regulations by the authorities, and their implementation by the NPP operators. It seems hardly possible to win this race against time – particularly in the face of economic pressure that might lead to the result that only low-cost measures are realized.

The inadequate protection against floods at the Blayais site illustrates the problem of delayed and furthermore outdated backfitting measures. In spite of the fact that the hazards of climate change are becoming more and more obvious, safety reassessments and improvements generally are only implemented – if at all – after an event occurred. This practice is aggravated by the fact that an event in one NPP does not necessarily lead to backfits in another plant.

As shorelines creep inland and storms worsen, nuclear reactors around the world face new challenges. By the time Hinkley Point C is finished, possibly in 2028, the concrete seawall will be 12.5 meters high, 900 meters long, and according to the regulator will withstand the strongest storm surge, the greatest tsunami, and the highest sea-level rise at the site. But the plans were drawn up in 2012, before the increasing volume of melting of the Greenland ice cap was properly understood and when most experts thought there was no net melting in the Antarctic.

IAEA's current global safety standards were published in 2011. These state that operators should only take into account the 18- to 59-centimeter sea-level rise projected by 2100 in the Intergovernmental Panel on Climate Change (IPCC)'s report, published in 2007. However, these values are outdated. The IPCC report, published in 2013/14, predicts a sea level increases of up to 100 cm by 2100.

Extreme Weather Events can also cause a failure of the electric power supply. Nuclear power plants generate electric power and supply it to the offsite grid. On the other hand, the plants themselves are dependent on a continuous electric power supply to operate, particularly for the instrumentation and safety systems, even when they are shut down. After the Fukushima accident, measures to cope with Station Blackout situations are improved. However, these measures are mostly the deployment of mobile equipment, which would be difficult to use in an accident situation.

Cold and heat waves represent a significant problem for the electricity generation sector. Unplanned outages of nuclear power plants due to excessively high-temperature water constitute clear examples of this. Reports showed that 40% of the NPPs in Europe have already experienced cooling problems because of high temperatures.

Every 24 hours that a 1 GW nuclear plant is shut down (assuming €0.05/kWh) costs the plant owner €1.2 million in lost revenue. Outages also lead to indirect costs. When an NPP is shut down owing to an extreme weather event, electricity customers must either experience a power outage or pay more for electricity from alternative sources to fill the gap. Renewable power generators, in contrast, decentralize electricity supply so that an accidental or intentional outage would have a more limited impact than the outage of larger nuclear facilities.

Case studies

The case of the **Hungarian nuclear power plant Paks** is of particular interest, since here we can examine both the present (Paks I Nuclear Power Plant) and future (Paks II NPP) of nuclear power plants under the effects of climate change. Climate change is projected to increase the likelihood, frequency, duration and intensity of extreme hydrological and soil moisture situations (flood, inland water, over-humidification and drought, often in the same year, in the same area) Annual precipitation in the XX. century decreased significantly in Hungary. In the temperature trend, the most uniform changes can be observed, as the national average is well in line with global change, and it is even slightly higher. Not surprisingly, climate change is the dominant factor in the changes of the Danube basin. Given the rise in surface temperatures within the entire Danube basin, it is expected that cooling water temperature will give rising to additional increasing issues. Hungary is the 16th most threatened country in the world in terms of expected drought frequency, which may not only deplete reservoirs but also reduce the water level and discharge of the Danube.

As the presented summary of studies and commentaries show, the current available options by the Government are not sufficient to provide solution for the challenges of climate change. And with the two new reactors, the situation can be worsened. The government's lack of transparency concerning those questions of cooling may turn as a very serious environmental and economic disaster.

The planning of the **new Dukovany unit** serves as an example of ignorance, but certainly it is rather the trend than the exception. In neighboring Slovakia two nuclear reactors are under construction and the EIA conditions recognized the need to make forecasts on water supply.

Also it seems that the water is regulated to fit the NPP's needs. Others, e.g. tourists and boat lovers have to negotiate with the dam authority to let sufficient water flow into the Jihlava river. At times people were not even allowed to water their gardens. This issue would require an open discussion, both regarding the Environmental Impact Assessment (EIA) for the Plant Lifetime Extension (PLEX) – which the Czech Republic refuses – and, when it comes to the decision, for a new plant.

Beznau in Switzerland, an old plant, is an interesting example for a change of permit due to climate change. Because the water temperature increased in the Aare River, the authorities tried to update the permit and encountered resistance by the operator. This means that:

- Climate change is a legal reason to withdraw permits
- For (not only new) NPPs this should be introduced to avoid the NPP owners from refusing to lower output/shut-down plant

Climate change-related impacts needs to become a part of Environmental Impact Assessments for new power plants and obviously not only nuclear power plants. A severe waste of resources (funding, construction materials, time etc.) needs to be prevented already before construction starts. Also for operating nuclear power plants and the effort to prolong their operation (PLEX) the water and in particular water temperature can be problematic.

In the Czech Republic, the biggest single water consumer with 40 % is the energy generation. Instead of constructing another water-intensive nuclear power plant, alternative sources should be seriously considered.

Another important issue is whether further restrictions will be imposed on other water consumers e.g. at Jihlava River to supply the NPP and whether this will be accepted in the very long run when climate crisis will hit everyday life much harder. This should be discussed in a citizen participation procedure.

With the examples of France and Beznau, this working paper showed that the problem has been around for decades, though always ignored and denied. This is also the case for the Mochovce site in Slovakia: While the operator continues to claim that the water supply is sufficient for the two additional units (Mochovce 3 & 4) and does not give answers to the concerning questions, some experts believe that another water dam (Slatinka) is necessary to ensure sufficient water for the Mochovce NPP over the dry months of the year.

Industry has no answer to this beyond shutting down the NPP or running the NPP with reduced power outputs. Well aware that the NPP manufacturers are trying to make NPP able to work in load-following operation, nuclear reactors are designed for continuous operation; also for economic reasons on/off regimes will prove unfeasible.

Nuclear power plants are a poor choice for addressing energy challenges in a carbon-constrained world. NPPs are prone to insolvable economic and environmental problems. Additionally, they are connected to problems of reactor safety, waste storage, weapons proliferation, and vulnerability to attack.

"Nuclear energy for climate protection" is an old narrative that is as inaccurate today as it was in the 1970s. Climate change guarantees lower profits for nuclear power plants but requires expensive retrofitting measures. Adaption measures to climate change are delayed or even avoided, so the risk of ageing plants continues to increase. Energy and climate policy should therefore target a quick withdrawal from nuclear energy. Subsidies for life-time extensions are not recommended because they support the risky, uneconomical nuclear industry. This is even more true for new construction.

Gregory Jaczko, former chairman of the US Nuclear Regulatory Commission states 2019 the nuclear technology is no longer a viable method for dealing with climate change: 'It is dangerous, costly and unreliable, and abandoning it will not bring on a climate crisis.'

2 Introduction

Should nuclear energy receive support because it might contribute to a CO_2-free energy supply? On the contrary – nuclear energy is highly unfit to withstand the effects of climate change, thus leading to increased nuclear risk rather than being part of supply security.

Oda Becker, Eszter Mátyás and Patricia Lorenz have produced a working paper for the Joint Project – Nuclear Risk & Public Control, examining potential impacts of climate change phenomena on the risk of new and old NPP as well as on planned ones. The focus is on gradual climate changes and on extreme weather events, both possibly resulting in water shortages and droughts, temperature rises in rivers, flooding, sea level rises, super-storms, tsunamis, biofouling, lightning, damages by ice, landslides and wildfires etc.

The impacts of these climate change phenomena on nuclear safety and supply security are discussed in general, followed by example of some nuclear facilities in the Joint Project countries and other nuclear countries. These case studies are about Paks (heating of the Danube), Dukovany and Beznau.

The first chapter of the working paper evaluates the contribution of nuclear power to solve energy supply security. To answer this question, also the main risks associated with nuclear power plants have to be examined. Thus, the second chapter deals with the changes in risks due to operation of nuclear power plants in times of climate changes.

3 Energy Supply Security in times of climate change

3.1 Limited contribution of new nuclear power plants to energy supply security

The contribution of new nuclear power plants (NPP) to energy security is very limited for two main reasons: significant delays between planning and operation of NPPs and the comparatively high cost of energy production from NPPs. Furthermore, the power production is not CO_2-free.

3.1.1 Significant delays between planning and operation of NPPs

Expanding nuclear power is impractical as a short-term response to climate change. Planning and approvals can take a decade (particularly for nuclear 'newcomer' countries), and construction another decade. The time lag between planning and operation of a nuclear power plant includes the times to obtain a construction site, a construction permit, an operating permit, financing, and insurance; the time between construction permit approval and issue; and the construction time of the plant.

In March 2007, the United States Nuclear Regulatory Commission (NRC) approved the first request for a site permit in 30 years. This process took 3.5 years. The time to review and approve a construction permit is another 2 years and the time between the construction permit approval and issue is about 0.5 years. Thus, the minimum time for preconstruction approvals (and financing) in the United States (US) is 6 years. An estimated maximum time is 10 years. The time to construct a reactor depends significantly on regulatory requirements and costs. Although reactor construction times worldwide are often shorter than the 9-year median construction times in the US since 1970, they averaged 7.4 years worldwide in 2015. As such, a reasonable estimated range for construction time is 4 to 9 years, bringing the overall time between planning and operation of a nuclear power plant worldwide to 10 to 19 years. (JACOBSEN 2019)

An examination of some recent nuclear plant developments confirms that this range is not only reasonable, but an underestimate in at least one case. The Olkiluoto 3 reactor in Finland was proposed to the Finnish cabinet in December 2000 to be added to an existing nuclear power plant. Its latest estimated completion date is 2020, giving a planning-to-operation (PTO) time of 20 years. The plan of Hinkley Point C in UK was starting in 2008. Construction began only on December 11, 2019. It has an estimated completion year of 2025 to 2027, giving it a PTO time of 17 to 19 years. (JACOBSEN 2019)

The Vogtle 3 and 4 reactors in US were first proposed in August 2006 to be added to an existing site. The anticipated completion dates are November 2021 and November 2022, respectively, given them PTO times of 15 and 16 years, respectively. Their construction times will be 8.5 and 9 years, respectively.

Plans for the Haiyang 1 and 2 in China were starting in 2005. Construction started in 2009 and 2010, respectively. Haiyang 1 began commercial operation on October 22, 2018. Haiyang 2 began operation on January 9, 2019, giving them construction times of 9 years and PTO times of 13 and 14 years, respectively. The Taishan 1 and 2 reactors in China were bid in 2006. Construction began in 2008. Taishan 1 began commercial operation on December 13, 2018, Taishan 2 on September 7, 2019, giving them construction times of 10 and 11 years and PTO times of 12 and 13 years, respectively. (JACOBSEN 2019*)*

According to the World Nuclear Industry Status Report 2019, the mean construction time for the nine reactors started up in 2018 was 10.9 years. The report states: According to a recent assessment, new nuclear plants take 5–17 years longer to build than utility-scale solar or onshore wind power, so existing fossil-fueled plants emit far more CO_2 while awaiting substitution by the nuclear option. In 2018, non-hydro renewables outpaced the nuclear program in China, by a factor of two, in India by a factor of three. (WNISR 2019)

Additionally, it can take five years or more to repay the energy debt expended in the construction of the reactor. A University of Sydney report states: "The energy payback time of nuclear energy is around 6.5 years for light water reactors, and 7 years for heavy water reactors, ranging within 5.6–14.1 years, and 6.4–12.4 years, respectively." (FoE 2019)

Taking into account planning and approvals, construction, and the energy payback time, it would be a quarter of a century or more before nuclear power could even begin to reduce greenhouse emissions in a nuclear newcomer country. (FoE 2019)

Stabilizing the climate is urgent, nuclear power is slow. (WNISR 2019) It meets no technical or operational need that renewables cannot meet better, cheaper, and faster. The longer the time lag between the planning and operation of an energy facility, the more the air pollution and climate-relevant emissions from the electric power grid. (JACOBSEN 2019)

3.1.2 Comparatively high costs of NPPs

Two studies conclude that in the first decade of this century, nuclear energy was not competitive with coal or natural gas.[1]To better understand the phenomenon, at the German Institute for Economic Research (DIW Berlin) carried out a descriptive empirical analysis of all 674 nuclear reactors used to produce electricity that have been built since1951. (DIW 2019)

Investment activity in the sector was analyzed alongside the political and institutional conditions under which the reactors were built. Four development phases were identified; competitive private-economy investment did not play a role in any of them.

1) The early phase of commercial use of nuclear energy in the post-war era (1945 until the 1950s) was marked by the advent of the Cold War between the U.S. and its partner countries on the one side, and the Soviet Union along with its satellites on the other side. The further development of nuclear weapons and other military applications was the focus. Nuclear power plants were primarily designed to be "plutonium factories with appended electricity production."
2) The second phase began in the 1950s with the spread of nuclear reactors. It was also marked by the geopolitics of the Cold War. The failure of the U.S. effort to control the flow of military-grade fissile nuclear materials by setting up an international authority (Atoms for Peace, later the International Atomic Energy Agency, IAEA) triggered a race with the Soviet Union to spread nuclear power plant technology in the countries of the respective block. In a few countries, the U.S. and Germany for example, massive subsidies were applied to acquiring private-economy energy suppliers to develop and operate nuclear power plants. But competitive, on-state-guaranteed money was not invested anywhere. At the same time, states such as India, Pakistan, and Israel, which were not tied to any block, developed their own nuclear programs.
3) The 1980s and 1990s saw the transition from a bipolar to a global, multipolar nuclear arms race. As a result, at least ten countries gained possession of the technology and knowledge

[1] See Massachusetts Institute of Technology, "The Future of Nuclear Power," Cambridge, 2003) and University of Chicago, "The Economic Future of Nuclear Power," Chicago, 2004.

required for nuclear weapons. Alongside the U.S., the United Kingdom, France, and the Soviet Union, the list comprises China, India, Pakistan, North Korea, Israel, and South Africa. None of the ten uses nuclear energy commercially via private, non-state-supported investment.

4) The present phase has been shaped by the rhetoric of the “nuclear energy renaissance,” but in reality, it is characterized by the decline of its commercial use in Western market economies. Particularly of note in this context are the bankruptcy of major nuclear power plant construction companies Westinghouse (U.S.)and Framatome (formerly Areva, France)and the efforts of energy suppliers to shut down unprofitable nuclear power plants as quickly as possible or shift the financial responsibility to the state. (DIW 2019)

The market for electricity has become increasingly liberalized since the 1990s, and there is little incentive for private investment in nuclear power plants. The development of nuclear energy has been left to other non-market systems, in which countries insist on developing their nuclear capability for reasons of policy, military strategy, etc.—above all, China and Russia.

The low investment being made in NPPs in Europe and OECD countries today yields foreseeably ubiquitous losses in the two-digit billions. For example, the cost of the Olkiluoto-3 in Finland has risen from the original estimate of three billion euros (1995) to more than 11 billion euros. This is equal to around 7,200 euros per kW (as of 2018). In France, in the wake of extensive cost increases and regular reports of substandard reactor safety, the entire nuclear expansion program of energy giant EDF is being critically examined. Further, the corporation’s high level of debt – over40 billion euros – is likely to lead to complete nationalization if bankruptcy is to be avoided. One of the two investment projects in the U.S. was cancelled after its cost doubled (VC Summer, Virginia). At the second project (Vogtle, Georgia), costs increased from the original 14 billion U.S. dollars in 2013 to an estimated 29 billion U.S. dollars in 2017 (equal to around 9,400 US$ per kW). (DIW 2019)

From a purely private economy perspective, a recent study examined the profitability of a NPP under a variety of energy sector conditions that are key influencing factors. The analysis assumes an exemplary plant with an electrical capacity of 1000 MW. The results showed that in all cases, an investment would generate significant financial losses. The(weighted) average net present value was around minus4.8 billion euros. Even in the best case, the net present value was approximately minus 1.5 billion euros. Considering all assumptions regarding the uncertain parameters, nuclear energy is never profitable. Society will be asked to bear a very large proportion of these costs.

Note: Worldwide, there are no financial service organizations that offer insurance to them. A study by *Versicherungsforen Leipzig* has determined the potential premium for adequate accident insurance for nuclear power plant operators. It was between four and67 euros per kWh. To compare: the current end consumer price for electricity is approximately 0.30 euros per kWh. (DIW 2019)

Often it is told the ongoing technological developments of nuclear power (Generation IV and small modular reactors – SMRs) could make nuclear power more efficient in the future. However, both concepts have their roots in the early phase of nuclear power in the1950s.The majority of Generation IV reactors are “fast breeders” that facilitate the more efficient use of nuclear fuel but have never been economically profitable and technologically hardly controllable. Most of the larger fast breeders that were developed in the 1970s have already been decommissioned.[2]

[2]Further, these reactor types encourage the proliferation of highly enriched, weapons-grade uranium or plutonium in the context of reprocessing fuel. This provides direct access to the material for military purposes.

SMRs are based on developments in the 1950s, particularly the military's attempt to use nuclear power to drive submarines. But even more modern approaches toward developing SMRs are not suitable as replacements for larger plants. On the one hand, as in the case of all nuclear power plants, the question of safety remains unanswered. Since reactor standardization is a key parameter for manufacturing SMRs, the worldwide specifications would have to be harmonized, which on the other hand would be difficult.

The economic history and financial analyses carried out at DIW Berlin show that nuclear energy has always been unprofitable in the private economy and will remain so in the future. (DIW 2019)

3.1.3 Current construction cost of nuclear power plants

In a nuclear project appraisal, costs fall into three categories (THOMAS 2019):

- Crucial: Construction cost and cost of borrowing
- Quite important: Non-fuel operations and maintenance cost
- Minor importance: Fuel purchase, spent fuel disposal, decommissioning

Decommissioning likely to happen more than 100 years after plant start-up, unknown when spent fuel disposal will happen. In 'discounted cash flow' calculations, basically assume real/notional fund created, earning interest till funds required. A fund earning 3% real over 100 years will have grown 20-fold. So, if decommissioning a reactor costs €2bn, the fund need only have €100m when reactor starts up. (THOMAS 2019)

Cost of borrowing depends on several factors but crucially on how risky the project is to the lender. No bank will lend money to a nuclear project unless the risks fall on someone else, e.g., taxpayers through loan guarantees or electricity consumers by guarantees. Thus, loan guarantees and cost pass-through are huge subsidies not offered to other options like renewables. Overnight costs exclude interest charges during construction. Depending on the interest rate, these might be expected to add 50% to the overnight cost. Overnight cost is useful for analytical purposes, but consumers must pay the interest charges so overnight costs can hide the real cost. Furthermore, the construction delays dramatically increase interest costs. (THOMAS 2019)

The current new built projects show considerable cost increases:

EPR (AREVA)

EPR with two reactors completed in China, two reactors under construction in Finland, and France and two reactors just starting construction in UK (THOMAS 2019):

- In 2002, EPR in Olkiluoto (Finland)was approved with cost of €2.5bn. In 2005 the construction started with estimated cost already €3bn, the completion was expected in 2009.But in 2019, costs were €11.4bn and the completion expected later than 2020.
- In 2005, the EPR in Flamanville (France) was approved with cost of €3bn. In 2007, construction started with cost of €3.3bn, completion was expected in 2012. In 2019, costs were increased to €10.9bn, completion now expected between 2022-24.
- In 2008, for the two EPRs in Hinkley Point C (UK), the costs were expected to be £4bn. In 2010, completion was expected in 2017. In 2013, costs were increased to £14bn. In 2019, the construction started, and the completion was expected 2025-27, costs are estimated to be £21.5-22.5bn.
- 2016, Areva collapsed in large part due to Olkiluoto losses. Now owned by EDF and likely to be nationalized.

AP1000 (Westinghouse)

Four AP1000reactors completed in China, two reactors under construction in US and two reactors abandoned in US.

- In 2012, the cost for the two reactors in Summer (US) was $9.8bn. Construction started 2013 with expected completion 2017-18. Early 2017, completion was expected in 2020. Late 2017, project was abandoned, because costs were estimated up to $25bn.
- In 2008, estimated costs for the two reactors in Vogtle (US) were $14.2bn. Construction start was in 2013. In 2016, $8.3bn loan guarantees and in 2017, $3.7bn additional loan guarantees were given. 2019, construction cost was $23-27bn, completion late 2021/2022 respectively.
- In 2017, Westinghouse files for bankruptcy due to losses on Vogtle & Summer. Now owned by Canadian company but unlikely to pursue new orders.

APR1400(KEPCO)

Two APR1400reactors completed and four reactors under construction in South Korea, four reactors under construction in the UAE. The APR1400 is seen as a cheaper, easier to build option than EPR or AP1000 on basis of rapid construction in Korea and low bid for UAE. APR1400 design was approved by NRC in 2019, but there were no US customers. 2010, KEPCO bid $3600/kW for four reactors for UAE, 30% lower than the EPR. KEPCO acknowledges design for Korea & UAE lacks safety features required for Europe, notably a core-catcher and a reactor building able to withstand an aircraft impact.

- The APR1400 reactors Shin Kori 3, 4 were completed in 2016 and 2019 respectively in South Korea after 8-10 years construction.
- Shin Hanul1,2 are under construction for 7-9 years, Shin Kori 5,6 started construction in 2017/18.Delays due to discovery in 2012 of large-scale falsification of documents (thousands of parts) requiring affected components to be replaced & problems with pilot operated safety relief valves (POSRVs).
- The construction of the four reactors at Barakah (UAE) started 2012-15, expected completion was 2017-20. Delays initially claimed due to lack of operators, now clear also quality problems. POSRV & cracks in all containment buildings. Completion now expected later than2020.

Costs of NPPs have increased 90-500% from project agreement to completion. All European & US NPPs projects have been built on the basis of sovereign loan guarantees and/or promises of full cost recovery from consumers. Losses essentially bankrupted the world's largest reactor vendors, Areva & Westinghouse. Hinkley Power contracted on a 35-year contract at £92.5/MWh, latest UK off-shore wind prices, <£40/MWh (both 2012 money). (THOMAS 2019)

To conclude, between 1951 and 2017, none of the 674 nuclear reactors built was done so with private capital under competitive conditions. Large state subsidies were used in the cases where private capital flowed into financing the nuclear industry. Investing in a new NPP leads to average losses of around five billion euros. The lack of economic efficiency goes hand in hand with a high risk with regard to the proliferation of weapons-grade materials and the release of radioactivity, as shown by the accidents in Chernobyl (1986) and Fukushima (2011). For all these reasons, nuclear energy is not a relevant option for supplying economical, climate-friendly, and sustainable energy in the future. (DIW 2019)

3.1.4 Electricity from NPPs is not CO_2-free

A nuclear power plant is not a stand-alone system. The nuclear chain is comprised of three sections: the frontend processes, the production process itself and the backend processes. (STORM 2017)

- The front end of the nuclear chain comprises five processes (mining, milling, refining and conversion, enrichment, fuel fabrication) to produce nuclear fuel from uranium ore.
- The midsection encompasses the construction of the NPP plus operating, maintenance and refurbishment during its operational lifetime.
- The back end comprises the 12 processes needed to manage the radioactive waste, including dismantling of the radioactive parts of the power plant after final shutdown, and to isolate the radioactive waste permanently from the human environment.

Each process of the nuclear chain consumes thermal energy, provided by fossil fuels, and electricity: the direct energy input. In addition, all processes consume materials, the production of which also consumed thermal energy and electricity: the indirect energy input. By means of an energy analysis the direct and indirect energy inputs of the full nuclear system can be quantified. The figures of the specific CO_2 emission of the full nuclear energy system found by a detailed analysis are summarized in Table 1.

Table 1: Main components of the nuclear process chain specific emission g CO_2/kWh (STORM 2017)

	gCO2/kWh	
uranium recovery (mining + milling)[3]	8.4	
other front-end processes	6.2	
sum front end processes		14.6
construction (mean)	23.2 ± 11.6	
operation, maintenance & refurbishments	24.4	
sum mid section processes		47.6 ± 11.6
back end processes excluding decommissioning and dismantling and mine rehabilitation	12.1	
decommissioning & dismantling (mean)	34.8 ± 17.4	
mine rehabilitation (ore grade dependent)	7.6	
sum back end processes		54.5 ± 17.4
sum full nuclear energy system		**117 ± 29**

Because of the uncertainties in the full nuclear chain several studies calculate different values. According to Jacobsen (2019) for example the overall emissions from new nuclear are 78 to 178 g-CO2/kWh, which is in the same magnitude as the values mentioned before. For comparison, the comparable CO2 emission of energy production from wind (onshore) is 4.8-8.6 gCO_2/kWh.

3.2 Limited contribution of ageing nuclear power plants to energy supply security

The contribution of the ageing nuclear power plants to energy supply security is limited. This is mostly because of the ageing related outages. In addition, there are some climate change related outages.

[3] Assumed feedstock of the nuclear energy system is uranium ore at a grade of 0.05% U (0.5 g uranium per kg ore), this is about the present world average grade

3.2.1 Ageing effects related outages

Proponents of nuclear power say that the reactors' relative reliability and capacity make this a much clearer choice than other non-fossil-fuel sources of energy, such as wind and solar, which are sometimes brought offline by fluctuations in natural resource availability. Yet no one denies that older nuclear plants, with an aged infrastructure often surpassing expected lifetimes, are extremely inefficient and run a higher risk of disaster.

The following section give examples for comprehensive ageing effects related outages in 2018in three countries.

3.2.1.1 France

The average age of the 58 reactors is 34.9 years (end of 2019). In 2018, the French nuclear power plants provided 71.7 percent of the country's electricity. The annual load factor at69.6 percent was still poor in 2018 but improved since a record low of 55.6 percent in 2016. The lifetime load factor remains constant below 70 percent (69.3 percent).

In 2018, generation performance was affected by exceptional damages and large generation incidents (costing around 12.5 TWh), longer-than-expected outages (costing around 5 TWh) and environmental constraints (costing around 2 TWh). The outage extensions experienced in 2018 were caused in equal measure by maintenance and operational quality issues, technical failures and project management deficiencies. Performance losses related to unplanned outages rose from a rate of 3.26% in 2017 to 3.7% in 2018 because of several exceptional incidents.

Additionally, the finding of carbon segregations in the pressure vessel of new build reactor Flamanville 3 had raised concerns about the possibility that other components could have been fabricated below technical specifications due to poor quality processes at Creosote Forge. On 25 April 2016, AREVA informed ASN that "irregularities in the manufacturing checks", the quality-control procedures, were detected at about 400 pieces fabricated since 1969, about 50 of which would be installed in the French currently operating reactor fleet. The "irregularities" included "inconsistencies, modifications or omissions in the production files, concerning manufacturing parameters or test results". According to EDF, in total, it has detected 1,775 "anomalies" in parts that were integrated into 46 reactors. (WNISR 2019)

3.2.1.2 United Kingdom

The average age of the 15 reactors in the UK is 35.9 years (end of 2019). In 2018, the nuclear share in electricity production was 17.7% and the annual load factor 68.4 percent.

2018 was a remarkable year for the nuclear industry in the UK. One the key developments was the extent of the age- related cracking of the two Advanced Gas-cooled Reactors (AGR) at Hunterston, leading to their extended closure and potentially their retirement.

Managing ageing reactors is a constant problem for any technology design, and the AGRs are no exception. In recent years problems with the core's graphite moderator bricks have raised concerns. In particular, keyway root cracks, exceeding the number the U.K. regulator, the Office for Nuclear Regulation (ONR) previously deemed permissible, have been found at one of the Hunterston B reactors. This is of concern as it can lead to the degradation of the keying system, a vital component as it forms the channels within the reactor, which house the fuel, the control rods and the coolant (CO_2). Such cracking or distortion could affect the insertion of the control rods or the flow of the coolant. There are also issues of erosion of the graphite and a number of the AGRs are close to the erosion limit set by the ONR. With age, the graphite bricks also distort and may eventually compromise the operation of the safety control rods. These issues are likely to be the life-limiting factor for the AGRs, as it is not possible to replace the graphite bricks.

In March 2018, during a scheduled outage, the operator (EDF) discovered a higher number of keyway root cracks in the older of the two reactors than was predicted by its computer models in 2016. Then, EDF announced that Hunterston B-1's present shutdown would be extended for further investigation and revised modelling, with the intention of restarting the reactor before the end of 2018.In December 2018, EDF estimated that Hunterston B-1 and B-2would be restarted in March 2019 and April 2019, but this deadline passed and, as of June 2019, restarts were scheduled for later in July and October 2019.

Age-related problems have also been found at similar-age reactors at Dungeness B, with Unit 2 closed for what was supposed to be a 12-week outage in August 2018 and then Unit 1 for "common statutory outage work", with both expected to restart in April 2019. However, the outage has been extended, with restart dates for the units being September and October 2019. (WNISR 2019)

3.2.1.3 Belgium

The average age of the seven reactors in Belgium is 39.8 years. Due to continuous technical issues and extended outages, the average load factor of the Belgian fleet plunged to 48.6 percent in 2018. On average, the units were down half of the year and in October 2018 power prices reached record levels (€205/MWh).

In summer 2012, the operator identified an unprecedented number of hydrogen-induced crack indications in the reactor pressure vessels of Doel-3 and Tihange-2, with respectively over 8,000 and 2,000—which later increased to over 13,000 and over 3,000 respectively—previously undetected defects. In spite of widespread concerns, and although no failsafe explanation about the negative initial fracture-toughness test results was given, on 17 November 2015, the Federal Agency for Nuclear Control (FANC) authorized the restart of Doel-3 and Tihange-2.

The technical assessment of the safety implications of the flaw indications remains the subject of intense controversy. Several independent safety analysis reports are highly critical of the restart authorizations. In April 2018, the International Nuclear Risk Assessment Group (INRAG) stated on Tihange-2 that "the risk of failure of the reactor pressure vessel is not practically excluded" and requested that "the reactor must therefore be temporarily shut down".

Additionally, in October 2017, the operator Electrabel identified serious flaws in the concrete of a building adjacent to the reactor buildings of Doel-3. These bunkered buildings contain backup systems for the safety of the facilities and are supposed to withstand impact from outside like an airplane crash. Some of these "anomalies at the reinforcements of the reinforced concrete [were] present since the construction of the building".Doel-3 was originally expected to be off-line for scheduled maintenance for 45 days, however, the outage lasted 302 days. Similar problems, to varying degrees, have been identified at Tihange-2 and -3, as well as Doel-4. Tihange-3, which was shut down on 30 March 2018 for planned maintenance and refueling, suffered subsequent delays.

The cumulation of planned outages that were extended repeatedly, plus unexpected outages, led to an unprecedented annual record. In 2018, the seven Belgian nuclear reactors cumulated a total of 1,265 outage days, representing an average of six months (181 days) per reactor. All of the seven units were offline at some point, with cumulated outages reaching between 31 days (Tihange-1) and 276 days (Tihange-3) per reactor. (WNISR 2019)

3.2.2 Climate changes related outages

When thinking of possible climatic effects on the resilience of the nuclear power plants in the region, heat waves are particularly concerning due to their impact on the temperature of the reactor's cooling water.

A heat wave may affect the operations of NPPs in two main ways: it could reduce their efficiency to turn fuel into electricity and it could increase the number of shutdowns. In 2003, for example, a heat wave forced the shutdown of more than thirty nuclear power plants in Europe. A similar event took place in 2018 when numerous nuclear power plants all over the world, from France to South Korea, had to cease their operations due to abnormally high temperatures. These events resulted in substantial economic losses. (CAIRO 2019)

A heat wave has consequences on the operation of nuclear reactors: Reactors must be permanently cooled to ensure their safety. For this purpose, water is taken from a river or sea. A period of drought can lead to a decrease in the level of the watercourse and its flow. The operator must ensure at all times that they remain sufficient to cool the safety systems.

The flow of the watercourse also affects the dispersion of liquid effluents from nuclear reactors. Thus, for example the French nuclear authority ASN has set, for each plant, a minimum value of the flow of the river for which effluent discharges can be made. Below this flow (low-flow situation), effluent discharge operations are prohibited, and the operator must store its effluents.

The water taken from the watercourse or the sea to cool the reactor is, in general, discharged at a higher temperature, either directly or after cooling in cooling towers allowing a partial evacuation of heat in the reactor. In order to preserve the environment, especially the ecosystem, the heating of the watercourse due to the operation of the NPP as well as the temperature of the water downstream are framed by limit values. If these limit values are exceeded, the operator must reduce the reactor power or stop it.

During severe droughts, the rivers possess neither sufficient water volumes nor flow-rates to sufficiently dissipate the ever-growing heat build-up. Continuing operation would result in "cooking" the river biosystems locally. Regulations exist in France (and elsewhere) preventing this effect. NPPs are required to curtail operation or shut down completely when discharge water exceeds such a heat threshold. (KRAFT 2017)

For river-cooled reactors, the heating of the river water caused by the plant is normally less than 0.3 C downstream of the plant. Thermal discharge to a river causes a gradual mixing of the relatively warmer water over several miles, avoiding the creation of a "thermal wall" that could block fish migration. [4]

3.2.3 Examples for weather-related events affecting the energy supply of nuclear power

3.2.3.1 France

Summer of 2003: France, Germany, Spain and other European nations are hit with extraordinary heat wave and drought – ultimately killing over 30,000 people. France, Germany and Spain are confronted with the dilemma of allowing reactors to exceed design standards and thermal discharge regulations

[4] A thermal study of the Rhone showed that the effects of thermal discharges from nuclear power plants remained very weak and localized.

to maintain power for cooling – or shutting the reactors. Spain shuts theirs down; France and Germany allow some of theirs to exceed standards and thermal discharge regulations, while shutting others. In France local firefighters are actually called out to hose down overheating reactor containments (at Fessenheim).In the course of the summer the French nuclear reactors at Blayais on the Gironda River estuary are alone allowed to exceed thermal discharge limits 50 times.

In 2009, France faced a river water crisis that forced the shutdown of one-third of its entire nuclear power fleet. Due to serious drought conditions, maintenance issues, and a worker strike, 80% nuclear-reliant France had to import electricity from England to meet power demand. One report indicated that 20GW of France's total nuclear generating capacity of 63GW was out of service, exactly when needed the most. Fourteen of France's 19 nuclear generating stations are sited on rivers.

A 500 million Euro plan called "Grands Chauds" (great heat) was started following the 2003 and 2006 heat waves to prepare French plants for hotter temperatures. The plan included nuclear safety modifications including increasing the capacity of units to handle hotter temperatures, including through the addition of heat exchangers, air conditioning in certain plant areas, as well as reworking engines on some emergency diesels to make them more efficient, EDF said. (NW2019b)

In the EDF nuclear fleet, 11 sites out of 19 are equipped with air cooling towers, while three plant sites, Bugey, St.Alban/St.Maurice and Tricastin, receive direct water intake from the river for once-through cooling. Over the last ten years, while France has experienced several heat waves — for example in 2003, 2006 and 2018 — the annual impact on nuclear power generation has always been less than 0.5%, with an average impact of only 0.3%. However, in 2018, France saw an 0.7% loss of output. In summer 2018, EDF lost 2.7 TWh in nuclear output due to heat-related restrictions at four power reactors. (NW2019b)

Summer of 2019: The heat wave in the summer of 2019 led again to the closure or output reduction of several reactors, including the two Golfech units and the two Saint Alban units. Environmental constraints refer to operating restrictions for several nuclear plants because of lack of cooling water or excess water temperatures.

French nuclear availability fell to 36.3 GW the afternoon of July 24, 2019 as over 5 GW of heat-related restrictions took effect at reactors across southern France. Power demand, meanwhile, peaked at a new summer record of 59.7 GW as soaring temperatures boosted cooling demand. Both reactors at the Golfech plant in southwest France, shut the evening of July 23,2019 for environmental reasons. EDF also extended heat-related output restrictions to the Tricastin and Bugey nuclear plants on the Rhone river in southeastern France July 24.Forty of France 's 58 reactor units are river-cooled. (NW 2019a)

3.2.3.2 Switzerland

In Switzerland, the Beznau nuclear plant reduced its output by 50% on several days in July 2019 as the temperature of the Aare River, which supplies its cooling water, reached 24 °C. With the aim that the Aare temperature does not exceed 25 degrees at the power plant. The move is in compliance with an interim ruling of the Swiss Federal Office of Energy, issued in early July, requiring the plant to reduce its output when the temperature of the river reaches unusually high levels. Operator Axpo protests and argues that it has made substantial investments in the plant in reliance on the permanent permit. (AZ 2019)

4 Increased risks climate change poses to NPP operation

4.1 General risk connected to the operation of NPPs

“Nuclear energy for climate protection” is an old narrative that is as inaccurate today as it was in the 1970s. Describing nuclear energy as “clean” ignores the significant environmental risks and radioactive emissions it produces along the process chain and beyond.

Nuclear power plants are a poor choice for addressing energy challenges in a carbon-constrained world. NPPs are prone to insolvable infrastructural, economic, social, and environmental problems. As mentioned above they face immense capital costs, significant lifecycle greenhouse gas emissions. Additionally, irresolvable problems with reactor safety, waste storage, weapons proliferation, and vulnerability to attack. These issues will be discussed in the following chapter.

4.1.1 Risk of severe accidents

The main risk of nuclear power is the risk of severe accident. On March 11, 2011, an earthquake measuring 9.0 on the Richter scale, and the subsequent tsunami that knocked out backup power to a cooling system, caused the nuclear reactors at the **Fukushima 1 Dai-ichi plant** in Japan to shut down. Three reactors experienced a significant meltdown and fuel rods in the spent fuel pool of a fourth reactor also lost their cooling. Locally, tens of thousands of people were exposed to the radiation, and 170,000 to 200,000 people were evacuated from their homes.

Till 2019, six of all nuclear reactors operating in history have had a partial or significant core meltdown. To date, meltdowns at nuclear power plants have been either catastrophic (Chernobyl, Russia in 1986; three reactors at Fukushima Dai-ichi, Japan in 2011) or damaging (Three-Mile Island, Pennsylvania in 1979; Saint-Laurent France in 1980). (JACOBSEN 2019)

In 2015, scientists have compiled the most comprehensive list of nuclear accidents ever created and used it to calculate the likelihood of other accidents in future. Their conclusion is that the chances are 50:50 that a major nuclear disaster will occur somewhere in the world before 2050. There is a 50 per cent chance that a Chernobyl event (or larger) occurs in the next 27 years.

The metric they use in assessing each accident is its total cost in U.S. dollars (based on the dollar value in 2013). They define an accident as “an unintentional incident or event at a nuclear energy facility that led to either one death (or more) or at least $50,000 in property damage.” Each accident must have occurred during the generation, transmission, or distribution of nuclear energy. That includes accidents at mines, during transportation by truck or pipeline, or at an enrichment facility, a manufacturing plant, and so on.

They then calculated the cost of each accident based on all the economic losses it caused, such as the destruction of property, the cost of emergency response, environmental remediation, evacuation, fines, insurance claims, and so on. Whenever an accident resulted in the death of an individual, the team added $6 million to the cost, a figure also used by various US agencies in calculating the value of a life. The resulting list ranks 174 accidents between 1946 and 2014 and includes their date, location, the monetary cost in U.S. dollars.(MIT 2015)

4.1.2 Proliferation risk and nuclear terror

A specific risk of nuclear power related to energy and environmental security is weapons proliferation risk. The growth of nuclear energy has historically increased the ability of nations to obtain plutonium or enrich uranium to manufacture nuclear weapons. Peaceful nuclear cooperation and nuclear weapons are related in two key respects. First, all technology and materials related to a nuclear weapons program have legitimate civilian applications. Second, civilian nuclear cooperation builds-up a knowledge-base in nuclear matters.

The Intergovernmental Panel on Climate Change recognizes this fact. They conclude, with "*robust evidence and high agreement*" that nuclear weapons proliferation concern is a barrier and risk to the increasing development of nuclear energy.

The building of a nuclear reactor for energy in a country that does not currently have a reactor increases the risk of nuclear weapons development in that country. Specifically, it allows the country to import uranium for use in the nuclear energy facility. If the country so chooses, it can secretly enrich the uranium to create weapons grade uranium as well as harvest plutonium from uranium fuel rods used in a nuclear reactor, for nuclear weapons. This does not mean any or every country will do this, but historically some have, and the risk is high. If a weapon is used, it may kill 2 to 20 million people and burn down a megacity, releasing substantial emissions. (JACOBSEN 2019)

Additionally, there is the risk of an attack against a nuclear facility. Since September 11, 2001, the potential terror threat NPPs are exposed to, received considerable public attention. For obvious reasons, this attention is mainly focusing on the hazard of the deliberate crash of a large airliner. However, those threats are much more diverse and complex. There are numerous potential targets for terrorist attacks. However, what makes an attack on a NPP very "attractive" for a terrorist group is the global attention this would generate. In recent years, the rise of terrorist groups who have sufficient resources placed nuclear security high on the political agenda**.**

Nuclear power plants are designed with safety provisions such as thick concrete walls and diverse systems providing multiple backups in case of an emergency. These provide some protection against attacks. However, about 85% of the about 450 reactors around the world were built before the 9/11 attacks and were not designed to withstand potential acts of sabotage. Old NPPs have numerous known design flaws which make them vulnerable to attacks. At the same time, it is known that they lack sufficient measures to manage a severe accident.[5]

Furthermore, in old plants, unexpected multiple failures of structures or components cannot be excluded in case of a terror attack; in particular, common cause failures of safety relevant systems cause concern. Reactor cores of old reactors are surrounded by a relatively thin-walled **reactor building** (less than 1 m). This design does not reflect current standards in science and technology. A thickness of about 2 m is applied for new NPPs.

If the reactor building is destroyed by an attack, it has to be assumed that the reactor's cooling circuit will be damaged. Because of debris and fire, safety and control systems will also suffer major damage. (If the pipelines of the cooling system are damaged, it would be irrelevant if the emergency cooling system still functioned, since it would no longer be able to be effectively fed in.)

The **spent fuel pool** is another vulnerable component of NPPs with considerable radioactive inventory. If an attack causes a breach of the concrete walls of a spent fuel pool, the cooling water will pour out. In case sufficient refilling is not possible, the fuel will heat up due to the decay heat. Once the fuel reaches the temperatures of 900 °C, the zirconium cladding of the fuel starts to burn in air. The resulting spent fuel fire would release a significant fraction of the cesium-137 from the fuel into the atmosphere. A recent study calculates a fraction of 75% (10-90%) of the cesium inventory. (The possible release depends on the density of the stored fuel.) (BECKER 2017)

[5]Note: Also for new NPPs, severe accidents with very high radioactive releases cannot be excluded.

4.1.3 Risks connected to mining and radioactive waste

Other risks discussed related to nuclear power are the risk of lung cancer and land degradation due to uranium mining. Uranium mining causes lung cancer in large numbers of miners because uranium mines contain natural radon gas, some of whose decay products are carcinogenic. Several studies have found a link between high radon levels and cancer. A study of 4,000 uranium miners between 1950 and 2000 found that 405 (10 percent) died of lung cancer, a rate six times that expected based on smoking rates alone. 61 others died of mining related lung diseases, supporting the hypothesis that uranium mining is unhealthy. In fact, the combination of radon and cigarette smoking increases lung cancer risks above the normal risks associated with smoking. (JACOBSEN 2019)

Another risk associated with nuclear power is the risk of **radioactive waste**. (JACOBSEN 2019)

Proponents of nuclear power are fond of pointing out that one kilogram of uranium can produce 50,000 kWh of electricity, while one kilogram of coal can only produce three kWh of electricity. However, nuclear plants convert almost all their fuel to waste with little reduction in mass. In the open fuel cycle, fuel is burned in reactors and not reused, meaning that about 95% of it is wasted. In the so called "closed" fuel cycle, plutonium is extracted from spent fuel, recycled, and reprocessed, but 94% of the fuel is still wasted. High level nuclear waste will take at least 10,000 years before it will reach levels of radiation considered safe for human exposure. (SOVACOOL 2008)

4.2 Additional risks of climate change phenomena to NPPs

4.2.1 Introduction

The IAEA distinguish climate change related phenomena between Gradual Climate Changes (GCC) and Extreme Weather Events (EWE).

4.2.1.1 Gradual Climate Change (GCC)

Mean annual surface temperature

In the near term, the global mean surface temperature is *likely* to rise by 0.3–0.7°C in the period 2016–2035 relative to 1986–2005 (*medium* confidence). It is *very likely* that the increase in mean temperature in the next two decades will be more rapid over land areas than over the oceans. (IAEA 2019)

Even if the Paris Climate Convention is adhered to, temperature increases of well over +1.5 and +2°C must be expected on land. It is also known that maximum temperatures generally rise more strongly than mean values. If the Paris Climate Convention, which is binding under international law, is taken seriously, global mean temperatures must not rise above 1.5-2°C. However, if we compare the emission paths necessary to achieve these goals with the ones actually adopted, we must continue to assume that climate scenarios will be much more extreme. (INRAG 2020)

According to the World Meteorological Organization (WMO), the signs and impacts of climate change – such as sea level rise, ice loss and extreme weather – increased during 2015-2019, which is set to be the warmest five-year period on record. The WMO report on the Global Climate in 2015-2019, released to inform the United Nations Secretary-General's Climate Action Summit, says that the global average temperature has increased by 1.1°C since the pre-industrial period, and by 0.2°C compared to 2011-2015.(WMO 2019)

Precipitation

Over the next few decades, it is *very likely* that zonal mean precipitation will increase in high and some midlatitude regions. Near surface specific humidity is *very likely* to increase over the next few decades. It is *likely* that there will be increases in evaporation in many regions. In the long term, it is *virtually certain* that in a gradually warming world, global precipitation will increase. In the most modest climate change scenario, the rate of *likely* increase is projected in the range of 1–3%/°C with a sensitivity range between 0.5 and 4%/°C at the end of the twenty-first century. There is *high* confidence that the annual mean precipitation in wet regions will increase, while in dry regions it will decrease. (IAEA 2019)

Due to the higher temperatures caused by climate change, higher precipitation intensities may also occur: According to the Clausius-Clapeyron relationship, at least 7% higher maximum precipitation must be expected per degree of warming. However, practice shows that increases of 10% and more can occur in thunderstorms and heavy precipitation events. (INRAG 2020)

The rise in the zero-degree limit means that parts of precipitation that were temporarily stored as snow at lower temperatures in the mountains now fall as rain and are fed into the rivers much more quickly. Finally, it can be observed - possibly as a result of the ice retreat in the Arctic - that weather conditions last longer or can occur several times with short interruptions. This leads to the fact that even without extreme precipitation intensities, extreme amounts of precipitation can occur due to the long duration of the rainfall. These changes in precipitation behavior are already being observed today - they will become even more severe in the course of the next decades and increase the risk. (INRAG 2020)

Sea level rise

Driven by climate change, global mean sea level rose 11–16cm in the twentieth century. Even with sharp, immediate cuts to carbon emissions, it could rise another0.5m this century. Under higher emissions scenarios, twenty first century rise may approach or in the extremes exceed 2m in the case of early-onset Antarctic ice sheet instability. (KULP 2019)

Relative to 1986–2005, the rise in global mean sea level for 2081–2100 will *likely* reach up to 0.55 - 0.82 m for the different scenarios. These IPCC figures apply to the lowest limit of the expected rise. Other experts derive a possible non-linear rise in sea level of 1 m within the next 50 years from ice surface losses in Greenland, and a rise of another 1.4 m within the following decade, i.e. 2.4 m to about 2070. These are extreme values, but they are derived from observations, while the conservative IPCC data have been calculated from models known not to reflect melting processes sufficiently well. (INRAG 2020)

Over the five-year period May 2014 -2019, the rate of global mean sea-level rise has amounted to 5 mm per year, compared with 4 mm per year in the 2007-2016 ten-year period. This is substantially faster than the average rate since 1993 of 3.2 mm/year. The contribution of land ice melt from the world glaciers and the ice sheets has increased over time and now dominate the sea level budget, rather than thermal expansion.

The Greenland ice sheet has witnessed a considerable acceleration in ice loss since the turn of the millennium. For 2015-2018, the World Glacier Monitoring Service (WGMS) reference glaciers indicates an average specific mass change of −908 mm water equivalent per year, higher than in all other five-year periods since 1950. (WMO 2019)

4.2.1.2 *Extreme Weather Events (EWE)*

Some types of extreme weather events are happening more often or are becoming more intense because of global warming. Typically, events are considered extreme if they are unlike 90% or 95% of similar weather events that happened before in that same area.

Global warming can contribute to the intensity of heat waves by increasing the chances of very hot days and nights. Warming air also boosts evaporation, which can worsen drought. More drought creates dry fields and forests that are prone to catching fire, and increasing temperatures mean a longer wildfire season. Global warming also increases water vapor in the atmosphere, which can lead to more frequent heavy rain and snowstorms. A warmer and moister atmosphere over the oceans makes it likely that the strongest hurricanes will be more intense, produce more rainfall, and possibly be larger. (IAEA 2019)

More than 90 % of the natural disasters are related to weather. The dominant disasters are storms and flooding.

Temperature extremes

As global mean temperatures increase, there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales. Heatwaves will be more intense, occur more frequently, last longer and affect larger areas than in recent decades. Nonetheless, occasionally cold winter extremes will occur even in a warming world. (IAEA 2019)

Heatwaves and drought have led to human losses, intensification of forest fires and loss of harvest. Heatwaves, which were the deadliest meteorological hazard in the 2015-2019 period, affecting all continents and resulting in numerous new temperature records. (WMO 2019)

Precipitation extremes

It is *likely* that the frequency and intensity of heavy precipitation events will increase over land in the coming decades, mostly driven by increases in atmospheric water vapor content and partially influenced by changes in atmospheric circulation. Regional scale changes are greatly shaped by natural variability and are also influenced by trends in future aerosol emissions, volcanic activity and land use changes; therefore, the combined outcome of anthropogenic forcing at regional scales is more difficult to project. Extreme precipitation events will *very likely* become more intense and more frequent over most of the midlatitude land areas and over wet tropical regions. (IAEA 2019)

It is likely that total atmospheric water vapor has increased several percent per decade over many regions of the Northern Hemisphere (where 99 % of all NPPs are located). More intense and more frequent precipitation events increased flood, landslide, avalanche und mudslide damage, and also soil erosion.

Wind extremes

Confidence is *low* in wind trends in general and also in the relationship between past trends in observed mean wind speed and trends in extreme wind events. Several factors explain why confidence is also *low* in projections of changes in extreme winds, except the more extensively studied but highly complex issue of tropical cyclones. (IAEA 2019)

Sea level extremes

Driven primarily by an increase in mean sea level and by the drastically decreasing return periods of extreme events, a significant increase in the occurrence of future sea level extremes is projected by the end of the twenty-first century. This trend is *likely* to start in the coming decades. Here again, confidence in region specific projections of storminess and associated sea storm surges is *low*. (IAEA 2019)

4.2.1.3 Example: Rainstorms over Europe

In the following an example for a climate changed related weather situation in Europe is described:

From late May until mid-June 2016, a persistent large-scale weather pattern with thunderstorms produced intense precipitation which caused both local flash floods and widespread flooding in central Europe. The floods struck many places with no warning. Southern and central Germany were the first to be affected by the severe weather when violent thunderstorms and hail hit on 26 May 2016.

Almost simultaneously, storms in France and the Benelux countries caused floods: at first only smaller rivers were affected, but the Loire and Seine later burst their banks too. In the town of Nemours to the south of Paris, the River Loing rose to a record level. In Paris, the Louvre and the Musee d'Orsay had to be closed and works of art moved to higher storeys.

From 31 May to 1 June, further flash floods followed in Saxony, Bavaria, and in Austria. In Simbach in Lower Bavaria, the stream of the same name rose from 0.5 meters to around 5 meters within just a few hours, flooding around 5,000 households. Seven people lost their lives. The floods in central Europe stemmed from an unusual general weather pattern that persisted for an exceptionally long time, from 27 May to 9 June.

The intense storms in Germany broke a number of records. It was the largest area to have ever been hit by a continuous period of thunderstorms prone to torrential rain in the observation period since 1960. This record is due to the **exceptional persistence** of the weather pattern. We are now observing persistent weather patterns more and more frequently during the summer half-year in the northern hemisphere. Their long duration can result in extreme outcomes. The summer of 2016 demonstrated that a single weather pattern can trigger both localized intense precipitation with flash floods and large-scale precipitation with river floods. Following the events of 2016 in Europe, it should be clear that extreme amounts of precipitation within a very short time are possible almost anywhere. (MUNICH RE 2017)

4.2.2 The impact of climate change on NPPs

With our climate-impacted world now highly prone to fires, extreme storms and sea-level rise, nuclear energy is touted as a possible replacement for the burning of fossil fuels for energy – the leading cause of climate change. Nuclear power can demonstrably reduce carbon dioxide emissions. Yet scientific evidence and recent catastrophes call into question whether nuclear power could function safely in our warming world. Extreme weather events, fires, rising sea levels and warming water temperatures all increase the risk of nuclear accidents, while the lack of safe, long-term storage for radioactive waste remains a persistent danger. (HUTNER 2019)

The climate change affects nuclear energy production in several ways, including

(1) The efficiency of nuclear power plants decreases with increasing temperature.
(2) Some sites may lose safety, with sea-level rise being of particular importance.

(3) Extreme weather events threaten the safety of NPPs additionally.

Regarding 1) and 2) loss of efficiency of nuclear power plants as well as location issues are primarily associated with gradual climate changes (e.g. gradual warming), while safety issues are rather linked to extreme events. **However, gradual climate change and extreme events are linked – rising sea levels, for example, also lead to extreme water levels during storms. In the case of lifetime extensions for nuclear power plants, the expected climatic changes are significant.**

Heavy precipitation (rain or snow), high or particularly gusty winds, snowstorms, freezing rain, thunderstorms, lightning, hail with particularly large grains and tornadoes are also among the potential hazards. In areas with more winter precipitation, snowstorms and ice build-up can block cooling water inlets and outlets, especially when wind is blowing at the same time. A special safety problem is the so-called biofouling, i.e. the disturbance by plants or animals that can settle at the inlets and outlets of the cooling water under appropriate conditions. Higher seawater temperatures may therefore make it necessary to relocate the cooling water inlets to lower levels.

Extreme weather events and climate-related hazards may directly affect NPPs, but may also be relevant to safety through indirect effects in the surrounding area, because they limit accessibility (e.g. forest fires or floods), are associated with cascade problems (e.g. a dam burst upstream) or because they affect the power grid (e.g. disturbance by falling trees) with consequences for the availability of off-site energy. (INRAG 2020)

4.2.2.1 Gradual Climate Change (GCC)

The most significant impacts of gradual climate change (GCC) on nuclear power plants are the degradation of thermal efficiency and the volume and temperature of water in adjacent water bodies affecting cooling water availability.

Higher ambient mean temperatures reduce the thermal efficiency of all thermoelectric plants, including that of nuclear power plants. IPCC scenarios project global mean surface temperature increases between 0.3°C and 4.8°C by 2100; near term increases are expected to be in the range of 0.3–0.7°C in the period 2016–2035.

If global mean temperatures rise by 0.4°C in 20 years, consistent with IPCC scenarios, average nuclear generation would decline by 0.16–0.28% at low temperatures and 0.92% at high temperatures. Assuming a linear increase in temperature, a 90% capacity factor, a 5% discount rate and a constant €0.05/kWh value of generation, these estimates imply that a 1 GW(e) nuclear power plant would lose generation owing to reduced thermal efficiency valued at approximately €4–6 million net present value over the next 20 years at low temperatures and around €21 million net present value at high temperatures. If current nuclear generation is projected for20 years for all current nuclear plants, the global cost of rising temperature is on the order of €1–6 billion.[6]

Reduces water availability: Decreasing annual precipitation would lead to long term reductions in the water levels in rivers or lakes that provide cooling water for existing nuclear plants, and this reduction could pose serious problems. In areas where long term rainfall patterns will reduce water availability, NPPs must compete with many other vital uses of scarce water. In some circumstances, generation may need to be curtailed or even halted if water levels are too low. Alternative cooling

[6] using the assumptions as above, a linear increase in temperature and a constant projection of 2224 TWh of nuclear generation

options are available or increasingly considered to deal with water deficiency, ranging from reusing wastewater and recovering evaporated water to installing dry cooling.

Higher average wind speeds: Higher average wind speeds brought on by changing climate can have some impact on NPPs. For plants near the coast, more persistent wind and fog can, over time, carry additional salt spray to those plants. Salt deposited in this way on exposed cables and metal parts will lead to faster corrosion and, potentially, to short circuits if the deposits are not cleaned regularly. For plants in dry areas, higher average wind speeds might deposit more dust and dirt. Such dust can cause problems with mechanical devices, electronic circuit boards, and so on. For both salt and dust, increased maintenance, appropriate shielding, and seals are effective solutions.

Sea level rise: Although sea level rise has not yet affected nuclear plants, it threatens to be one of the most economically damaging climate change events. Any flooding can be problematic for a nuclear power plant, but sea level rise in combination with storms could lead to site inundation.

4.2.2.2 Extreme Weather Events (EWE)

Nuclear power plants are built to withstand EWEs on the basis of past experience. However, as climate changes, past events are becoming an increasingly inappropriate basis for the prediction of the severity of future events. Existing nuclear power plants may become vulnerable to EWEs, and the siting and design of future nuclear power plants need to account for a changing climate. Various types of EWE can affect critical safety systems and increase the risk to human health and the environment.

Generally speaking, many acute safety threats from EWEs can be minimized by shutting down nuclear reactors until an event has passed, but this strategy leads to increasing outages as climate change and EWEs become increasingly unfavorable. Moreover, a shutdown state during an EWE may not be the safe state. Adapting plants so that reactor shutdowns become less frequent would minimize outages as well as avoid costly plant related damages that would have occurred without plant adaptation.

Although the accident at the Fukushima Daiichi nuclear power plant was caused by a tsunami, which is unrelated to climate change, this tragic event underscores the vulnerability of NPPs to extreme flooding. In the aftermath of the Fukushima Daiichi accident, the nuclear power industry and its regulators reassessed nuclear plant safety against extreme natural hazards, including flooding, wind, ice storms and extreme temperatures. Several EWEs can damage critical components or disrupt their interconnections. Preventive and protective measures include implementing technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown). (IAEA 2019)

Most EWEs tend to exacerbate the impacts on nuclear power plants of gradual changes in the related climate attribute. The increasing frequency of extreme hot temperatures and low precipitation periods aggravates the impacts of already warmer conditions: reduced thermal and cooling efficiency, overheated buildings and water availability problems. Cooling of buildings, especially those housing key instrumentation and control equipment, is crucial for nuclear power plants.

Structures and building related systems, such as ventilation, must also withstand EWEs. Integrity of the containment structures is critical to ensure safety, as is integrity of structures protecting spent fuel and radioactive waste storage. Buildings that house diesel generators, control equipment, and so on, must also be able to withstand high winds, projectiles driven by high winds, floods and heavy loads due to rain or snow. Extreme pressure differentials accompanied by high winds, as well as smoke and ash, can impair ventilation systems, without which personnel would be unable to continue to operate in affected buildings.

Landslides, forest fires and wildfires are not EWEs, but they can be triggered by extreme weather. Climate change can intensify storms and rainfall patterns that lead to landslides. Climate change can also intensify drought, which creates the conditions for a wildfire. Such events can disrupt transmission lines connecting a nuclear plant with the grid system. Nearby landslides and fires can potentially inhibit nuclear plant personnel from entering or exiting the plant. Another indirect combined impact is smoke blown from wildfires to power plants, which may damage sensitive equipment and hinder the access of critical personnel, supply deliveries and emergency response workers.

Combination of Extreme Weather Events

For an assessment of the hazards, the possibility of two extreme events occurring at about the same time also has to be taken into account.

- Two extreme events can have the same cause (as in the case of a tropical cyclone which is accompanied by heavy rain, giving raise to floods).
- Furthermore, because of the increasing frequency of extreme events, it cannot be excluded that an NPP site will be hit by two independent events within a short time – the second event occurring while the damage from the first has not yet been repaired.

4.2.3 Vulnerabilities of Nuclear Power to Extreme Weather in the Past

Since 1980, the IAEA has maintained a database of events at nuclear plants, as reported by Member States, called the International Reporting System for Operating Experience (IRS). Certain Member States may report a particular type of event and others may not. Therefore, broad conclusions from analysis of the data must be made with caution. Nevertheless, the IRS is the best single source of information on weather related events at nuclear facilities worldwide over the last 30 years. As such, the IRS can provide insight into the most reported EWE vulnerabilities facing nuclear power plants, how those vulnerabilities may be changing over time, and how nuclear plants have been adapting.

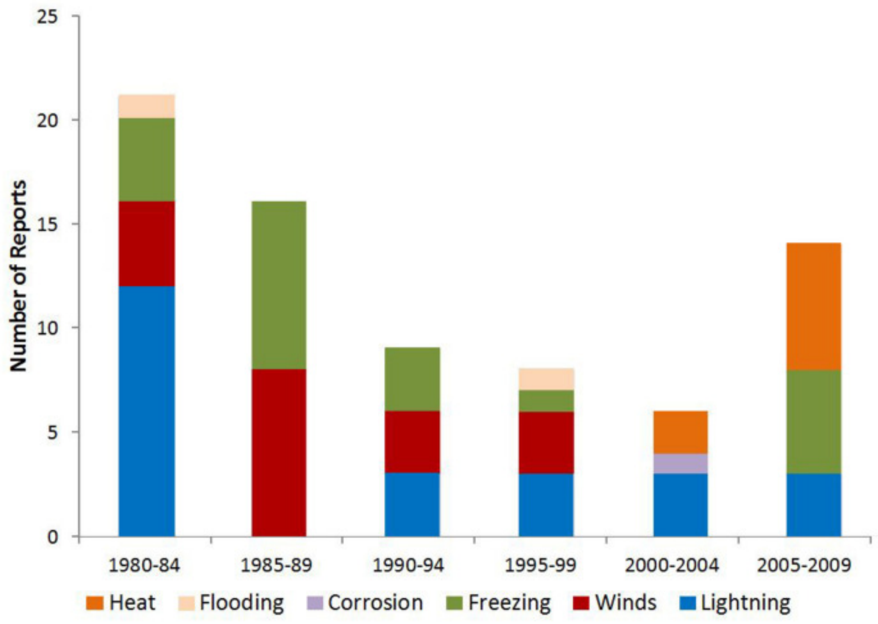

Figure 1: IRS for operating experience reports by weather events between 1980 and 2009 (IAEA 2019)

Of the 3665 reports in the IRS between 1980 and 2010, only a small fraction (74 cases, about 2%) involved weather or climate events. The overwhelming majority (88%) of the reported EWEs primarily affected only three major systems: water cooling systems (28%), electrical control systems (27%) and transmission grid systems (32%).

From 1980 to 1999, the events were remarkably balanced between lightning (33%), winds (33%) and freezing (30%), with a few flooding events (4%). The first half of the 2000s saw two new types of event: heat and corrosion. In the second half of the 2000s, over half of the reports were heat related. Five reports were related to freezing, the most since the second half of the 1980s.

Obviously, new heat related events suggest that climate change may already be having an impact on nuclear plants. The fact that freezing events had steadily declined from the latter half of the 1980s and suddenly rose again also suggests that these incidents may also be climate related. (INRAG 2019)

4.2.4 Flooding und storm

Flooding is another symptom of our warming world that could lead to nuclear disaster. Many nuclear plants are built on coastlines where seawater is easily used as a coolant. Sea-level rise, shoreline erosion, coastal storms and heat waves – all potentially catastrophic phenomena associated with climate change – are expected to get more frequent as the Earth continues to warm, threatening greater damage to coastal nuclear power plants. (HUTNER 2019)

Local high precipitation events can cause floods directly at the site of power plants and can damage buildings, equipment and downstream fuel cycle components, such as spent fuel storage (e.g. on-site dry casks). Floods upstream in the river basin may carry large amounts of debris and items accumulated on the riverbank, which would necessitate precautionary measures to be taken to protect cooling water intake. Adaptation options include hard measures — such as flood protection by dams, embankments, flood control reservoirs, ponds, channels, drainage improvement, and the rerouting and isolation of water pipes — and soft measures, such as the zoning and restricting of activities in flood prone areas.

Cooling needs of nuclear reactors dictate a location at the sea or at a large river. Flooding due to one or more natural causes such as runoff resulting from precipitation or snow melt, high tide, storm surge, seiche and wind waves that may affect the safety of the nuclear installation are possible. Information relating to upstream water control structures shall be analyzed to determine whether the nuclear installation would be able to withstand the effects resulting from the failure of one or more of the upstream structures. The expected main effects of flooding on NPP are as follows:

- The presence of water in many areas of the plant may be a common cause of failure for safety related systems, such as the emergency power supply systems or the electric switchyard, with the associated possibility of losing the external connection to the electrical power grid, the decay heat removal system and other vital systems.
- Considerable damage can also be caused to safety related structures, systems and components by the infiltration of water into internal areas of the plant, induced by high flood levels caused by the rise of the water table. Water pressure on walls and foundations may challenge their structural capacity. Deficiencies in the site drainage systems and in non-waterproof structures may also cause flooding of the site.
- The dynamic effect of the water can be damaging to the structure and the foundations of the plant as well as the many systems and components located outside the plant.

- A flood may transport ice floes in very cold weather or debris of all types which may physically damage structures, obstruct water intakes or damage the water drainage system.
- Flooding may also affect the communication and transport networks around the plant site. The effects may jeopardize the implementation of safety related measures by operators and the emergency planning by making escape routes impassable and isolating the plant site in a possible emergency, with consequent difficulties in communication and supply.
- Flooding can also contribute to the dispersion of radioactive material to the environment after an accident.

Waste is stored on the site before permanent disposal facilities are prepared, thus there is a risk that floods could disturb or dislodge radioactive waste and release radioactive material to the environment. As part of the probabilistic safety assessment (PSA), on-site storage should be carefully assessed with respect to the threat of flooding due to climate change, and appropriate measures, such as additional protective earthworks surrounding waste storage areas, should be implemented if flooding is deemed a risk. (IAEA 2019)

Extreme winds and storms (tornadoes and other rare events) can damage buildings, cooling towers and storage tanks. Upgrading construction standards can reduce the risk of structural damage. Storm surges, superimposed on sea level rise, increase the flood risk for all facilities in low lying coastal areas.

High winds and lightning have always been a threat to nuclear plants, and the threat will rise as these EWEs become more intense with climate change. Generally speaking, critical safety systems are well protected by reinforced structures designed to withstand extreme winds. Typically, the greatest threat from wind is its ability to disrupt power from the grid system, either off the site or via the plant's internal power connections. Without connection to the grid system for any length of time, a nuclear plant's reactors must sometimes be tripped to stop generating electricity.

Electronic control and monitoring systems consist of sensitive electronic equipment and miles of cables and sensors, all of which can be damaged by lightning strikes or corroded by moisture, dust, sand and salt. Climate change can increase the intensity of storms that result in lightning strikes as well as bolster the underlying causes of corrosion, which can lead to short circuiting.

Although the probability is low that multiple systems will fail simultaneously, the threat is there and needs to be considered. Lightning can short circuit or create false signals in instrumentation and can also short circuit on-site power connections, backup diesel connections and controls at nuclear power plant sites. Exposure would be reduced by ensuring that circuits are insulated and grounded, key circuits are buried underground and diesel generator controls are shielded.

The following table shows example for **possible impacts of precipitation and storm** (RSK 2013):

Prolonged periods of heavy rain, possibly in combination with strong winds	The power plant sites are all flat and open to the surrounding area so that the water can principally flow off during heavy rain. It should be checked whether in the case of an extreme heavy rain event, sufficient drainage for all plants is ensured, also taking into account the potential for clogging of drainage paths. As an additional aspect, the possibility of rainwater ingress during heavy rain combined with extreme storm, e.g. via vents or through the intake ports, and the potential consequences thereof for the supply air for the emergency diesel generators should be examined.

Strong wind, tornado (negative pressures)	For statements on the formation of negative pressures or resulting pressure gradients, the degree of potential negative pressures should be determined and a possible relevance be assessed.
Sand/dust storms (from dried agricultural land)	It should be examined to what extent sand/dust storms are to be postulated due to site-specific conditions of agricultural use and the soil conditions and whether in this case, adequate precautions are in place to maintain the operability of emergency diesel generators. Here, the possibilities of the entry of other airborne material (such as leaves) should also be taken into account.

4.2.4.1 Increasing threat of flooding

As shorelines creep inland and storms worsen, nuclear reactors around the world face new challenges. By the time Hinkley Point C is finished, possibly in 2028, the concrete seawall will be 12.5 meters high, 900 meters long, and durable enough, the UK regulator and French engineers say, to withstand the strongest storm surge, the greatest tsunami, and the highest sea-level rise.

The independent nuclear consultant Pete Roche, a former adviser to the UK government and Greenpeace, points out that the new seawall does not adequately take into account sea-level rise due to climate change. The wall is strong, but the plans were drawn up in 2012, before the increasing volume of melting of the Greenland ice cap was properly understood and when most experts thought there was no net melting in the Antarctic. Now estimates of sea level rise in the next 50 years have gone up from less than 0.3 to 1 m, well within the operating lifespan of Hinkley Point C. (HAKAI 2018)

At least 100 US, European, and Asian nuclear power plants built just a few meters above sea level could be threatened by serious flooding caused by accelerating sea-level rise and more frequent storm surges. Some efforts are underway to prepare for increased flooding risk in the future. But a number of scientific papers published in 2018 suggest that climate change will impact coastal nuclear plants earlier and harder than the industry, governments, or regulatory bodies have expected, and that the safety standards set by national nuclear regulators and the International Atomic Energy Agency (IAEA), are out of date and take insufficient account of the effects of climate change on nuclear power.

According to a map[7] prepared by the World Association of Nuclear Operators (WANO), around one in four of the world's 460 working commercial nuclear reactors are situated on coastlines. Many were built when climate change was barely considered a threat.

In the United States, four reactors have been identified by Stanford academics as vulnerable to storm surges and sea-level rise. David Lochbaum, a former nuclear engineer and director of the nuclear safety project at the Union of Concerned Scientists (UCS) says over 20 flooding incidents have been recorded at US nuclear plants since the early 1980s. The most likely cause of flooding is the increasing frequency of extreme events. There was no consideration of climate change when most US plants were built.

[7] https://www.carbonbrief.org/mapped-the-worlds-nuclear-power-plants

IAEA's current global safety standards were published in 2011. These state that operators should only "take into account" the 18- to 59-centimeter sea-level rise projected by 2100 in the Intergovernmental Panel on Climate Change (IPCC)'s fourth assessment report, published in 2007.

The IPCC report, published in 2013–14 has sea level rising 26 to 100 cm by 2100, depending on how far temperatures continue to rise and the speed at which the polar ice caps melt. A one-meter increase, combined with high tides and a storm surge, significantly increases the risk of coasts and NPPs being swamped.

According to the World Nuclear Association (WNA), most reactors will have been long decommissioned by the time any significant sea-level rise takes place. However, flooding already is becoming much more frequent along the US coastline. According to the US Environmental Protection Agency (EPA), nearly all of 27 regularly measured coastal sites have experienced a significant increase in flooding since the 1950s, with the rate accelerating in many locations along the East and Gulf Coasts where many reactors are situated. The most comprehensive research yet conducted also shows sea-level rises are accelerating as ice caps melt. Such is the speed of ice melt observed since 2007 that even the 2013 IPCC estimates of sea-level rise are thought to be outdated.

Sea-level rise was not considered when the first British NPPs were built in the 1960s. In the UK, analysis by the government's floods and coastal erosion team found in 2012 that 12 of the country's 19 nuclear plants would be at risk of erosion or coastal flooding by the 2080s without more protection. Those at Bradwell, Hinkley Point, Hartlepool, Sizewell, Dungeness, and Oldbury were considered "high risk."

On top of sea-level rise, the added impact of flooding from storm surges must be considered as well. Since 1970, the magnitude and frequency of extreme sea levels (ESLs), which can cause catastrophic flooding, have increased throughout the world. New satellite studies by the US government's National Oceanic and Atmospheric Administration (NOAA), NASA, and other leading scientific institutions all show mean sea level rising and magnifying the frequency and severity of ESLs.

And new research suggests that every 1 °C increase in global average temperatures could lead, via increased sea level and more severe storms, to a two to sevenfold increase in the risk of surges that are the magnitude of those caused by Hurricane Katrina, which struck New Orleans and other US southern coastal cities in 2005. (HAKAI 2018)

4.2.4.2 Flooding caused by Super Storms

There is a risk resulting from climatic changes, already in progress, combined with nuclear risk. The main cause is the thermal imbalance between the warm and cold air over the ocean, which is considerably amplified with global warming. To find a new equilibrium, that is, a mean temperature (and pressure), both areas tend to mix their air, a process that can unleash extremely fierce winds. This amplification will steadily increase as long as the polar caps keep melting, constantly bringing cold water onto the surface of the surrounding oceans where it acts as a floating lid.

Unsalted water is lighter, cooling the air above and preventing the warmth thus trapped in the depths to diffuse rather quickly into the atmosphere. The resulting winds may reach up to about 500 km/h. These super-storms will literally raise ocean levels by several meters when pushing the water in front of them. Giant waves up to 30 meters, twice the height of the one generated by the tsunami that hit the Fukushima Daiichi nuclear power plant, could then drive boulders weighing more than 2,300 tons to the up to 20-meter high shoreline.

Super-storms will indeed be more frequent than powerful earthquakes, and related giant waves, able to push 2300-ton boulders along the ocean floor, far more numerous and higher than the one that damaged the Fukushima power plant. (MOREU 2019)

4.2.5 Heat and cold waves

Of relevance for the safety of nuclear power plants can be particularly high or low temperatures, prolonged heat or cold episodes as well as dry phases, and particularly high or low humidity values. (INRAG 2020)

Extreme weather events are related to the extreme values of environmental variables. One of these variables is temperature and, when such extreme values persist across several days, a cold or heat wave takes place for low and high values of temperature, respectively. The World Meteorological Organization (WMO) proposes the following definition for a heat wave and cold wave respectively(ATMOSPHERE 2017):"*A marked unusual hot weather (Max, Min and daily average) over a region persisting at least two consecutive days during the hot period of the year based on local climatological conditions, with thermal conditions recorded above given thresholds*" and, in a similar way, it defines a cold wave.

During **heat waves** high temperatures affect the generation capacity of NPPs due to increased air and water temperature.

During droughts and heat waves, the loss of electricity production may exceed 2% per degree Celsius given that cooling systems of power plants are limited by physical laws, regulations and access to cold water. It has been reported that near to 40% of the NPPs in Europe have already experienced cooling problems because of high temperatures.

Temperature limits for discharging water could represent a loss of between 12% and 16% of the generation capacity of central and eastern US power plants by the middle of this century. In addition, operating costs may increase during heat waves given the need of more staff (requiring an increase of between 50% and 100%) and cascading failures leading to blackouts will become more likely. For example, a heat wave can make it impossible to generate electricity in a plant yet at the same time it may increase energy demand because of air conditioning.

Conversely, transmission and distribution systems lose efficiency at high temperatures because they limit the power of the transformers and lines and expand the resistance of electric transmission in networks, thereby increasing energy losses. The capacity of transformers decreases by 1% for each °C; in copper lines the temperature of the resistance increases by 0.4% for each °C. Hence, total network losses increase 1% for every 3 °C. Moreover, heat waves increase cooling demands, thereby boosting electricity consumption to its highest value and testing the ability of the system to meet this demand. In this sense, demand could increase by as much as 21% on particularly hot days by the end of the century.

Heatwaves in the 2000s led to low water levels and/or high water temperatures that forced nuclear plants in Europe to curtail output, and in some cases to shut down altogether, for an extended period. As mentioned above, in the summer of 2003, Europe experienced a severe heatwave that led to power reductions and outages because ambient water temperatures in many places were too high for power plants to discharge heated water from cooling systems. France lost 5.3 TWh from 17 nuclear plants operating at reduced capacity as a direct result of the heatwave. The state-owned utility, ÉDF, estimated that the heatwave cost the company €300 million; the price for electricity at the peak of the heatwave was €1000/MWh, whereas as typical summer peak prices are €95/MWh.

Wildfires are strongly influenced by weather and climate phenomena. Drought substantially increases the risk of wildfire in most forest regions, with a particularly strong influence on long-lived fires. There were a massive forest fires in Canada and Sweden in 2018. (WMO 2019)

As a secondary impact, heat can foster the rapid growth of **biological material**, which can clog cooling water intake, leading to reduced generation or shutdown. Indirect biological impacts are simple to manage by increasing the maintenance of screens to ensure that biological matter does not clog water intake systems.

The effects of **cold waves** on the energy sector include breakdowns in power plants. They could also cause failures in airlines and towers, since ice and snow may accumulate in the insulation under freezing conditions, bridge them and cause a flashover.

A cold wave in France in January 2010 resulted in a peak in demand for energy; every °C reduction in winter temperatures represented an increase of about 100 GWh in consumption per day. A cold wave affected Spain in January 2017. Because of it, Spain faced a rush in the prices of electricity because of the combination of the meteorological conditions and other market constraints such as the need to supply electricity to France because of several stops for nuclear plants maintenance and an increasing price of fossil fuels. Electricity prices peaked on 25 January 2017 with a mean price of 112.8 e/MWh, the highest ever recorded in Spain. (ATMOSPHERE 2017)

The following table shows possible safety impacts of **long-lasting droughts or of low temperatures** and issues should be clarified in safety analysis. (RSK 2013)

Water level extremely low for prolonged periods of time	It should be shown that in case of a prolonged drought, a loss of water supply via the receiving water is either not to be postulated or that under such conditions the alternate heat sink cannot be affected in addition to the primary heat sink at the same time.
External fires	It should be examined whether, particularly during strong winds, external fire can result in effects on installations of the plant which may lead to a loss of vital safety functions.
Freezing rain / ice storm / snow storm (direct effects on the plant)	For plants with emergency cooling system cooled via cells, clarification is needed as to whether these coolers can freeze. The grids and slats in the building openings for ventilation or supply air for the emergency diesel generators could freeze or be covered up by wind-blown snow. In this context, not particularly low temperatures but other unfavorable boundary conditions (such as rain or high humidity at temperatures just below freezing) are of significance. It should be shown for both cases that this is either not to be postulated or that there are sufficiently effective and robust precautions in place for prevention (e.g. heating), removal (e.g. by administrative regulations) or for the management of the related effects.
Ice floes (on the receiving water)	It should be shown that the formation of ice barriers at the site is either not to be postulated or that there are sufficiently effective and robust precautions in place for prevention, removal or for the management of the related effects.

Air temperature extremely low, also for longer periods of time	Operating experience shows that, e.g., pipes may freeze. Appropriate measures are to be provided by which the vital safety functions will also be maintained under these conditions.
Ambient or receiving water temperature extremely low for prolonged periods of time and receiving water level extremely low for prolonged periods of time	The combination of these conditions may be relevant. It should be examined whether under such conditions not only the primary heat sink but also the alternate heat sink may be affected at the same time.
Formation of slush ice/floating ice	At some sites, sudden drops in temperature led to the formation of slush ice/floating ice which may affect the intake of cooling water. It should be examined whether under such conditions not only the primary heat sink but also the alternate heat sink may be affected at the same time.

4.2.6 Vulnerability of Nuclear Power Plants in the Case of Grid Failure

Extreme Weather Events can cause a failure of the electric power supply. Nuclear power plants generate electric power and supply it to the offsite grid. On the other hand, the plants themselves are dependent on a continuous electric power supply to operate, particularly for the instrumentation and safety systems, even when they are shut down. A typical nuclear power plant is connected to the electric grid through three or more transmission lines.

Heavy storms can lead to multiple damage of the transmission lines, and hence to loss of off-site power. Also, there can be grid failures even if transmission lines in the vicinity of the NPP remain intact. Should the power lines to the NPP be cut-off or a regional electrical grid collapse occur, onsite emergency generators are designed to automatically start. Every NPP has emergency power supplies, which are often diesel-driven. These generators provide power to special electrical safety distribution panels. If the emergency diesel generators (EDG) fail, the situation at the plant becomes critical (“station blackout”). A natural disaster that disables the incoming power lines to a nuclear power station coupled with the failure of on-site emergency generators can result in severe accident.

Apart from the diesel generators, there are also batteries that supply direct current in case of an emergency; however, the batteries cannot provide electricity for large components such as pumps and have only very limited capacity. Without electricity the operator loses instrumentation and control power leading to an inability to cool the reactor core. Counter measures (accident management) are practically impossible. If the blackout lasts for a long time, not only the reactor, but also the fuel in the spent fuel pool can overheat, contributing to radioactive releases.

After the Fukushima accident, measures to cope with Station Blackout situations are improved. However, these measures are mostly the use of mobile systems, which would be difficult to use in an accident situation and need actions by the staff.

4.2.7 Examples for weather related events as threats for the safety of NPPs

The potential threat climate change constitutes for nuclear power plants can be illustrated by looking at events that have already taken place at NPPs. Such events are getting more frequent with the beginning climate change and must be regarded as precursors of worse incidents and accidents yet to come.

Examples of Storm Events

- U.S., 1992: In August 1992, Hurricane Andrew passed directly over Turkey Point NPP (Florida), with a sustained wind speed of 230-280 km/h. There are two nuclear reactors at the site. The plant lost all offsite power during the storm and the following five days. All offsite communications were lost for four hours during the storm and access to the site was blocked by debris and fallen trees. The fire protection system was also destroyed. The NPP is one of the few US reactors with important electrical power cables installed on the exterior of the reactor containment buildings. These cable trays and conduits were coated with a fire-resistant material. The hurricane force winds stripped much of the fire resistant coating off these exterior applications, exposing them to any subsequent fire. This was very significant because the Turkey Point site includes two fossil-fueled units. The fuel oil storage tank of one unit was ruptured by a wind-generated missile spilling over a large amount of combustible fuel oil onto the site. Wind gusts of 282 km per hour and a 4.9-meter surge did only limited damage, but if the sea levels had been as high as are now projected, it could have led to a major disaster. Hurricane Andrew was historic because this is the first time that a hurricane significantly affected a nuclear power plant. (HIRSCH 2005)
- Sweden, 2005: In January 2005, four reactor units in Sweden were forced off-line by a storm meteorologists characterized as the worst in almost 40 years. Hurricane-force winds, torrential rain and high waves battered the entire Baltic. Western and southern Sweden, as well as eastern Finland, were particularly hard-hit. It was the first time Swedish NPPs had been forced to shut down because of the weather. (HIRSCH 2005)
- U.S., 2016: Hurricane Matthew tracked up the east coast of Florida and past the Carolinas after devastating Haiti, the Dominican Republic, Cuba and the Bahamas. Hurricane warnings prompted the operator to declare an unusual event for St. Lucie Nuclear Plant, which was close to the storm’s path. Plant staff conducted severe weather procedures at St. Lucie and at Turkey Point Power Plant. So did Brunswick and Shearon Harris plants and H.B. Robinson. Robinson operators safely shut down the plant because of a loss of off-site power. Harris also experienced loss of off-site power. (NEI 2018)

Examples of Flooding

- U.S., 1993: In July 1993, the operator of the Cooper NPP on the Missouri River, Nebraska, was forced to shut down the reactor as dykes and levees collapsed around the site closing many emergency escape routes in the region. Below grade rooms in the reactor and turbine buildings had extensive in-leakage with rising water levels. For example, water levels rising inside the reactor building impinged on electrical cables and equipment, for example in the reactor core isolation cooling (RCIC) pump room. The RCIC system is critical to plant safety in the event of loss of offsite power. (HIRSCH 2004)
- France, 1999: The Blayais site consists of four 900 MWe PWRs. Blayais-1, was put into commercial operation in 1981. During the night of 27-28 December 1999, these exceptionally bad weather conditions combined with inadequate protection measures against external flooding caused by swell, resulted in the flooding of rooms of the power plant nuclear islands and safety related systems. The severe weather also led to disturbances on the electrical network: the 225 kV auxiliary electrical power supply of all four units was lost for about 24 hours and the 400 kV main electrical power supply of Units 2 and 4 was also lost for several hours. A flood caused by the confluence of the rising tide with exceptionally strong winds

resulted in the partial submergence of the Blayais site. The flood started two hours before the tidal peak. The winds pushed the water over the protective dyke.
The water infiltrated into the duct cover slabs located in the North part of the nuclear power plant, flooding the sub-levels of the administrative buildings and common auxiliaries building. Then, the water propagated into the rooms of Units 1 and 2 through doors and openings, reaching the sub-levels of the electrical buildings, the connection galleries of the water pumping station, the sub-levels of the peripheral and fuel buildings.
As a result of this flooding, Units 1 and 2 were brought to shutdown state with the steam generators used for cooling the primary coolant and ready for connection to the reactor heat removal (RHR) system. Meanwhile, Unit 4 was shut down and then brought to hot shutdown state (Unit 3 was already shut down for maintenance).It has to be noted that, during the first hours of the incident, the arrival of the additional teams from outside the nuclear power plant was impossible owing to the damage resulting from the storm (flooding of the access routes, many tree falls…).
Lessons Learned: Severe weather conditions caused a flooding of the reactor building basement and thus the simultaneous failure of major safety systems. Due to the availability of electrical power (either from the grid or from EDGs) the plants could be shut down and cooled via operational systems. Nevertheless, the event showed that events affecting more than one unit on a site could result in additional difficulties as some auxiliary systems are common to all units on the site. It has revealed also some weaknesses in the site protection against external flooding.
The French standard safety rule contains two criteria for flood protection: (1) placing the platform that supports safety-relevant equipment at a level at least as high as the maximum water level; and (2) blocking any possible routes through which external waters could reach reactor safety equipment located below the level of the site platform. At Blayais, both criteria were not met: the concrete platform was 1.5 meter too low; and the resistance of the fire doors in the tunnels to the underground safety equipment was miscalculated: the waters surged into the tunnels and simply broke through the doors. Before the incident, EDF declared that the underground tunnels were perfectly safe. Before the floods, EDF had been planning to raise the dike around Blayais by 50 cm, to 5.70 m, as required by the 1998 safety analysis report. This work had been delayed. Furthermore, the waves on December 27 rose to more than a meter above the dike level of 5.20 m to 6.20 m. (HIRSCG 2004, NEA 2014)

- Ukraine, 2000: in summer 2000, reactor 3 at the Chernobyl NPP was shut down due to flooding caused by a strong storm. Workers had to pump water out of the reactor building. (HIRSCH 2005)
- France, 2003: EDF shut two PWRs at Cruas in December 2003 in response to rainfall along the lower Rhone River, prompting French nuclear safety authority to activate its emergency response center for only the second time up to this date. Filters on heat exchangers between the component cooling system and the essential service water system at Cruas-3 and -4 were clogged, hindering operation of the residual heat removal system. At the nearby Tricastin site, clogging of filters on the conventional site caused two more 900-MW PWRs, Tricastin-3 and -4, to scram. (HIRSCH 2005)
- UK, 2013: The operators of the Dungeness NPP were forced to shut down a reactor in 2013 because of a Fukushima-style flood scare. Operator EDF was ordered to shut down the reactor at Dungeness B while it corrected botched work to sea defense fortifications. An EDF internal report found the shingle bank sea defenses at Dungeness were “not as robust as previously thought” and could easily be overwhelmed. In December 2012, researchers reported that the existing sea defenses actually could be outflanked, which could lead to

catastrophic flooding of the reactors. EDF informed the Office of Nuclear Regulation (ONR). The ONR allowed energy generation to continue but amended its license to instruct EDF to immediately shut down the reactor should a “severe flood warning” for the area be issued. (NEI 208)

- U.S.,2015: Heavy rains generated record-setting flooding from Illinois to the Gulf Coast for more than two weeks. Nuclear plants in the region included Fort Calhoun and Cooper nuclear stations, Callaway, Arkansas Nuclear One, Grand Gulf, River Bend and Waterford. (NEI 2018)

Other Events

- *France, 2009:* During the night of 1 December 2009, a massive amount of vegetable matter (around 50 m^3 compared with a monthly average of 5 m^3) blocked the water intake of the common pumping station of Cruas NPP units 3 and 4, by clogging the pre-filtration trash racks. The total loss of heat sink of unit 4 lasted 10 hours. (NEA 2014)
- USA, 2014: Polar Vortex 1 brought record-setting cold temperatures and severe winter weather. Two weather-related shutdowns were confirmed for the entire fleet during the vortex: Beaver Valley 1 in Pennsylvania shut because of a transformer failure related to the severe low temperatures, and Fort Calhoun in Nebraska was temporarily shut down when ice impaired the operation of one of six river water intake gates. (NEI 2018)

4.2.8 Possible Countermeasures

Nuclear power plant structures, systems, and components (SSCs) important to safety are to be designed to withstand the external effects of natural phenomena such as tornadoes, hurricanes, or floods without loss of capability to perform their safety functions. Extreme values for wind, precipitation, snow, temperature and storm surges, based on empirical data from the weather statistics, are used for calculating the design parameters and estimating the impact load from severe weather conditions.

The apparent increase of frequency and intensity of extreme weather conditions in the past few years has resulted partially in a re-assessment of potential consequences of such effects and heightening of the standards for NPP design. For example, regarding flooding of nuclear power plants in Germany, the plants now have to be designed against an event with a probability of 1:10,000 per year, while it was 1:1,000 years before.

The estimation of probabilities for extreme events resulting from climate change, however, is extremely difficult due to fact that there is no sufficient database for such estimates. Furthermore, because the situation is constantly evolving, any data that can be acquired may be outdated by the time their evaluation is concluded. The time lag is still more drastic for the drafting of new rules and regulations by the authorities, and their implementation by the NPP operators. It seems hardly possible to win this race against time – particularly in the face of economic pressure that might lead to the result that only low-cost measures are realized.

While it is undisputed that extreme weather events (EWE) will become more frequent with climate change, it is difficult to quantify these changes. NPPs are designed to withstand very rare events. The probabilities of occurrence for licenses are usually derived from past data series using statistical methods. In a phase of climate change, however, these data series are no longer relevant, and the derivation procedures are no longer valid. It is a matter of forecasting the frequency of very rare events at certain locations, which must be derived from model calculations. Models, however, reflect the mean ratios much more reliably than extremes. Apart from a few special cases, science is overwhelmed with precise statements on the probability of occurrence of rare events. In flood protection and the construction industry, which would need similar statements, safety factors are sometimes added whose scientific validation is questionable. In the case of nuclear energy, this route is not recommended because the risk is too great in the case of under-dimensioning. (INRAG 2020)

The inadequate protection against floods at the Blayais site illustrates the problem of delayed backfitting (however, in this case, even the backfit would not have prevented flooding).In spite of the fact that the hazards of climate change are becoming more and more obvious, safety reassessments and improvements generally are only implemented – if at all – after an event occurred. This practice is aggravated by the fact that an event in one NPP does not necessarily lead to backfits in another plant.

Apart from improving design, advance warning in case of extreme events can contribute to safety. For example, the U.S. NRC is now observing the development of storms. About 12 hours before expected hurricane-force winds, NRC will enter one of its response modes and begin receiving continuous status updates from all of the nuclear facilities in the hurricane's path.

4.2.8.1 Basic adaptation options

The IRS database reveals that for most plants built to a high margin of safety with respect to external events, increased maintenance, new procedures and minor physical changes are sufficient to adapt to many climate threats. For example, stopping plant materials from clogging the water intake can be as simple as more frequent inspection and cleaning by maintenance crews. Other nuclear plants may need minor alterations in some water intake systems. For instance, ice blockage of water intake can be avoided by diverting some hot water discharged from the cooling system back to the area around the intake. Frozen pipes can be prevented by adding heat tracing. Lightning damage can be prevented by maintaining proper grounding and burying certain outside cables.

The marginal costs of adapting to these types of EWE do not appear to be significant when compared with the costs of plant outages. Other adaptation measures can be costlier, such as raising the height of dykes surrounding a plant to protect against storm surges. Adapting water cooling to lower water levels and hotter temperatures may be very costly.

4.2.8.2 Adaptation to heat and drought and implications for cooling

The most common nuclear reactor is a pressurized water reactor (PWR), which has three circuits. The first circuit is where heat is produced in the reactor. This heat is then transferred to a secondary circuit through a steam generator; this steam drives the turbines to produce electricity. The third circuit is then used to release to the environment (i.e., heat sink) the residual heat from the condensed steam. The first and secondary circuits, or loops, are closed off from one another.

Surface water, in general, has been used for cooling NPPs, especially for the once- through cooling system. Once-through cooling means water is taken from the sea, or river or lake, and passes through a condenser. In 2005, the U.S. Environmental Protection Agency (EPA) began taking action to abolish once-through cooling. Other countries have also sought to take similar measures. The reason for this is that once-through cooling can have an environmental impact on biota such as fish; as a consequence, some NPPs have adopted a different form of cooling, such as using cooling towers. Cooling towers can have a variety of different designs. We have wet cooling towers, naturally driven cooling towers, forced cooling towers, dry cooling towers, hybrid cooling towers. (NEI 2019)

NPPs withdraw large volumes of water. NPPs typically use wet cooling systems, which are either once through or recirculating. Once through systems withdraw a large volume of water and then discharge the warmed water back to the source. Even though withdrawal rates are high, water consumption is only about 15% of the diverted water. However, the sheer volume of water withdrawn can be disruptive when low water levels are brought on by heat and drought. In addition, once through systems discharge warmer water than recirculating systems, which can lead to violations of water temperature regulations.

More recently built nuclear plants near rivers and lakes typically use recirculating systems with large natural or mechanical draft cooling towers, cooling ponds, cooling lakes or cooling canals. Recirculating systems withdraw much less water (about 96.5% less) but actually consume over4.5 times more than once through systems because they employ evaporation as a means to facilitate cooling. In places where the least consumption of water is a critical priority, dry cooling may be the best option. Dry cooling consumes only 5% of the water compared with wet recirculating cooling.

A study by the Electric Power Research Institute (EPRI) estimated the costs of replacing once through cooling with wet recirculating retrofits at thermal plants in the US. The study found that the average cost calculated at net present value for a nuclear plant (average size 1538 MW) would be US $1.9 billion or US $1239/kW, including capital costs, extended outage revenue losses, and heat rate and energy penalties.[8]

The need for larger cooling towers translates into much higher construction costs. The cost of building dry cooling for a new power plant is estimated at3–4 times the cost of a wet recirculating system and 4–5.5 times the cost of a once through wet system. If dry cooling retrofits are also 3–4 times the cost of wet recirculating retrofits, then, on the basis of the EPRI cost study, the cost for dry retrofits would be on the order of US $3600–4800/kW. Dry cooling retrofits would approach the(theoretical) cost of building an entirely new nuclear plant.

An owner of an existing plant or a prospective owner of a new plant must carefully weigh the added costs of dry cooling against the expected lost revenue from future reduced output and outages stemming from heat and drought that accompany wet systems. With much higher construction costs than wet cooling, dry cooling is an expensive option for new nuclear plants and is almost certainly not economically feasible as a retrofit for most existing plants. For dry cooling to be economically viable at a prospective new site, water resources need be severely limited and other generation options relatively expensive.

4.2.8.3 Cost of flood protection

At the Dungeness NPP, a flood defense wall between 1.6m and 2m high has been constructed all the way around the plant at a cost of 2.5 Million Euro. It is part of a 5.6 Million Euro investment in flood protection including work inside the station, such as sealing trenches, installing dam boards and raising equipment height. (BBC 2014)

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[8] Note: Recirculating cooling systems may reduce forced outages and related costs for existing once through plants that discharge water into bodies that may reach thermal limits with a changing climate. These potential cost reductions are not considered in the EPRI study.

4.2.8.4 Examples for adaption measures

The next table summarizes the most important impacts of climate change (gradual climate change (GCC) and extreme weather events (EWE)) on nuclear power plants energy, together with the related adaptation options.

Table 2: impacts of climate change on nuclear energy and related adaptation options (IAEA 2019)

Impact	Potential vulnerabilities	Examples of adaptation options
Higher mean temperatures	Decreasing thermal efficiency Decreasing cooling efficiency	Select sites in cooler local climates when possible Design different cooling systems
Lower mean precipitation	Less and warmer cooling water, leading to potential reductions in output or even short-term shutdown	Reuse wastewater, recover evaporated water in recirculating systems Improve wet cooling; install dry cooling
Increased windiness near coasts and dry areas	Salt sprays from sea leading to long term corrosion and short circuit of exposed electrical equipment; dust and sand carried by wind, leading to equipment malfunction	Weather seal critical equipment
Sea level rise	Flooding of low lying coastal sites	Raise dykes and other protective embankments
Extreme heat	Heat can limit water discharge if temperatures are too high for water quality regulations, which can in turn reduce generation or force a shutdown Heat can further reduce the effectiveness of cooling Heat can foster the rapid growth of biological material that can clog cooling water intake, leading to reduced generation or shutdown	Reduce generation to avoid raising stream temperatures from discharged water above regulation Switch from once through cooling to recirculating to reduce temperature of discharged water Switch from wet cooling to dry cooling Increase maintenance of screens to ensure that biological matter does not clog water intake system
Extreme cold	Ice can clog water cooling systems, leading to reduced generation or automatic shutdown Ice can inhibit plant access Freezing pipes can lead to internal flooding Ice can damage the grid system	Route heated water from cooling system to inlet area Insulate critical piping
Precipitation	Excessive rain or snow can collapse unreinforced structures Excessive rain or snow can inhibit plant access to critical personnel and supply deliveries	Ensure that all buildings housing critical systems are reinforced Develop emergency weather plans Establish special procedures for removal of snow and ice
Drought	Low water levels can force plants to reduce generation output or shut down	Implement alternative cooling options: reuse wastewater, Recover evaporated water in recirculating systems, Switch to dry cooling systems

High winds	Wind generated missiles can damage buildings and backup generators High winds can knock out grid system interconnection	Install tornado missile shields
Floods or sea level rise	Some coastal plants are increasingly vulnerable to storm surges as sea level rises and storms become more intense, whereas other plants may be vulnerable to river floods, both of which can force an automatic shutdown but can also damage critical safety systems and grid system interconnections and threaten spent fuel storage	Consider flood risks in site selection for new plants Build earthworks to minimize risk of flooding Upgrade flood resistant doors Raise elevation of backup diesel generators
Lightning	Lightning can short circuit or create false signals in instrumentation Lightning can short circuit on-site power connection and backup diesel connections and controls	Ensure that circuits are insulated and grounded Bury key circuits underground Shield diesel generator controls
Forest fire and wildfire	Forest fires and wildfires can disrupt plant access to critical personnel, supply deliveries and emergency responders	Develop emergency access and response plans in case of nearby forest fires and wildfires

4.2.8.5 Direct and indirect costs of not adapting

Several extreme weather events (EWEs) can damage critical components or disrupt their interconnections. Preventive and protective measures include implementing technical and engineering solutions (circuit insulation, shielding, flood protection) and adjusting operation to extreme conditions (reduced capacity, shutdown). (IAEA 2019)

Without adaptation, in the worst-case scenario significant plant damage and potential release of radioactive material can occur.

Typical costs, however, will come in the form of lost revenue while the plant is shut down as a result of an EWE. Every 24 hours that a 1 GW nuclear plant is shut down (assuming €0.05/kWh) costs the plant owner €1.2 million in lost revenue. Outages also lead to indirect costs. When a NPP is shut down owing to an EWE, electricity customers must either experience a power outage or pay more for electricity from alternative sources to fill the gap.

In some circumstances, especially when a region is highly dependent on electricity supply from a nuclear plant (e.g. in small developing countries), an unexpected outage can lead to a wider blackout and impose substantial indirect economic costs. These costs vary considerably from country to country, as they are based fundamentally on the economic structure of a particular country. If a 1 GW nuclear plant were to shut down for 24 hours (disregarding a wider blackout that could be triggered by the shutdown), the value of the lost load in the Netherlands would be €206 million (assuming that the customers of the nuclear plant do not have power from other sources). Many developing countries have less value added from electricity generation than the Netherlands and would also have lower values of lost load, but the loss would be no less significant to the economies of those countries.

4.3 Specific risks of weather-related events for ageing NPPs

4.3.1 General consideration of problems of ageing reactors

Nuclear power plants experience two kinds of time dependent changes:

- Physical ageing of structures, system and components (SSCs), which results in degradation, i.e. gradual deterioration in their physical characteristics.
- Obsolescence of technologies and design, i.e. their becoming out of date in comparison with current knowledge, standards and technology.

The term "**physical ageing**" encompasses the time-dependent mechanisms that result in degradation of component quality. Even though the fundamental ageing mechanisms are well-known in principle, their potential to lead to incidents and accidents may not be fully recognized before the actual events take place. Furthermore, unexpected combinations of various adverse effects may result in the failure of technical equipment, leading to the loss of required safety functions. Thus, in old NPPs several undetected failures exist, these failures threaten the safety of the NPP but also the energy security.

Choice of materials, design and manufacturing process all influence the occurrence and acceleration of ageing mechanisms. Due to lack of operational experience in the earlier years of construction of NPPs, the choice of materials and production processes was not always optimal. To limit ageing related failure at least to a certain degree, a comprehensive ageing management program (AMP) is necessary. In case of obvious shortcomings, the exchange of the components is the only possibility to prevent a dangerous failure. Changes of mechanical properties often cannot be recognized by non-destructive examinations. Therefore, it is difficult to get a reliable, conservative assessment of the actual state of materials. Furthermore, due to limited accessibility due to the layout of components and/or high radiation levels not all components can be examined sufficiently. Therefore, it is necessary to rely on model calculations in order to determine the loads and their effects on materials. All in all, AMP rely on the optimistic assumption that cracks and other damage and degradation will be detected before they lead to catastrophic failure. However, this is not the reality.

Taking seriously the fact that experience with operating nuclear reactors beyond the design lifetime is limited, the claim made by the industry that the safety related equipment is sufficiently monitored to prevent failure, cannot be fully believed. Moreover, due to the economic situation operators intend to avoid comprehensive checks and maintenance. AMP so far implemented have not been sufficient to avoid the occurrence of serious ageing effects. (INRAG 2020)

Conceptual and Technological Ageing (Obsolescence): Safety design of NPPs is very important to prevent as well as to deal with accidents. Concerns are growing due to the Fukushima accident, as it revealed that there could be basic safety problems with the all operating units especially with the older ones, whose design was prepared back in the sixties or seventies. Safety design of all operating plants is outdated and showing deficiencies (e.g. in equipment qualification, separation, diversity, protection against external events). Old reactor types, e.g. VVER-440/V213, have several design weaknesses, which cannot be resolved by performing back-fitting measures. Development of science and technology continuously produces new knowledge, e.g. about possible failure modes, properties of materials. This leads to technological ageing of the existing safety concept in NPPs. At the same time, as a result of lessons learnt in particular by major accidents at Three Mile Island, Chernobyl and Fukushima Daiichi, earlier safety concepts are becoming obsolete. Furthermore the 9/11 terror attacks showed the need for increasing the protection against external hazards. Older nuclear power plants have not been designed to withstand the impact of commercial aircraft or other terror attacks. Very often, new regulatory requirements are applicable only to new NPPs, while for existing plants different criteria are applied. These concerns, among others, the protection against fire. (MRAZ 2015)

The design of the Candu reactors (units 1 and 2 of Cernavoda NPP) shows many shortcomings, among others (HIRSCH 2005):

- Material degradation of the pressure tubes is a persisting problem of existing CANDU plants. Hydride cracking and fretting were observed at the Cernavoda-1.
- The fuel used is natural uranium (i.e. not enriched), and heavy water serves as coolant and moderator. This combination has seriously negative safety implications. The void coefficient of reactivity is positive, so that any loss-of-coolant accident could lead to a power excursion (sudden rise of power). A loss-of-coolant with shut down failure (scram) will result in rapid melting of the fuel and possibly common mode breach of the containment.
- The large zirconium inventory of the CANDU could react exothermically with steam during a severe accident. This reaction produces hydrogen, which is a threat for the containment stability, because it reacts explosively with air in the containment.
- The reactor building has a pre-stressed concrete structure (diameter 41.46 m with a cylindrical perimeter wall of only 1.07 m thickness). It is seismically qualified, but external threats as natural disasters, airplane crash and other human impacts as terrorism and sabotage are not considered in the design.
- The Spent Fuel Pool is located outside the containment, which could result in a major release of radioactive substances in case of an accident.

Design weaknesses and vulnerability against external hazards of WWER-440/V213 (Paks 1-4 and Dukovany 1-4)

- The WWER-440/V213 is a second-generation WWER of Russian design with six primary cooling loops. This reactor type is not equipped with a full-pressure containment. The so-called confinement consists of compartments, which enclose the essential primary circuit components: steam generator, pipelines, pumps, shut off valves and Reactor Pressure Vessel. But the confinement itself does not guarantee to hold back the radioactive steam from large leaks but needs to condense the steam in the special pressure relief system (Bubbler Condenser). A failure of the relief system can cause the confinement to burst and result in a major emission of radioactive material.
- The vulnerability of the WWER-440/V213 against external hazards is relatively high: The reactor building does not provide sufficient protection against external impacts like airplane crashes or explosions but houses two reactors. WWER-440 plants are twin units, located in a common reactor building.
- Furthermore, the Spent Fuel Pool (SFP) is located outside the containment in the reactor building. An airplane crash could cause a severe accident with a large radioactive emission: the worst case could even lead to releases from two cores and molten fuel from two Spent Fuel Pools.

Important design weaknesses of the WWER-1000/V320 reactor (Kozloduy - and -6 and Temelín NPP) are:

- The WWER-1000/V320 reactor is fitted with a full-pressure single containment; however, it has a basic shortcoming not encountered in western PWRs. The lower containment boundary (containment basement) is not in contact with the ground but is located at a higher level inside the reactor building. In case of a severe accident, melt-through can occur within

approx. 48 hours. The containment atmosphere will then blow down into parts of the reactor building that are not leak-tight resulting in high radioactive releases. The reactor building – including the Main and Emergency Control Rooms – will have to be abandoned.
- The plant layout has weaknesses that make the redundant safety systems vulnerable to hazardous systems interactions and common-cause failures due to fires or internal floods

4.3.2 Results of the EU stress tests for specific countries

4.3.2.1 Cernavoda NPP (Romania)

In Romania, there is one nuclear power plant (Cernavoda NPP), which is located in Constanta county, about 2 km southeast of the Cernavoda town boundary. Cernavoda NPP is owned and operated by the National Company Nuclearelectrica (Societatea Nationala Nuclearelectrica, SNN)

Cernavoda NPP has two pressurized heavy water reactors (PHWR) of CANDU 6 design. These are the only units in Europe based on the CANDU (CANadian Deuterium Uranium) technology. The plant project was initiated in the 1970s and was initially proposed to house five units. Construction began in 1980 on all the reactors, but this was scaled back in the early 1990s to focus on unit 1, which was completed in 1996. The second unit was connected to the grid in August 2007. Unit 1 and 2 (650 MWe net capacity each) generated 18 percent of Romania's electricity in 2018 (WNA 2020b).

The operating time of 30 years for unit 1 and 2 will end in 2026 and 2037, respectively. In September 2017 SNN decided to refurbish unit 1 for lifetime extension with detailed plans to be approved in 2021. This announcement causes concerns, because already today the design of CANDU 6 reactors is very outdated, for example external threats as airplane crash and other human impacts as terrorism are not considered in the design. Also ageing of the pressure tubes is an issue.

National Actions Plan (NacP)

The Romanian NAcP listed 33 measures, 13 of these measures were already implemented in 2013. The implementation of improvement measures is clearly scheduled, and the end date of the process is December 2015. At the end of 2014, 24 measures have already been implemented, eight measures are in progress and one measure is planned. (RNR 2014)

The action plan was revised in December 2017. There is a delay in the implementation of Action 31 (new seismically qualified location for the on-site emergency control center and the fire fighters.) This action was estimated to be completed by the end of 2018. (RNR 2017)

Flooding and Extreme Weather Events

The Cernavoda site elevation is about two meters higher than the calculated **Design Basis Flood** (DBF). During the stress test procedure, the regulator assessed the existing margins as being adequate and no additional measures were required to protect the plant against **external flooding**. However, flooding turned out to be a neglected issue: the Peer Review Team criticized that the dangers connected with extreme flooding events have been analyzed insufficiently, because margins for flooding have been assessed with limited identification of cliff edge effects and weak points; and pointed out that for a number of safety significant equipment located underground the protection against flooding needs to be improved (so that protection does not rely solely on the elevation of the platforms). Furthermore, the peer review team criticized the lack of routine inspections of the flood protection design features.

Some limited measures have been done:

- According to the NAcP, potential measures to improve protection against flooding have been identified. (No. 2) *However, it was not explained which measures have been performed.*
- In addition, sandbags have been made available on site to be used as temporary flood barriers, if required. (No. 3) *It is not appropriate that the sandbags are the only measure to protect specific weaknesses.*
- Routine inspections of the flood protection design features, such requirements were to be established by 2013. (No. 7)
- Design modifications to replace selected doors with flood resistant doors and penetrations sealing in buildings containing safety related equipment in rooms below the plant platform level were performed by 2015. (No. 5)

The Peer Review Team pointed out, that there is only limited information about **extreme weather conditions**, information regarding the plant capability beyond the design basis and the identification of cliff-edge effects and weak points are lacking. Thus, the plant resistance against extreme weather is still unknown.

Until 2015, only the specific procedure, which is in place for extreme weather conditions in order to include the proactive actions for plant shutdown, was reviewed. (No. 1)

The Peer Review highlighted the need of further work for assessing margins to cliff-edge effects due to external events. It was recommended that CNCAN obtains good quality programs from the operator SNN and ensures that the work is appropriately followed up. (No. 10) According to updated NAcP 2017, this measure is still only *"planned".* Thus, no target date for implementation is set. CNCAN stated that this work is depending on the development of a common methodology, at EU-level. **This is one of the examples showing that CNCAN is not fulfilling the tasks of a nuclear authority. CNCAN performance does not comply with international standards.**

Transparency

The NAcP – along with all EU stress test documents – is accessible on the regulator's website but only in English language. The word "transparency" is not mentioned at all in the NAcP. In January 2015 CNCAN was invited by NGOs in Romania and Bulgaria to speak at a round table on nuclear safety but did not manage to send a representative. The nuclear authority on the other hand did not hold a public meeting on nuclear safety with the public.

On behalf of the NGO TERRA Mileniul III the experience with transparency during the past period was characterized as trying to comply with existing laws, however, does CNCAN as most Romanian authorities still provide answers without giving away usable information. (BECKER 2015)

Conclusions

The analysis of the update NAcP showed that seismic risk, flooding and extreme weather events have not been sufficiently addressed by the operator of the Cernavoda NPP. The Romanian Regulator CNCAN (National Commission for Nuclear Activities Control) did not insist on the implementation of the measures, which the EU Peer Review Team had drawn up as necessary.

Romania is one of the most active earthquake regions in Europe. The Peer Review Team criticized that **seismic upgrading** has been not been considered and safety margins have not been quantified adequately. However, the regulator CNCAN sticks to the opinion that the seismic margins are sufficient and further measures are not necessary. Thus, the regulator missed the idea of the stress tests. Although the probability of an earthquake exceeding the plant's design limit is low, the possibility of a severe earthquake persists, which could trigger a severe accident.

Only limited work has been done during the last years to improve the protection against earthquake and flooding. But even worse: no substantial improvements are envisaged for the future.

The stress tests revealed that **flood protection is insufficient**. A number of safety significant equipment is located in underground rooms of the NPP, making the implementation of flood resistant doors and sealing of penetrations necessary. On extreme weather conditions like heavy winds, snow and rain and the plant´s capabilities to withstand their effect, the Peer Review Team found out, that only limited information is available.

Mobile equipment is presented as the solution to compensate deficiencies of the reactors and the spent fuel pools. Procurement and testing of mobile equipment were done. **There can be no guarantee that the staff will be able to prevent a severe accident in a complex situation arising after an earthquake - with mobile equipment only.**

When trying to assess the overall safety situation, we need to take into account not only the information the stress tests provided, but incorporate the specific safety issues of the CANDU reactors: Units 1 and 2 of the Cernavoda NPP have been operating for only relatively short periods (since 1996 and 2007 respectively), but the reactors were designed in the 1970ies and thus the design is very outdated. Several design weaknesses of the reactor cannot be remedied – in particular the possibility of violent power excursion in case of loss of safety systems and the vulnerability against external hazards.

Besides earthquakes also **terror attacks** could cause a severe accident. A large amount of radioactivity can be released not only from the reactor core but also from the **spent fuel pool which is located outside the containment**. Moreover, material degradation due to ageing effects of the pressure tubes are a persisting problem of existing CANDU plants and have already occurred at the Cernavoda-1 plant. The operating time of Cernavoda 1 and 2 is 30 years, which will last until 2026 and 2037, respectively. However, life-time extension is planned.

4.3.2.2 Kozloduy NPP (Bulgaria)

The Kozloduy NPP is located in the north-west of Bulgaria on the Danube River, 5 km to the east of the town of Kozloduy and 200 km to the north of Sofia. Kozloduy 5 and 6 (WWER-1000/V-320 reactors, net capacity of 963 MW each), put into operation in 1988 and 1993 respectively, are the only reactors still operating in Bulgaria; Kozloduy NPP-Plc. is operating these units. In 2018, the Kozloduy NPP provided about 35 percent of the Bulgaria's electricity (WNA 2020a).

The units 5 and 6 of Kozloduy NPP were licensed to operate until 2017 and 2019 (30 years design life-time). There was work done to **extend the operating lifetimes** by 30 years and to reach a total of 60 years (until 2047 and 2049, respectively)**.**

National Action Plan

The Bulgarian National Action Plan (NAcP) in 2012 listed 63 measures. Some of the actions referred to in the NAcP are quite complex, actually covering several actions. Thus, 14 actions were defined. (BNRA 2014).

In December 2018, the BNRA updated the status of the Updated NAcP. In this revision, one new measure related with the development of procedure for actions of the emergency teams during the simultaneous accidents in different units/installations at the site was added. The updated NAcP 2018 comprises totally 78 measures and activities, 5 of them were still ongoing: Construction of KNPP off-site Emergency Response Centre (ERC) (D-1-2); installation of measuring channels to monitor and evaluate the concentration of steam and oxygen in the containment (D-3-2); installation of an additional pipeline to the spent fuel pool cooling system to allow cooling the spent fuel by mobile means (FD-2-4-1); feasibility study of direct water injection to the reactor core from an external source (FD-2-4-2); feasibility study of direct water supply to SGs from an external source (FD-2-4-3). (BNRA 2018)

Flooding and Extreme Weather Events

The site is located at the first non-flooded terrace of the Danube. The average height of the site elevation is about two meter above the calculated water level of the **Design Basis Flood** (DBF). However, in case of external flood corresponding to DBF the Bank Pumping Station (BPS) would be flooded. Thus, possibilities for protecting the equipment of the BPS were to be investigated by October 2012. (B-2-1) *According to the results of the conducted studies changes were made in the relevant instructions for the personnel at the bank pumping station in case of flooding hazard due to rising of the Danube River level.* **However, obviously no permanent reliable protection will be installed instead the plant´s safety will fully depend the staff performing the correct actions.**

A measure to enhance the plant robustness in case of external flooding and to avoid secondary effects of beyond design basis flood of external sites was to be performed by November 2012. (B-1-1). **Again, this measure also consisted only in the development of an emergency response procedure for the operating personnel in case of damage of Zhelezni Vrata-1 and Zhelezni Vrata-2 Water Power Facilities.**

In December 2012, activities to improve the condition and the protective functions of the dike in the region of the Kozloduy valley have been initiated. These activities have been completed in December 2014. (B-3-1)

The scenarios for **Beyond Design Basis Flood** showed that some locations of the site could be flooded due to the limited sewage and drain system capacity; the Peer Review Team highlighted the relevance of back-fitting measures. The modernization of the sewage network and drain pump system were to be performed by October 2013. (B-2-3). Due to problems with the equipment supply, the technical specification was revised, and the final completion date was postponed to November 2015.

Measures to protect the water intake of the plant sewage network in case of Kozloduy valley flooding were to be developed by October 2013. (B-2-2) *The selected concept is based on tanks with mobile pumps for sewage water retain. The provisions to prevent water penetration into the plant sewage were implemented by December 2016 (FB-2-2-1).* **However, again the measure depends on actions of the staff instead of installing permanent and reliable technical solutions.**

Extreme weather events were not sufficiently evaluated, because the operator did not take possible combinations of extreme weather conditions (e.g. heavy rains and strong winds) into consideration. Thus, an analysis of extreme weather conditions on the KNPP site, using probabilistic methods according to the IAEA methodology, and considering combinations of extreme weather conditions was performed. (E-1) **However, results were not presented; no further measures were mentioned.**

Transparency

The NAcP of Bulgaria – along with all other reports in relation to the European stress test – is accessible through the home page of Bulgarian Nuclear Regulatory Authority (BNRA), both in English and in Bulgarian.

The nuclear energy law of Bulgaria stipulates the requirement for BNRA to openly and transparently communicate regulatory decisions and safety information to the public. To satisfy this, BNRA uses several channels and mechanisms, as web page, media, formal letters and Annual Report to provide all necessary information to the public. The law also requires the licensees to inform the public about possible radiation risks associated with the facilities and activities. (ENSREG RR-BG 2015)

As the tone of this official explanation suggests, the prevailing approach is that the authority is the only one to know and decide about nuclear safety and thus provides information to the public about its activities. A real effort to enter an open discussion did not take place and the regulator is still trying to cover up the fact, that the operator is not willing to perform necessary steps. (BECKER 2015)

Conclusions

In case of extreme flood some locations at the NPP could be flooded due to the limited sewage and drain system capacity. Instead of installing permanent and reliable technical solutions, the necessary intervention depends on actions of the staff.

The stress tests revealed that a review of **extreme weather** hazards like heavy rains and strong winds is necessary. However, at the end of 2015 not even the analysis of the extreme weather hazards has been completed. **Results and possible improvements are not mentioned in the last update of the NAcP.**

Seismic resistance at NPP Kozloduy has not increased since Fukushima accident in 2011 until today. To cope with Beyond Design Basis Earthquakes (DBE) or other external events, only two mobile diesel generators (MDGs) were to be delivered by December 2013.

At the end of 2020, only feasibility studies to ensure the cooling of the fuel in the reactor core and the spent fuel pool are planned, thus it is not sure that any improvements will be implemented and if so, whether they will be adequate, and when they might start functioning.

In 2011 the Stress Tests revealed that the NPP Kozloduy does not have sufficient Severe Accident Measures (SAM) in place to contain the development of severe accidents, among them the inability to deal with the molten core to prevent a major release of radioactive substances. However, only the study about this important issue is to be performed by December 2021.

The updated National Action Plan 2018 shows that the operator as well as the nuclear regulator lack a responsible attitude towards nuclear safety. They both underestimate the urgency to implement those measures or shut the plant down, at least until those measures are completed. Economic considerations may be the reason for this reluctance. Contrary to previous decades, even old nuclear power plants are hardly competitive on the European Electricity Markets with electricity prices which hit a historic low.

To license a Plant Lifetime Extension (PLEX) as intended, i.e. increasing the originally designed lifetime of 30 years by 30 years entails high nuclear risk.

4.3.2.3 Paks NPP (Hungary)

In Hungary one NPP (Paks NPP) is in operation. It is located 5 km south of the city center of Paks, 114 km south of Budapest and 1 km west of the River Danube. Paks NPP comprises four units of WWER-440/V-213 reactors. The four units are placed in two building structures in a twin arrangement. The first grid connection of unit 1 and 2 was in 1982, unit 3 and 4 followed in 1984 and 1986. In 2018, the Paks NPP provided 50.6 percent of Hungary's electricity (PRIS 2020)

Paks NPP is owned and operated by Paks Nuclear Power Plant Ltd, which is a subsidiary company of state-owned Hungarian Power Companies Ltd (*Magyar Villamos Művek*, MVM).

The original design lifetime was 30 years, so the four units would have reached the end of their operation times between 2012 and 2017. The Hungarian Atomic Energy Authority (HAEA) has approved life-time extension for all four units. A lifetime extension of 20 years is envisaged. (WNA 2019a)

National Action Plan

In the Hungarian National Action Plan (NAcP) 49 detailed actions are listed. The implementation of improvement measures is clearly scheduled with the specified timeframe to implement all the measures until the end of 2018 (HAEA 2012). In the updated NAcP, delay is indicated in the case of four actions (HAEA 2015)

The HAEA reviewed the Action Plan again in December 2017. It was stated that six of the not finished tasks will met the final deadline (end of 2018) while the implementation of six tasks will undergo delay. (among others: Construction of a new Backup Command Centre (No. 49)). The system that should be able to prevent the long-term over-pressurization of the containment should be completed by the end of 2020 for all units. (No. 30)) (HAEA 2017)

Flooding and Extreme Weather Events

The level of the machine room, which houses the safety important Essential Service Water (ESW) system pumps, is below the water level of the Danube in case of the calculated **Design Basis Flood** (DBF)[9]. Thus, it was necessary to seal the penetrations of the machine room wall. The modification is to be performed by December 15, 2015. (No. 6) *According to the updated NacP, this modification was done*.

Regarding **extreme weather** events, the Peer Review Team highlighted the need for strengthening the protection (e.g. against extreme precipitation and snowmelt or lightning). During stress tests procedure numerical values of the safety margins of the extreme weather conditions were not available, because the evaluation of loads caused by weather impacts in frame of the last Periodic Safety Review (2008) was not in compliance with modern expectations. A new assessment was to be conducted by 2012.

A list of such system components important to safety which are endangered by lightning was to be compiled by December 15, 2015. Based on the list, reinforcement will be specified. (No. 13) *Supplementary repair of external lightning protection systems based on the revealed deficiencies was done. Modification of cable paths and shielding of relay tables have been commenced.*

The inspection and maintenance procedures to be applied in the situation of extreme low level of the Danube were not satisfactory. The missing instruction was to be developed by December 15, 2013. (No. 12).

Transparency

The Hungarian Atomic Energy Authority published the Hungarian National Action Plan on its website in Hungarian and on the ENSREG website in English. (HAEA 2014).

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[9]In emergency situations, the ESW system supplies Emergency Diesel Generators (EDG), Emergency Core Cooling System (ECCS) and cooling of the Spent Fuel Pool (SFP) with cooling water; when the ESW system fails, only the fire water system could provide cooling water.

The HAEA, on its website, continuously informed the public about the situation evolving in Japan and its consequences. The authority made available all relevant information on the preparation for, and execution of, the targeted safety re-assessment (TSR) in framework of the EU stress tests as well as on the extraordinary review made by the IAEA.

Additionally, a "Bulletin" is published every six months, which includes information that may satisfy professional needs as well; Bulletins are sent in printed format to wider scope of people and organizations. Another communication channel is the HAEA newsletter, through which the authority provides information on the major events every three months. The HAEA, according to law, annually reports its activity to the Hungarian Parliament. This report is discussed within the relevant committees of the Parliament, which finally endorse it.

According to the Hungarian NGO Energy Klub, the transparency level concerning the stress test of the Paks NPP is still lower than would be necessary. The nuclear regulator HAEA provides information only in irregular intervals on its own initiative on the matter, and that information is inexpressive. The website of the HAEA does not contain specific pages dedicated to the stress test, and the timeline of the hits that are provided by the search engine of the website is confused. However, HAEA answers in details to the questions raised in official letters asking for information. (BECKER 2015)

Conclusions

When trying to assess the overall safety situation, we need to take into account not only the information the stress tests provided but incorporate the specific safety issues at the site and of the reactors at this site.

The original Paks NPP was not designed to withstand seismic loads, but Paks NPP underwent comprehensive reinforcement and qualification programs. According to the National Action Plan of 2012, the further upgrading should be completed by 2015. However, one important measure is delayed - and the measure which has been chosen in the first place was replaced by a cheaper solution. The seismic issue needs to be taken very seriously, because the quantitative assessment revealed that only narrow seismic safety margins available. The most pressing unsolved seismic issue is the **potential for soil liquefaction**, as it could act as an important initiator for the simultaneous failure of several safety systems. According to Austrian experts it is unclear whether active faults in the site vicinity are adequately considered in the seismic hazard assessment which is of utmost importance for the reliability of the assessments.

The most important severe accident management (SAM) issue is the **cooling of the reactor pressure vessel (RPV)** by flooding the reactor cavity to prevent RPV failure. The calculations of this in-vessel retention (IVR) concept were only justified in the frame of limited experimental analyses. The Peer Review Team recommended considering a failure of RPV, despite the fact the Hungarian regulator claims a failure of this new measure as being highly unlikely; the evaluation of the consequences of RPV failure is not required by HAEA.

During the (slow) increase of pressure caused by steam produced during the external cooling of RPV, the unfiltered release through the stack could be necessary to avoid containment failure. However, the **installation of a filtered venting system is not planned**. Instead an active containment cooling system should be introduced. Moreover, the envisaged specific containment cooling is only adequate if reliable in-vessel retention can be guaranteed, but this is not completely proven yet as mentioned above.

All four units are supposed to be in operation for additional 20 years. In addition, the power uprates which were performed during the last years accelerated the ageing process. Degradation effects of safety-related systems and components could significantly aggravate the development of an accident or even trigger a severe accident.

To remedy all design weaknesses (in particular wall thickness of the reactor building and location of the Spent Fuel Pool) of the outdated WWER 440/V213 reactor type is not possible. Taking into account the existing risk of terrorism, it is irresponsible to operate a nuclear power plant with such a high vulnerability to external attacks.

The combination of design weaknesses, ageing impacts and the seismic hazards revealed by the stress tests show that the Paks NPP life-time extension would pose an irresponsibly high nuclear risk.

4.3.2.4 Dukovany NPP (Czech Republic)

The nuclear power plant Dukovany (EDU) is situated in the southwest of the city of Brno. Four WWER-440/V213 reactors are operating at the Dukovany NPP. The reactors were put into operation between 1985 and 1987. In 2018, the nuclear power plants in the Czech Republic, Dukovany and Temelín, provided about 34.5 percent of electricity (PRIS 2020).

In 2009, ČEZ commenced its **Long-Term-Operation (LTO) project** to **extend** the operating lifetime of the Dukovany reactors **by 10 years** to 2025. Further lifetime extension of up to **60 years** is **under consideration**. According to SÚJB, safety improvement and equipment modernization make it possible to consider operating Dukovany NPP until the year 2045.

National Action Plan

The National Action Plan (NAcP) of the Czech Republic defines 76 actions/activities for Dukovany and Temelín NPPs. The ENSREG NAcP Peer Review Team criticized that in several cases it is not clear to which extent the NAcP is covering some of the ENSREG recommendations/findings. (ENSREG RR-CZ 2015)

The updated NAcP explains that many of the listed measures are already in an advanced stage of implementation since they were proposed before the Fukushima events on the basis of Periodic Safety Report (PSR) results. (SUJB 2014)

According to the updated NAcP, additional measures (Actions 77-84) which emerged from a detailed analysis of ENSREG documents, have been added to the NAcP. The deadline to implement all necessary measures was the end of 2016. (SUJB 2014) However this is not the final date of the implementation of the necessary back-fittings. Those measures which consist of performing a study or analysis may result in the need to identify new measures.

By the end of 2019, all actions for Dukovany are finished. For Temelín, one measure is ongoing: the implementation of measures for maintaining long-term containment integrity should be finished between 2022-2024 (SUJB 2019)

Due to location of the plant several tens of meters above the closest rivers the plant sites are not endangered by **external flooding** caused by rivers, nevertheless flooding caused by extreme rainfall could result in a dangerous situation. The following measures were done:

- Flood protection of the Emergency Control Centre (ECC) was implemented in 2012. (No. 9)
- Sealing of entrances of cable ducts was performed in 2013. (No. 10)
- Sealing of entrances of diesel generator station was performed in 2013. (No. 11)

The Stress Tests revealed several safety relevant issues which may arise from **extreme weather conditions**: several civil structures did not meet the design basis requirements with respect to wind and snow loads. Most important was the limited capability of the cooling towers in respect of strong wind. The implementation of the ventilator towers for ensuring independent ultimate heat sink was performed between 2014-2016 (No. 33).

Furthermore, considerations for extreme snow loads showed low or no margin for the generator halls, its collapse which might endanger the operability of the essential service water (ESW) system. Structure reinforcement against extreme weather phenomena was to be implemented by 2014. (No. 1) However, the updated NAcP do not explain what kinds of measures have been done, thus the reliability could not be evaluated.

In 2012, the ENSREG Peer Review Team pointed out that some problems resulting from extremely low temperatures should be reconsidered (freezing of open water, pipelines, and congelation of diesel fuel). However, the results of the re-assessment of the possible impact of extremely low temperatures were not mentioned. It was even not mentioned whether this re-assessment has been done carefully.

The procedures for special handling of weather-related hazards are not sufficient, some specific additions might be necessary to the emergency management procedures. Procedures for managing extreme conditions on the site (wind, temperature, snow and earthquake) were to be completed by 2013. (No. 7) However, as mentioned above, these procedures only rely on insufficient analyses.

According to the updated NAcP 2019, review analyses are underway to re-prove sufficient resistance to the effects of climatic extremes for all civil structures, systems and components which ensure performance of the basic safety functions. No further information was provided. (SUJB 2019)

Transparency

The NAcP and the updated NAcP are accessible on the regulator's website, though in English only. Most countries published NAcP providing information which is often incomprehensible und incomplete. However, the Czech report is even less useful when compared to other countries´ reports. In spite of ENSREG critique, the information of the updated NAcP 2014 continues being insufficient and incomprehensible.

At the same time the public is kept in the dark: The public received the following information by the operator: „The stress test results for NPP Dukovany (...) confirmed the decisions taken to improve the original project as effective and correct. No situation was found, which requires immediate solutions. The NPP can cope with highly unlikely severe accidents (...).“

And still, only those two – SUJB and CEZ – negotiate in a closed procedure which safety measures to realize or postpone – which is a dangerous game. (BECKER 2015)

Conclusions

The stress test revealed that the Dukovany NPP is not prepared to withstand an accident caused by a natural hazard like an earthquake which obviously could affect all four units at the site. The target date to implement the upgrades was end of 2016. However, this is not the final date of implementation of necessary back-fitting. Those measures which consist of performing an analysis may result in further measures. In 2012, the Peer Review Team highlighted the **importance of the on-going earthquake reinforcements**, which is scheduled to be completed in 2015. But also after finishing the back-fitting measures, the protection will not be adequate. Further back-fitting will be probably be necessary after the seismic PSA systematically analyzed the threat including seismic induced flooding and fire, which is to be completed by 2015. Until now no prove was provided to confirm that the seismic hazard assessment is reliable**.**

The stress tests have identified that the **considerations for extreme low temperatures may be too simple**, not taking into account the realistic related effects, e.g. Station Blackout. This example shows that CEZ without SUJB intervening did not take the lessons from Fukushima and the idea of the EU stress tests seriously. The fact that SUJB did not take very idea of stress tests seriously led the Peer Review Team to formulating a number of recommendations; however, the regulator did not follow them up adequately.

The **only heat sink at Dukovany NPP were the cooling towers** with their capabilities being endangered by strong wind and earthquakes. The solution chosen by the Czech side is the construction of new cooling towers. However, a second heat sink is still lacking, because the old cooling towers can be seen as a reliable heat sink.

The stress tests revealed that the **severe accident management** (SAM) measures are **not sufficient**. Dukovany NPP has no means to cope with a core melt accident, thus **a severe accident with a major radioactive release could result**. An external reactor pressure vessel (RPV) cooling and thereby retention of the molten core inside the RPV was to be implemented by 2015. However, doubts about the reliability of the concept exist.

The licensed operation time (30 years) of units 1 – 4 ended between 2015 and 2017.The Czech authorities performing the life-time extension of the NPP Dukovany without any public debate or EIA procedure. Further lifetime extension to 2045, which means an operation time of 60 years, is under consideration.

Material degradation and design weaknesses of the very old units can significantly aggravate the development of an accident caused by an earthquake or other external or internal events. In particular the essential service water system is prone to leaks and could fail unexpectedly. Furthermore, there are design weaknesses that cannot be remedied, e.g. the low protection against terror attacks.

5 Case studies

This chapter presents three case studies for examining climate change impacts focussing on use of water the NPPs Paks, Beznau and Dukovany.

5.1 Paks

Eszter Mátyás from Energiaklub in Hungary prepared a study on water scarcity caused by climate change, and its impacts on the need for cooling water for nuclear power plants at the Paks site. The case of Paks is special in a sense, since here we can examine both the present (Paks I Nuclear Power Plant) and future (Paks II NPP) of nuclear power plants under the effects of climate change.

The study presents how Hungary's climate developed in the last few centuries and how the climate influences the operation of the nuclear power plant in Paks.

In the past few years, Paks NPP has been facing several operational problems due to the changing climate and its effect on the river Danube. But as both the currently operating four, and the planned two new reactors at Paks are pressurised water reactors, the existence of the nuclear power plant depends on the Danube. Hungarian climate has been changing significantly from the early 20th century and now we are facing the consequences of this change. As the case study presents, several malfunctions of the NPP directly inferred from climate change. However, in the light of the Paks II project, the problem to be solved is even greater. The study presents that in the case of Hungary, although several cooling options are available, solving the problem of climate change is very politically dependent. Substantive changes will only be achievable if the regulatory system and the political will both agree on the accomplishment. Since the Hungarian Government is committed to nuclear energy in the fight against climate change, it would be crucial to make modifications in the operation of Paks NPP by recognising the problems caused by climate change.

Climate change affects Hungary's climate in many ways but in connection with nuclear power plants, the most aching effects are the water issues. Several options exist to solve cooling issues of the current four reactors of Paks and the future two reactors of Paks II, but these are highly dependent on the regulations and decisions made by the authorities and the government. Recent years have shown that not only the regulatory system is full of open to interpretation rules but the lack of political will also makes it difficult to achieve substantive changes. Greater transparency of the measurement processes and the inclusion of the civil society and experts would improve the quality of the developments and could reduce the errors experienced so far. Malfunctions of the cooling process should be a warning sign for the planning of Paks II and greater attention should be paid to the climate condition changes. After all, the Hungarian government believes that nuclear energy is the solution for climate crisis, therefore it is crucial to take climate change seriously and modify the operation of the NPP according to it.

Find the whole study in Annex I.

5.2 Nuclear Powers Plants Running Dry: Dukovany

This overview shows the practical implications of the increasing dryness and reduced water flow in rivers on nuclear power plants. Nuclear power plants are not an option for countering the climate crisis because they are rather vulnerable. In addition, nuclear industry and politicians ignore the enormous water consumption compared to other electricity generating options as well as the insecurities in forecasting the water streams' development and that scarcer water might be needed more urgently for other purposes.

Background

The Czech Republic has a total of six reactor units in operation, four in Dukovany, two in Temelín. After the crash of the tender to start the construction of two more reactors in Temelín in 2014, the National Nuclear Action Plan was passed. There the idea of two more reactors at each site was formulated, with no timetable which site should be first. However, purely political reasons led to the now favored option of one reactor at the Dukovany site; construction is to start in 2029, completion in 2036. Expected operational time is 60 or even 80 years. On top of 20 years of planning and construction this project needs to take into account the effects of the climate crisis for the next 100 – 120 years.

Dukovany NPP: At this site currently **2040 MW** are installed. Four second generation VVER-440/213 are operating since their start-up in 1985 and 1987. The units were up-rated to generate 505 MWe output each and underwent a life-time extension which is valid until 2035 – 2037, respectively. However, another 10 year prolongation is being discussed.

The long-standing plan to start the construction of one additional unit is referred to as Dukovany V. The new unit (1200 MW) should be built in parallel to the four units (2040 MW) already operating at the site. A maximum of 3600 MWe was agreed: the older units then will be decommissioned one by one, with or without additional prolongation until 2047.

The water issue

Generally recognized is the climate crisis phenomena of increasing lack of rain, however, the impacts differ. In recent years, the public and even the politicians in the Czech Republic recognized this as one of the most urgent problems that need to be solved. The Czech Republic is among the hardest to be hit. Also the natural phenomena of less rain meets insensible agricultural practices and an energy supply system with a high need of water.

A summary be the USDA May 2020[10]:

"The drought in the Czech Republic is described as the worst in 500 years. Water deficit in rivers and soil reached high levels very early in the year. Scientists, as well as farmers, and government representatives, describe the situation as critical. The Czech Government has come up with various measures to combat drought. Losses on agricultural crops are estimated between 20 and 40 percent for this year. The dry spell in the Czech Republic started six years ago but water shortages this year have pushed the Czech Republic to what has been described as the worst drought in 500 years. This year, again, the water deficit (of both groundwater and river water) increased. The main reason is a lack of precipitation and increasing average temperature. Mild winters with lack of snow contribute to the significant water deficit in spring largely. Scientists, as well as farmers, and government representatives are concerned. On May 12, the National Coalition for Combating Drought met, and the Czech Government came up with various plans in order to combat drought in the future. Losses on agricultural crops in 2020 are estimated between 20 and 40 percent."

[10] USDA, Report Number: EZ2020-0006. May 22,2020

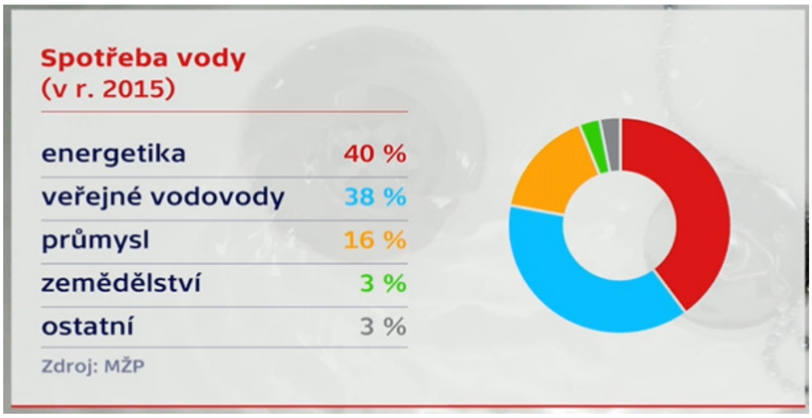

Figure 2: According to official data[11] for 2015, the Energy production is the single biggest water consumer in the Czech Republic with 40 %, which is more than the waters supplied to the consumers connected to the public water distribution with 38 %, followed by Industry 16 %, agriculture 3 % and 3 % other).

When planning a reliable electricity supply for the next 100 years of climate crisis, nuclear energy is certainly among the least suitable solutions:

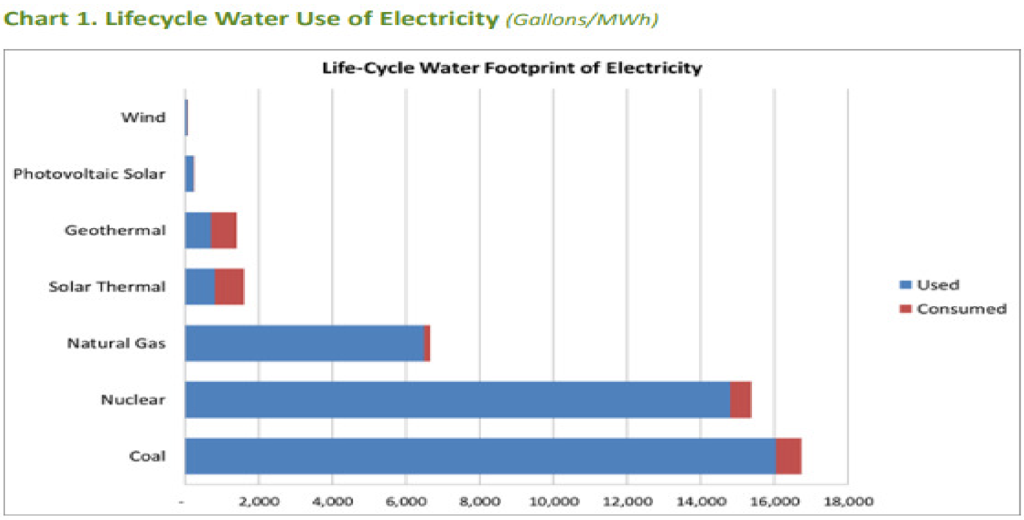

Figure 3: Lifecycle Water Use of Electricity

The Czech Republic would have an alternative option to construct one more unit: at the other nuclear site – Temelín – where also two more reactors are planned. Regarding the water supply this plant is so far in a non-critical situation, since Temelín is located at the Vltava River. However, for political reasons Dukovany was chosen for now.

NPP Dukovany water supply

The Czech NPP Dukovany and Temelín both use a so-called closed cooling system with cooling towers which need less water than NPPs with a once-through cooling system. Still, Dukovany takes 55 million m3 of water from the Jihlava River and returns only half it.

[11] Environmental Ministry of the Czech Republic: https://www.ceskatelevize.cz/ivysilani/1097181328-udalosti/217411000100324/obsah/532679-spotreba-vody-v-cr

The 2017 Environmental Report for the new unit provided a description:

"The most important watercourse in the area of interest is the watercourse Jihlava, flowing about 1 km north of the existing EDU1-4 area. Jihlava River starts on south-facing slopes of Lísek at Jihlávka and flows into a middle Nové Mlýny reservoir at Ivaň. The Dalešice Mohelno waterworks system is situated on the river Jihlava in the area of interest, consisting of the Dalešice reservoir and the Mohelno reservoir (which is a balancing reservoir). The waterworks create a reservoir providing water take-off for the Dukovany Power Plant and at the same time they have other functions related to power and water systems. Water for the Dukovany Power Plant is pumped from the Mohelno water reservoir into which waste and rain waters from the power plant flow as well through the Skryjský creek. The Mohelno dam forms a reservoir approximately 7 km long. The dam is a concrete gravity dam with a run-off river power plant located directly in its body. It was put into operation in 1978 and serves for equalising of outflow from the Dalešice pumped storage plant and forms a lower reservoir for pumping. The average annual flow rate in the Mohelno profile is 5,35 m3/s, with average annual flows varying most often between 3 and 6 m3/s. The highest instantaneous flow rate was recorded during the 2006 flood (125 m3/s). At a distance of approximately 1.5 km south of the existing EDU1-4 area, the Olešná watercourse flows further through the affected territory. This watercourse starts north of Valeč municipality and flows from the left into Rokytná River at Tulešice. Average annual flow at entry is approximately 0.08 m3/s. Surface water from the affected territory is drained by the small water flow Rouchovanka to the Rokytná watercourse, which is a significant watercourse mouthing from the right into the Jihlava watercourse in Ivančice. The northern part of the affected territory is drained by the Oslava river, the largest tributary of the Jihlava watercourse, also mouthing in Ivančice. "

The annual flow rates observed (climate scenario + 0°C) and corrected (climate scenario +2°C) are shown in the following table.

Table C.51: Annual average monthly flow rates in the profile Jihlava - Dalešice under the dam (the Dalešice reservoir dam)

Year	$Q_{r,+0°C}$	$Q_{r,+2°C}$	Year	$Q_{r,+0°C}$	$Q_{r,+2°C}$	Year	$Q_{r,+0°C}$	$Q_{r,+2°C}$	Year	$Q_{r,+0°C}$	$Q_{r,+2°C}$	Year	$Q_{r,+0°C}$	$Q_{r,+2°C}$	Year	$Q_{r,+0°C}$	$Q_{r,+2°C}$
	[m³/s]			[m³/s]			[m³/s]			[m³/s]			[m³/s]			[m³/s]	
1932	3.65	3.33	1946	6.42	6.93	1960	8.97	6.88	1974	4.66	4.14	1988	6.99	5.91	2002	9.94	8.61
1933	3.10	2.81	1947	6.79	7.50	1961	6.69	5.67	1975	5.12	4.82	1989	3.92	3.86	2003	4.80	4.66
1934	2.91	2.65	1948	7.50	7.54	1962	7.52	6.71	1976	5.58	7.22	1990	2.95	2.65	2004	6.98	7.07
1935	5.59	6.47	1949	3.88	3.19	1963	5.20	4.95	1977	7.29	6.53	1991	3.30	2.44	2005	6.22	5.63
1936	5.14	4.16	1950	4.20	4.19	1964	5.19	4.30	1978	3.66	3.12	1992	4.80	4.89	2006	9.13	8.59
1937	6.81	6.03	1951	5.06	4.78	1965	14.23	13.29	1979	5.47	4.68	1993	3.90	3.70	2007	5.33	4.96
1938	6.71	5.33	1952	4.65	4.54	1966	8.24	6.50	1980	6.35	5.57	1994	4.26	4.00	2008	4.10	4.06
1939	13.11	10.58	1953	4.60	4.14	1967	7.68	6.23	1981	6.41	5.57	1995	5.96	5.02	2009	6.71	6.02
1940	8.72	8.84	1954	4.21	3.41	1968	5.58	5.05	1982	5.88	5.68	1996	9.00	7.07	2010	8.55	6.42
1941	18.06	16.77	1955	6.93	6.17	1969	5.65	5.46	1983	4.55	4.44	1997	7.90	6.74	2011	4.84	4.20
1942	6.93	6.03	1956	6.46	7.43	1970	6.50	6.35	1984	4.33	3.65	1998	4.53	3.80	2012	4.37	4.40
1943	2.46	1.90	1957	5.99	4.89	1971	4.69	4.26	1985	7.47	6.84	1999	5.67	5.15	2013	8.05	6.23
1944	7.17	6.34	1958	7.41	6.31	1972	4.56	3.90	1986	6.74	6.35	2000	6.49	6.62	2014	4.20	2.27
1945	6.30	6.12	1959	4.24	3.26	1973	3.40	2.20	1987	10.76	9.91	2001	6.68	5.15	2015	5.29	4.78

More detailed data on flow series and the climate model are given in Annex 4.1 of this documentation.

Figure 4: Data from EIA Dukovany 2017:

Water (e.g., water source, consumption) Water consumption: raw water: up to 73,000,000 m3/year. This value represents the maximum (for thickening in the cooling circuits 2 and 3) annual raw water take-off for two NNS[12] units, each with a capacity of up to 1200 MWe, the maximum annual take-off for one NNS unit of 1200 MWe will be to 36,500,000 m3/year. The average (for thickening in the cooling circuits 2 and 5) annual raw water take-off for two NNS units, each with a capacity of up to

[12] NNS = new nuclear unit

1200 MWe, will be up to 68,000,000 m3/year. This data corresponds to the climate scenario + 2°C. The raw water source will be the Jihlava River. Raw water will mostly (approximately 98%) be used for refilling the power plant cooling circuits, the rest (up to 2%) for production of demineralised water, service, fire-fighting and other purposes. Existing water take-off from the Jihlava River for EDU 1-4 is limited to 63,000,000 m3/year (actual take-off ranges up to 55,000,000 m3/year), total take-off for the duration of NNS (one unit with a capacity of up to 1200 MWe) and EDU 1-4 concurrent operation or NNS (one unit with capacity of up to 1750 MWe) and EDU 2-4 concurrent operation will not exceed 99,500,000 m3/year. The need for raw water for construction purposes will be on the order of 1 million m3/year, the assumed source is the existing public water main and eventually the Mohelno water reservoir by means of the EDU1-4 existing raw-water supply system. During operation decommissioning, raw water take-off will gradually decrease. Potable water: up to 140,000 m3/year. The given value represents potable water take-off for two NNS units, take-off per unit will be up to 70,000 m3/year (actually the contracted quantity will be higher). The potable water source will be a connection to the public water main. Potable water will be used for drinking and hygienic purposes but also partly for service purposes. The existing permissible potable water take-off for EDU 1-4 is 350,000 m3/year (however, up to approximately 80,000 m3/year is used from this amount), and accordingly the total potable water take-off during the period of concurrence of NNS (one unit) and EDU 1-4 shall not exceed approximately 150,000 m3/year (the contracted quantity will be higher). Drinking water take-off will be increased to several 100,000 m3/year for construction purposes. During operation decommissioning, potable water take-off will gradually decrease.

Current situation at Dukovany

The situation is critical at the Jihlava River, the Dalešice water, which is also supplying the Dukovany site, is at times losing more water than it is accumulating.

As early as in the summer of 2003, CEZ already was confronted with so low water volumes in the water reservoir Mohelno that CEZ was forced to issue a warning that full operation will not be possible under current heat waves. Another problem occurred already back then: Water quality was insufficient for the plants purposes, because it contained a high level of salts and minerals.[13]

Projects to reduce cooling water needs

It took CEZ 15 years to act upon this and introduce water saving measures. In 2020 CEZ announced their intent to reduce water consumption by taking less from the Dalešice water dam. In the second half of 2020, measures worth 370,000 euros were introduced in order to help save two to eight million cubic meters of water. The measures seem to apply some stabilizers to limit the residue in the technological systems.

Another more expensive project which will be tested at Dukovany is supposed to achieve even higher savings. Currently NPP Dukovany uses around 55 million cubic meters of water. Also the renewal of the cooling towers' interior led to a reduction in water use. This measure would test the introduction of desalination to remove impurities in the water. A reduction of water consumption of another 8 to

[13] https://www.kurzy.cz/zpravy/73730-cez-je-dukovany-zvazuje-omezeni-provozu/

16 million cubic meters of water annually should be become possible according to this plan; costs would be around 40 million euros. However, in a first step a test facility will be built[14].

Political reactions and consequences

While the problem is being recognized and the responsible decision-takers - the government and also the two-third state owned utility CEZ - admit there might not be sufficient water available to supply the cooling water need for the new NPP and the four old units, they only just announced reduced output as a response: if necessary one or more units will be taken off-line[15].

CEZ claims that all five suppliers would deliver their reactors "custom-made" to fit into the needed output range of 1000-1200 MW net output. On top of the water supply limits this most recent claim has a very serious political background: Only Rosatom, the Russian reactor manufacturer, lists a standard 1200 MW reactor in its product portfolio. Therefore the electricity utility CEZ declared that all five companies which already showed interest in participating in the tender will fit into this range; referring also to the option of ordering EDF'S EPR (under construction with 1650 MWe in Flamanville) with an output of 1100 MWe, although no such case has been known in the past years. The design and the licensing of such a made-to-fit model would drive costs and planning and construction time of the new-of-a-kind NPP through the roof. At the same time there seems to be an ongoing project to develop a smaller EPR.

5.3 Nuclear Powers Plants Running Dry: Beznau

Climate change already arrived in Switzerland followed by the well-known effects, which can be summarized as follows:

1. Drier summers
2. Heavier precipitation
3. More hot days
4. Winters with little snow

[14] http://www.halonoviny.cz/articles/view/53527755
[15] Daniel Beneš, ČEZ' Chief Executive Officer at press conference on May 28, 2020 in Prague

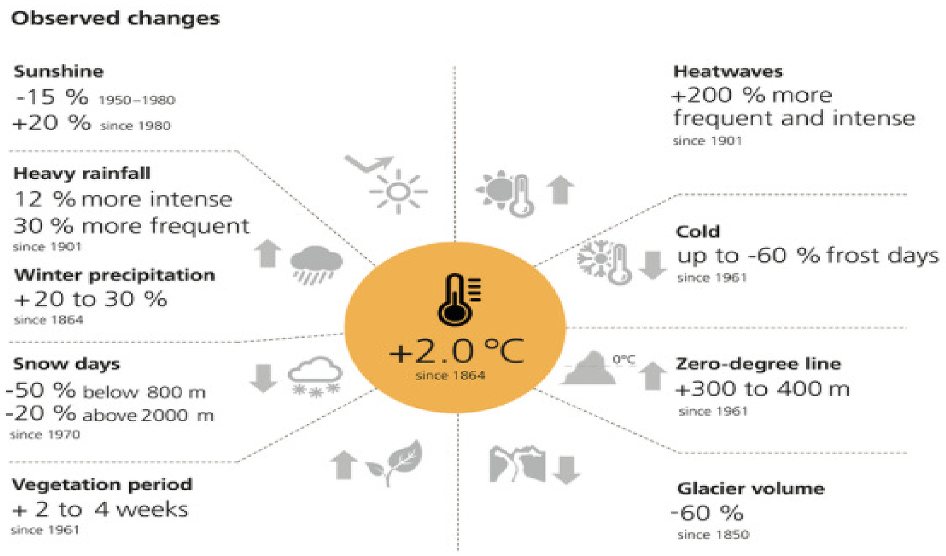

Figure 5: Observed climate changes in Switzerland

The Swiss National Centre for Climate Services NCCS[16] describes the climate changes: "*All regions in Switzerland are considerably warmer than they used to be. The near-surface air temperature has risen over the last 150 years by about 2 °C – a considerably greater increase than the worldwide average. Nine out of the ten warmest years since records began have been in the 21st century. Heavy precipitation events have also become more intense and more frequent.*

In Switzerland, there has been reliable long-term measurement of the climate since 1864. The data shows clear evidence of climate change. For instance, the near-surface air temperature in Switzerland has increased over the last 150 years by about 2 °C. This warming is considerably greater than the global average (0.9 °C). Since the 1980s, our climate has been experiencing its fastest ever-recorded warming.

As a result of these temperature increases, we now have more frequent and warmer periods of hot weather than before. Moreover, the volume of the Alpine glaciers has shrunk by about 60 percent since the middle of the 19th century. Since 1970, the number of annual days of snowfall at 2,000 meters above sea level has diminished by 20 percent, and below 800 meters above sea level, it only snows half as often as it did then. The vegetation period is two to four weeks longer than in the 1960s."

- Swiss NPP Beznau is the oldest NPP in Europe (operated since 1969)
- Beznau units I and II are located at the Aare River
- Cooling water for both units is taken from the Aare River

For the River Aare, where Beznau takes in the water for cooling and where it discharges the heated up water (no cooling towers), this means: Until 2000, the critical temperature of 25 degrees Celsius was exceeded only in 1976 and 1998 on two days each years. For some fish e.g. graylings

[16] https://www.nccs.admin.ch/nccs/en/home/climate-change-and-impacts/observed-climate-change-in-switzerland.html

temperatures above 25° degrees C are life-threatening. However, in the recent 15 years this occurred more often with two years showing very high temperature levels: In 2003, the temperatures were above 25 degrees on 22 days and in 2018 on 23 days. Exceptions were made for NPPs, however, in 2018, a new regulation was announced.

Authorities' response

NPP Beznau's cooling water discharge permit was based on a regulation from 1975. In 1999 a stricter water protection regulation (Gewässerschutzverordnung) was introduced. It stipulated that cooling water must not be discharged into watercourses when their temperature is above 25° C. With an immediate order the responsible Ministry (BFE) forced the Axpo-owned NPP in 2019 to reduce output by 50% or to stop the operation altogether once 25° C were reached; reasons being damages to fish and other aquatic life.

The operator Axpo protested, calling the measures exaggerated and insisted that the 20 year old permit was valid and refused a new discharge permit procedure. The Ministry made clear that **climate change is a new legal situation**. This turned the old permit invalid and in need of re-evaluation. Axpo announced that they might even challenge the new regulations in court. The NPP operator stated that "voluntary regulation" would be given preference. Currently the new permit is being prepared by the responsible ministry.

Beznau's situation is not an exception: Another Swiss NPP – Mühleberg – found itself in a similar situation. Since 2015 it had to run on 80% output already as early as 2003, 2005 and 2006. For Mühleberg the limit is 20,5° of Aare water temperature. In 2015, NPP Mühleberg generated 2940 millions kWh, 23,6 less than in 2014. This reduced output is a consequence of technical problems and the high water temperatures which forced the NPP to run on 20 percent only for a total of 16 days[17]. However, Mühleberg is shut-down for good since Dec 20, 2019.

[17]https://www.srf.ch/news/regional/bern-freiburg-wallis/akw-muehleberg-produzierte-weniger-strom.Accessed June 21, 2020.

6 Conclusions

The present phase of nuclear power has been shaped by the rhetoric of the *“nuclear energy renaissance”,* but in reality it is characterized by the decline of its commercial use in Western market economies. Particularly of note in this context are the bankruptcy of major nuclear companies Westinghouse (U.S.) and Framatome (formerly Areva, France) and the efforts of energy suppliers to shut down unprofitable nuclear power plants as quickly as possible or shift the financial responsibility to the state.

The economic history and financial analyses carried out at DIW Berlin in 2019 show that nuclear energy has always been unprofitable in the private economy and will remain so in the future. Between 1951 and 2017, none of the 674 nuclear reactors built was done so with private capital under competitive conditions. Large state subsidies were used in the cases where private capital flowed into financing the nuclear industry. Nuclear energy is never profitable. Society will be asked to bear a very large proportion of the costs.

The lack of economic efficiency goes hand in hand with a high risk with regard to the proliferation of weapons-grade materials and the release of radioactivity, as shown by the accidents in Chernobyl (1986) and Fukushima (2011). For all these reasons, nuclear energy is not an option for supplying economical, climate-friendly, and sustainable energy in the future.

Expanding nuclear power is impractical as a short-term response to climate change. Planning and approvals can take a decade and construction another decade. Nuclear plants take 5–17 years longer to build than utility-scale solar or onshore wind power, so existing fossil-fueled plants emit far more CO_2 while awaiting substitution by the nuclear option. In 2018, non-hydro renewables outpaced the nuclear program in China, by a factor of two, in India by a factor of three.

Describing nuclear energy as “clean” ignores the significant environmental risks and radioactive emissions it produces along the process chain and beyond. Considering the full nuclear chain, the overall CO_2emissions from new nuclear power plants are about 10 times higher than energy production from onshore wind generators.

Renewable power technologies in general have environmental benefits because they create power without relying on the extraction of uranium and its associated digging, drilling, mining, transporting, enrichment, and storage. As a result, renewable energy technologies provide a much greater potential for substantial carbon emissions reductions than significant investments in new nuclear power generation.

Proponents of nuclear power say that the reactors’ relative reliability and capacity make this a much cleaner choice than other non-fossil-fuel sources of energy, such as wind and solar, which are sometimes brought offline by fluctuations in natural resource availability. Yet no one denies that older nuclear plants are extremely inefficient and run a higher risk of disaster.

Ageing effects threaten the safety of old nuclear power plants. Even though the fundamental ageing mechanisms are well-known in principle, their potential to lead to incidents and accidents may not be fully recognized before the actual events take place. Furthermore, unexpected combinations of various adverse effects may result in the failure of technical equipment, leading to the loss of required safety functions. In old NPPs several undetected failures exist, these failures threaten safety as well as the energy security.

For example, due to continuous technical issues and extended outages, the average load factor of the Belgian fleet plunged to 48.6 percent in 2018. The average age of the seven reactors in Belgium is about 40 years.

Taking seriously the fact that experience with operating nuclear reactors beyond the design lifetime is limited, the claim made by the nuclear industry that the safety related equipment is sufficiently monitored to prevent failure, cannot be fully believed. Moreover, due to the economic situation operators intend to avoid comprehensive checks and maintenance.

Safety design of NPPs is very important to prevent as well as to deal with accidents. Concerns are growing due to the Fukushima accident, as it revealed that there could be basic safety problems with all operating units, especially with the older ones, whose design was prepared back in the sixties or seventies. Their safety design is outdated and showing deficiencies, which cannot be resolved by performing back-fitting measures.

A specific risk of the use of nuclear power is the proliferation risk. The growth of nuclear energy has historically increased the ability of nations to obtain nuclear weapons. Nuclear power plants and nuclear weapons are related in two key respects. First, all technology and materials related to a nuclear weapons program have legitimate civilian applications. Second, civilian nuclear cooperation builds-up a knowledge-base in nuclear matters. The Intergovernmental Panel on Climate Change (IPPC) recognizes this fact. They conclude, with "*robust evidence and high agreement*" that nuclear weapons proliferation concern is a barrier and risk to the increasing development of nuclear energy.

With our climate-impacted world now highly prone to fires, extreme storms and sea-level rise, nuclear energy is touted as a possible replacement for the burning of fossil fuels for energy.

Yet scientific evidence and recent catastrophes call into question whether nuclear power could function safely in our warming world. Extreme weather events, fires, rising sea levels and warming water temperatures all increase the risk of nuclear accidents, while the lack of safe, long-term storage for radioactive waste and proliferation remain persistent issues.

Global warming can contribute to the intensity of heat waves by increasing the chances of very hot days and nights. Warming air also boosts evaporation, which can worsen drought. More drought creates dry fields and forests that are prone to catching fire, and increasing temperatures mean a longer wildfire season.

Global warming also increases water vapor in the atmosphere, which can lead to more frequent heavy rain and snowstorms. A warmer and moister atmosphere over the oceans makes it likely that the strongest hurricanes will be more intense, produce more rainfall, and possibly be larger. A scientist warned 2019 about super-storms and related giant waves, able to push 2300-ton boulders along the ocean floor, far more numerous and higher than the one that damaged the Fukushima power plant.

The climate change affects nuclear energy production in several ways, including

- The efficiency of nuclear power plants decreases with increasing temperature.
- Some sites may lose safety, with sea-level rise being of particular importance.
- Extreme weather events threaten the safety of NPPs additionally.

The IAEA distinguishes climate change related phenomena between Gradual Climate Changes (GCC) and Extreme Weather Events (EWE). Regarding the loss of efficiency of nuclear power plants as well as location issues are primarily associated with gradual climate changes, while safety issues are rather linked to extreme events. However, gradual climate change and extreme weather events are linked – rising sea levels, for example, also lead to extreme water levels during storms.

If global mean temperatures rise by 0.4°C in 20 years, a 1 GW(e) nuclear power plant would lose generation owing to **reduced thermal efficiency valued** at approximately €4–21 million net present value over the next 20 years. If current nuclear generation is projected for 20 years for all current nuclear plants, the global cost of rising temperature is on the order of €1–6 billion.

The risk of flooding is another symptom of our warming world that could lead to nuclear disaster. Many nuclear plants are built on coastlines where seawater is easily used as a coolant. Sea-level rise, shoreline erosion, coastal storms and heat waves – all potentially catastrophic phenomena associated with climate change – are expected to get more frequent as the Earth continues to warm, threatening greater damage to coastal nuclear power plants.

We are now observing persistent weather patterns more and more frequently during the summer half-year in the northern hemisphere. Their long duration can result in extreme outcomes. The summer of 2016 demonstrated that a single weather pattern can trigger both localized intense precipitation with flash floods and large-scale precipitation with river floods. Following the events of 2016 in Europe, it should be clear that extreme amounts of precipitation within a very short time are possible almost anywhere.

While it is undisputed that extreme weather events will become more frequent with climate change, it is difficult to quantify these changes. The probabilities of occurrence for licenses are usually derived from past data series using statistical methods. In a phase of climate change, however, these data series are no longer relevant and the derivation procedures are no longer valid. Science is overwhelmed with precise statements on the probability of occurrence of rare events. In flood protection safety factors are sometimes added whose scientific validation is questionable. In the case of nuclear energy, this route is not recommended because the risk is too great in the case of under-dimensioning.

Furthermore, because the situation is constantly evolving, any data that can be acquired may be outdated by the time their evaluation is concluded. The time lag is still more drastic for the drafting of new rules and regulations by the authorities, and their implementation by the NPP operators. It seems hardly possible to win this race against time – particularly in the face of economic pressure that might lead to the result that only low cost measures are realized.

The inadequate protection against floods at the Blayais site illustrates the problem of delayed and furthermore outdated backfitting measures. In spite of the fact that the hazards of climate change are becoming more and more obvious, safety reassessments and improvements generally are only implemented – if at all – after an event occurred. This practice is aggravated by the fact that an event in one NPP does not necessarily lead to backfits in another plant.

As shorelines creep inland and storms worsen, nuclear reactors around the world face new challenges. By the time Hinkley Point C is finished, possibly in 2028, the concrete seawall will be 12.5 meters high, 900 meters long, and according to the regulator will withstand the strongest storm surge, the greatest tsunami, and the highest sea-level rise at the site. But the plans were drawn up in 2012, before the increasing volume of melting of the Greenland ice cap was properly understood and when most experts thought there was no net melting in the Antarctic.

IAEA's current global safety standards were published in 2011. These state that operators should only take into account the 18- to 59-centimeter sea-level rise projected by 2100 in the

Intergovernmental Panel on Climate Change (IPCC)'s report, published in 2007.However, these values are outdated. The IPCC report, published in 2013/14, see sea level rise up to 100 cm by 2100.

Extreme Weather Events can also cause a failure of the electric power supply. Nuclear power plants generate electric power and supply it to the offsite grid. On the other hand, the plants themselves are dependent on a continuous electric power supply to operate, particularly for the instrumentation and safety systems, even when they are shut down. After the Fukushima accident, measures to cope with Station Blackout situations are improved. However, these measures are mostly the deployment of mobile equipment, which would be difficult to use in an accident situation.

Cold and heat waves represent a significant problem for the electricity generation sector. Unplanned outages at nuclear power plants by excessively high-temperature water constitute clear examples of this. It has been reported that near to 40% of the NPPs in Europe have already experienced cooling problems because of high temperatures.

Every 24 hours that a 1 GW nuclear plant is shut down (assuming €0.05/kWh) costs the plant owner €1.2 million in lost revenue. Outages also lead to indirect costs. When an NPP is shut down owing to an extreme weather event, electricity customers must either experience a power outage or pay more for electricity from alternative sources to fill the gap. Renewable power generators, in contrast, decentralize electricity supply so that an accidental or intentional outage would have a more limited impact than the outage of larger nuclear facilities.

Nuclear power plants are a poor choice for addressing energy challenges in a carbon-constrained world. NPPs are prone to insolvable economic and environmental problems. Additionally, they are connected to problems of reactor safety, waste storage, weapons proliferation, and vulnerability to attack.

"Nuclear energy for climate protection" is an old narrative that is as inaccurate today as it was in the 1970s.Climate change guarantees lower profits for nuclear power plants but requires expensive retrofitting measures. Adaption measures to climate change are delayed or even avoided, so the risk of ageing plants continues to increase. Energy and climate policy should therefore target a quick withdrawal from nuclear energy. Subsidies for life-time extensions are not recommended because they support the risky, uneconomical nuclear industry. This is even more true for new construction.

Gregory Jaczko, former chairman of the US Nuclear Regulatory Commission states 2019 the nuclear technology is no longer a viable method for dealing with climate change: *"It is dangerous, costly and unreliable, and abandoning it will not bring on a climate crisis."*

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8 Annex I: Case study: Nukes and climate: how climate change affects the past, present and future of Paks Nuclear Power Plant

By Eszter Mátyás, Energiaklub

8.1 Introduction

"Stabilizing the climate is urgent, nuclear power is slow" (Mycle Schneider WNISR)

In the century of climate change, it is urgent to understand, why many claims that nuclear energy could be the solution for the climate crisis. As this case study of Hungary will present, there are several country and climate characteristics that determine the present and future of nuclear power plants. The case of Paks is special in a sense, since here we can examine both the present (Paks I Nuclear Power Plant) and future (Paks II NPP) of nuclear power plants under the effects of climate change. When it comes to water scarcity caused by climate change, most attention is paid on drinking water and water used in agriculture, while the energy industry is a major beneficiary of the Earth's water resources. There is a great need for water in the cooling of nuclear power plants.

This paper will present how Hungary's climate developed in the last few centuries and how the climate influences the operation of the nuclear power plant in Paks. Here it will also be discussed how the planned two new reactors of Paks II investment will be affected by the climate crisis and what problems occurred in the past that could be concerning for the future of nuclear energy in Hungary.

8.2 Hungary's Climate specificities

The climate of Hungary is determined jointly by the oceanic, Mediterranean and continental climate. These, together with the relief effects of the Carpathian Basin, result in a variable climate. (Due to strong fluctuations, trends in climate parameters are not always statistically validated.) (Láng, Csete, Faragó, 2006.) Climate change is projected to increase the likelihood, frequency, duration and intensity of extreme hydrological and soil moisture situations (flood, inland water, over-humidification and drought, often in the same year, in the same area). (Várallyay, 2006.)

Hungary's climate was determined by seven climate types at the beginning of the century and by five at the end of the century. The moderately cool, dry and moderately cool, moderately moist types were no longer dominant, but the spatial extent of the warm, moderately dry climate increased significantly. Most types of climate between 1901 and 1930, with the exception of one test point, can be found in later periods. (Skarbit, Ács, Breuer, 2014.)

Annual precipitation in the XX. century decreased significantly. Especially in spring, when the seasonal rainfall was about 75% of the beginning of the century. The amount of summer precipitation has remained essentially unchanged over the past hundred years. There have been dry summers in the past, but with the gradually rising summer temperatures, the effects of recent dry periods are much greater. Autumn and winter precipitation decrease by 12-14%. Winter precipitation does not seriously affect the annual precipitation, as the average amount of precipitation in the winter months is the lowest compared to other seasons. (Láng, Csete, Faragó, 2006.)

The most uniform changes are in the temperature trend. The national average is well in line with global change, and it is even slightly higher. While winters and springs are predominantly warming to the annual average, summers annuals are higher (about 1 ° C) and autumns are lower (0.4-0.5 ° C). Over the past 30 years, warming has accelerated. In Hungary, the minimum and maximum temperatures are increasing to a similar extent. (Láng, Csete, Faragó, 2006.)

The characteristics of the temperature data in Hungary fit well with the global trends in temperature, but due to the smaller area, its' variability is higher. The tendency of warming is mainly reflected in the summer temperatures, with an increase of 1.17 ° C from the beginning of the last century to the present day. The average summer temperature between 1971 and 2000 was 19.7 ° C. There have also been cooler summers in the last decade, but the low values have characterized the first half of the century. And in the last thirty years, average summer temperatures have risen by almost 2 ° C. Annual precipitation in Hungary is decreasing. Rainy years were more likely to occur in the first half of the last century, a decline of 7% from 1901. The occurrence of dry summers is relatively even, indicating that drought is a regular feature of our country's climate. Summer precipitation is not significant but is increasing. Precipitation is highly variable in space and time, making it more difficult to detect trends due to climate change than with temperature. While the average annual temperature has shown a clear, significant increase over the last 30 years, the change in precipitation cannot be clearly detected even with a longer period of 50 years, with 95% confidence. (Bartholyi, Bihari, Horányi, 2011.)

An additional problem may be that less precipitation arrives more intensely. On the one hand, this worsens the utilization of precipitation, i.e. the water balance, because less water seeps into the soil, on the other hand, it increases runoff, which means an increased risk of flooding. (Láng, Csete, Faragó, 2006.)

In Hungary, the frequency, magnitude and damage consequences of drought and inland water are different. Large-scale drought areas are more likely in the future than inland or flood areas affecting local or smaller areas. Although the main threat to the volatility of atmospheric resources in agriculture is drought in Hungary, the events outlined in recent years demonstrate the need to prepare for drought, inland water, floods, frost damage, hail, local floods, thunderstorms, more specifically to their potential prevention, the damage reduction, the restoration, the preparation of the legal background and redress. (Láng, Csete, Faragó, 2006.) Assessing the adverse effects of falling precipitation, it has been repeatedly stated in recent years that desertification is also occurring in Hungary. However, since the rainfall in the country is smaller than 400 mm in drier years, it is only in exceptional cases that we cannot talk about desertification. It is better to consider a significant decrease in precipitation as drought. (Bisselink, Bernard, Bernhard, Gelati, 2018.)

How these changing climate conditions affect the river Danube, which has a crucial role in the operation of the Paks nuclear power plant are presented in the next paragraph.

8.3 Danube basin characteristics

The Danube River Basin is a significant water source in the Central-European region: it includes 19 countries, is utilized as a major transportation route and serves as an important habitat for wildlife and fisheries. As the 2018 European Commission's Joint Research Centre report presents, 2°C increase due to climate change would lead to "increased flooding and water scarcity, significantly drier summer months and substantial flood damage in cities along the Danube River and its tributaries." (2018.)

As it can be deduced from the previous paragraphs, climate change is the dominant factor in changes of the Danube basin.

The JRC report also discusses that water scarcity is projected to be more severe and protracted, especially during the summer months within the southern and eastern Danube basin. The end-of-the-century climate scenario of the report shows substantial increases in water scarcity in Hungary, especially during the summer months. (JRC, 2018.)

Due to the characteristics of the nuclear power plant, as a pressurized water reactor, Paks NPP's existence relies on the Danube. Therefore, it is crucial to have sufficient freshwater resources. But as the JRC report points out, the water temperature of the available cooling water is very important, since restrictions apply in many cases to the allowed temperature of the water after cooling. Given the rise in surface temperatures within the entire Danube basin, it is expected that cooling water temperature will give rising to additional increasing issues. (JRC, 2018.) These trends in changing climate and river characteristics have significant impact on the Paks NPP and Paks II. The reason why it is ambiguous are presented in the next chapter.

8.4 Why the trends are problematic?

In the summer of 2018 and 2019, the operation of the Paks nuclear power plant was in jeopardy, because according to environmental regulations the water temperature of the Danube should not exceed 30 degrees Celsius 500 meters from the mouth of the cooling water channel. This should be monitored continuously as the Danube crosses the 25 ° C limit, and after mixing with the cooling water used, the power output of the power plant should be reduced by 0.1 ° C in increments of 0.1 ° C until the Danube falls below the specified temperature limit water.

Between July and August 2018, the water of the Danube was 25 for almost a month, often above 26 degrees, and in early August this year temperatures were rising to 26.2 degrees Celsius. The Paks power plant officially said last year 29.8 degrees was the highest measured at the 500-meter point, avoiding the need to shut down more than 50 percent of the country's electricity production. (CDP Report)

But according to an August report by the World Resource Institute, Hungary is the 16th most threatened country in the world in terms of expected drought frequency, which may not only deplete reservoirs but also reduce the water level and discharge of the Danube. (qubit.hu) Otherwise there would be enough water in the Danube - according to a previous statement of the power plant, 100 cubic meters of water are needed for the four reactor units per second, and the lowest Paks Danube discharge so far is 800 cubic meters. That is why one of the impact studies of the Teller-Lévai project, which is preparing for the expansion of Paks, states that the combined operation of the current 2000 and the planned additional 2400 megawatts of reactor capacity can no longer be solved with the Danube water. The study suggested that cooling towers be built for cooling or that the Danube should be swamped with a cross barrier (the latter would create a difficult to handle situation by slowing down the flow and overheating the water). (qubit.hu) According to Jávor as well, the official plans water issues are unrealistic. As he discusses, the estimation of 1500m3/sec water discharge from the Danube, taken as a basis for warm-water transfusion, is not correct-it's too high. in keeping with hydrological studies made for the expansion of the operational time of the Paks power plant, the little water discharges from the Danube are literally below 900 and 1000m3/sec. The mistaken selection of base data for modelling suggests that the adequate assessment of accessible data was not administrated. It is highly improbable that a 1500m3/sec water discharge from the Danube and a 33-Celsius-degree extraction-water would occur simultaneously. The modelling of warm-water transfusion should be done again, now taking realistic values of water flow and water level likewise like the realistic distribution of water recirculation. (Jávor, 2015.)

With the two new reactors of Paks, current situation could worsen. As Zsuzsanna Koritár pointed out, another critical point of the impact study of Paks II is the proper heating of the new blocks and the heat load on the Danube. The timeframe of the parallel operation of the 6 blocks is substantially important. According to the EIS, the heating of the reactors is solved with freshwater cooling, which generates risk both on the environmental and the security side. (Koritár, 2015.) Koritár's article discussed the important question of personal responsibilities as well, which are missing from the impact study and the plans of Paks II at the moment.

But as it was presented above, not just the planned new reactors depend highly on the Danube, but the current reactors too. And as it was shown, climate change affects the operation of the NPP. In the past few years, as Hungary was facing several extreme weather occurrences, problems emerged that reveal the mistakes that exist in the system of Paks NPP. In 2018 Hungary experienced extreme heat during the summer. As the temperature raised, Energiaklub submitted a freedom of information request to the Hungarian National Atomic Agency to find out how the increased temperature influences the daily operation of Paks NPP. Since the authority did not provide the information, Energiaklub travelled to Paks to measure the temperature of Danube. The results of measurements upstream from the nuclear plant showed the water temperature to be 25-26 °C. Downstream, however, the temperature rose to above 30 °C at several points.

As János Ősz, engineering professor of the Budapest University of Technology stated afterwards, it is a common practice for nuclear plants to have a limit for the water temperature of the river where they dispose of their cooling water. For Paks the cut-off is set at 30 °C, but it can be lower. In France, for example, it is 28 °C and in the beginning of August some reactor blocks of three nuclear plants were stopped accordingly when the water temperature rose above that value. (atlatszo.hu) As the measurements of Energiaklub showed, in the case of Paks, water temperature was indeed higher than accepted, but as later the General Directorate of Water Management stated, their official measuring tools were broken because of the heat and the low water which made it impossible for them to monitor the water temperature every hour. They switched to one measurement a day, performed by hand at 7 every morning, the time when the water is the coolest. (atlatszo.hu)

This experience is a great example of how the Hungarian authorities deal with such issues. As the Hungarian government is not a "believer" in climate change, they are not exactly up to date on how to act in situations where climate crisis clearly affects everyday operation of a nuclear power plant.

Shortly after Energiaklub published the findings and a video, the company running the nuclear plant, MVM Paksi Atomerőmű Zrt. sent its official water temperature data. On the day of the measurements of the temperature to be over 30 °C the official thermometer measured 28.42 °C. The nuclear plant registered the highest water temperature, 29.88 °C, at the beginning of August. This is only 0.12 °C lower than the temperature at which the nuclear plant must be stopped in order to protect life in the river.

While there was a difference between the data of Energiaklub and that provided by the nuclear plant regarding the area downstream from the plant, the two datasets matched in regard to the area upstream: 25,7 °C. (atlatszo.hu)

This event did not only reveal how the process of measuring water temperature works improperly but highlighted another important weakness of the system- the question of transparency. Namely only after Energiaklub's investigation Paks NPP had published data on water temperature measurements. Ever since then there is a subpage on the website of Paks on the details of water issues.

Despite the developments in 2018, Paks NPP continuously ignores the rules and does it without transparency. The nuclear power plant just recently, in February released hotter water than permitted. According to a recent order issued by the Baranya County Government Office, the Paks Nuclear Power Plant has released warmer water into the Danube than it could have under its existing permits. In addition, "used water" at temperatures above the limit was discharged into the river in February, which makes it even more strange because it cannot be explained by the surge in production to meet increased consumer or network demand. According to a document, the government office initiated the procedure only 3 days earlier, and only doubted that the Paks Nuclear Power Plant had failed to comply with one of its environmental permits. According to which "in order to protect the Danube's thermal pollution, the difference between the temperature of the discharged and the receiving water should not be greater than 11 degrees Celsius and the temperature of the receiving water below +4 degrees Celsius should not be more than 14 degrees Celsius". However, at dawn on February, the power plant's own measurements, from 3.48 to 4.05, were 11.2 degrees Celsius.

The deviation from the upper limit does not seem to be much, but the limits set in the environmental permit justify the operating framework within which the operation may pose a load that is considered to be tolerable for the Danube wildlife. Exceeding the limit value can therefore also be described as environmentally harmful. (napi.hu)

What made this case interesting despite the above discussed additional problems is that such errors were previously only made during summertime, and not in the middle of the winter. It also draws attention to the fact that during the operational time of a nuclear power plant not even the smallest differences from the regulations can be accepted.

8.5 Possible solutions

As it was discussed in the former paragraph, several problems occurred by climate change are not solved yet at Paks NPP and if we take a look at the plans of Paks II, it is the same situation. Although the minister in charge of the Paks II investment stated, that the engineers of the power plant are preparing for the local conditions, cooling in our case, there are some solutions that should be discussed which are absent from the state communication.

Based on the analyses of Jávor, it is necessary to develop a flexible, cost-effective solution in the field of refrigeration in the future for the additional reactors, which is able to monitor changes in climate, water regime and critical temperatures. (Jávor, 2015.) According to him, the return of heated cooling water must be ensured while complying with wildlife protection regulations. He proposes four possible solutions in the field of water cooling of Paks II NPP, that are the following:

- Water cooling could be decoupled from wildlife protection requirements by providing a closed cooling water system such as a cooling lake. Closed cooling water systems are common in nuclear power plants to the east and west of us. The water of the artificial cooling pond is not subject to the requirements of wildlife protection. Therefore, the water temperature limits may be primarily adapted to the requirements of the technology.
- In the case of recirculation, in addition to the current performance, the effect of onshore introduction and natural mixing is currently sufficient. The increasing amount of hot water as a result of the expansion necessitates the use of more intensive mixing methods. These could be split-point introductions or multi-point introductions. The effectiveness of this may be limited by the increase in the water temperature of the Danube due to climate change, and on the other hand by the decrease of the water temperature limits. In the long run, the effectiveness of the solution may be limited, and further intervention may be required.
- The third option is to improve the critical operating conditions in an open cooling water system connected to a natural stream. There is a relationship between water depth and water temperature maximum. By raising the water level, the peak water temperature can be reduced. Increasing water depths along the Danube section to reduce peak Danube water temperatures can simultaneously solve water abstraction and navigation problems. Raising the water level can be achieved by damming. Mixing can be significantly increased by the equipment of the dam facility, such as water turbines.
- The investor's commitment to water cooling is clear from the Environmental Impact Study. On the other hand, the reasons for excluding cooling towers and air as heat-absorbing media have not been or become known. In the absence of a proper justification, it is questionable whether this alternative can indeed be disregarded in the future. (Jávor, 2015.)

Many options are available for the future of nuclear industry in Hungary as we can see on how to deal with cooling issues and climate change. But as the recent official communication and absence of transparency and civil reconciliations present, about-turn is needed from the Hungarian government to realize these much-needed amendments.

8.6 Conclusion

Climate change affects Hungary's climate in many ways but in connection with nuclear power plants, the most aching effects are the water issues. As the case of Hungary presented, several options exist to solve cooling issues of the current four reactors of Paks and the future two reactors of Paks II, but these are highly dependent on the regulations and decisions made by the authorities and the government. Recent years have shown that not only the regulatory system is full of open to interpretation rules but the lack of political will also makes it difficult to achieve substantive changes. Greater transparency of the measurement processes and the inclusion of the civil society and experts would improve the quality of the developments and could reduce the errors experienced so far. Malfunctions of the cooling process should be a warning sign for the planning of Paks II and greater attention should be paid to the climate condition changes. After all, the Hungarian government believes that nuclear energy is the solution for climate crisis, therefore it is crucial to take climate change seriously and modify the operation of the NPP according to it.

8.7 References Annex

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