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D2.4.1
Combinations of co-occurring external hazards relevant for nuclear power plant safety

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MAWECLI (MArine and WEather events in the changing CLImate as potential external hazards to nuclear safety) project in the SAFER2028 Programme

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Abstract

In this literature review of recent publications on compound external hazards, we focus in particular on events that are of importance from the perspective of nuclear power plant (NPP) safety, especially in Finland. We investigate altogether 30 recent articles on compound events and related methods. As examples of compound hazards, we address five different phenomena: compound flooding, precipitation and wind speed extremes, freezing rain and wind gusts, atmospheric heatwaves and drought, and high temperatures in the atmosphere and the sea.

1 Introduction

This literature review report is part of task T2.4 ”Towards a synthesis of relevant combinations” in the MAWECLI project plan (2023-2025). The objective of the task was to take initial steps towards a synthesis of combinations of co-occurring external hazards that are meteorologically plausible and may have a plant level effect. In addition to this review report on safety-significant external event combinations, a workshop entitled ”MAWECLI workshop on NPP relevant marine and atmospheric events and their combinations” was organized to gather knowledge and ideas on the topic from the stakeholders of the project, i.e., representatives of the Radiation and Nuclear Safety Authority (STUK) and NPP companies.

The workshop was successfully held between the MAWECLI project members, safety authorities and NPP representatives at the Finnish Meteorological Institute on 28 May 2025. The workshop was a continuation of MAWECLI ad hoc meetings that have been organized annually to present the latest results of the project and to discuss potentially interesting new topics for future work with the stakeholders. In the workshop in May 2025, presentations and discussion on the next steps on the following topics took place: coastal floods and cyclones; high sea levels due to clustered cyclones; extreme sea levels and waves caused by synthetic cyclones; co-occurrence of meteotsunamis, convective storms and lightning; extreme air temperatures in the past and future climate; marine heatwaves and high seawater temperatures; strong winds; wind speeds and wind gusts; environments and climatology of derechos; and snowfall events. In addition to these topics, new ideas arising from the stakeholders side were welcomed to be expressed and discussed.

The aim of this report is to summarize the most recent knowledge on co-occurring hazards relevant in the perspective of NPP safety. First, we describe the risks posed by combined hazards, and discuss on the methodological choices and challenges related to estimation of these complex events. Then, we give examples of recent scientific publications related to specific combined events. Finally, we discuss how these findings might be utilised in the future work.

2 Nature of compound events

Climate warming is affecting the intensity and frequency of several types of natural hazards worldwide. This may have consequences for the safety of nuclear power plants, among other critical infrastructure. Globally, there have already been multiple cases of nuclear power plants being forced to shut down due to events associated with climate variability and change (Kim et al., 2024).

Zscheischler et al. (2018) examined future climate risk due to compound events. They defined compound events as combinations of weather and climate drivers that contribute to societal or environmental risk. They pointed out that usually processes giving rise to extreme events interact with each other and are spatially and/or temporally dependent. Compound events may lead to large impacts and damages to society but they are complex to study, particularly due to dependencies between drivers and/or hazards. Few occurrences in the history and changing likelihoods of the contributing processes makes the prediction of these events in the future challenging. The authors of the study concluded that most major weather and climate-related catastrophes are caused by compound effects of multiple drivers and that methodologies accounting for compound events need to be developed in order to enhance risk assessments of extreme events.

Four different types of compound events were introduced by Zscheischler et al. (2020), namely preconditioned, multivariate, temporally compounding, and spatially compounding events. Guidelines on how to study these types of events are given by Bevacqua et al. (2021). A statistical method related to multivariate compound events is to use copula approaches for studying the dependence structure between the individual variables of the combination (Tavakol et al., 2020). A copula is a function that links or joins a multivariate distribution function to its single dimension marginal distribution functions (Nelsen, 2007). Lately, Zscheischler et al. (2022) noted that due to the complex nature of the compound events, storylines could be used to investigate physically plausible event pathways. The traditional way to represent uncertainty in physical aspects of climate change is based on ensembles of climate model simulations. A storyline, on the other hand, is a physically self-consistent unfolding of past events, or of plausible future events or pathways (Shepherd et al., 2018).

An extensive review of the rapid growth of compound weather and climate event research during the period 2012-2022 is provided by Brett et al. (2025). Altogether 366 peer-reviewed scientific articles were identified, and within these papers, about 30 different compound drivers and/or hazard components were analysed more than once. According to the review, compound floods as well as high-temperature low-precipitation events are the most studied in the literature. High-precipitation high-wind events are also relatively frequently studied, whereas few if any of the papers reviewed by Brett et al. (2025) examined high-air-temperature-high-sea-temperature events.

Current knowledge of natural hazards and extreme events in the Baltic Sea were reviewed by Rutgersson et al. (2022). Many extreme events in the region are connected to the large-scale atmospheric dynamics, including storms originating from the North Atlantic region. Similarly to Zscheischler et al. (2018), Rutgersson et al. (2022) stated that the most dangerous events are typically combinations of several factors. A good example of effects of combined drivers in the Baltic Sea is how extreme sea levels in the Baltic Sea coasts depend not only on individual storms but on the underlying total water level of the basin. Rantanen et al. (2024) found that extreme sea levels in the Baltic Sea are usually associated with not one, but multiple passing extratropical cyclones within a week. This is because clusters of cyclones are typically accompanied by long-lasting westerly winds that push water from the North Sea through the Danish straits, increasing the total water level of the Baltic Sea basin. Rutgersson et al. (2022) further stated that knowledge about compound events is still fragmented and development of statistical methods (including machine learning) to understand these phenomena is needed.

Kim et al. (2024) made a worldwide literature-review based investigation of climate change related external events that could potentially impact nuclear power plants. Based on the outcomes, they suggested recommendations for future tasks. The main conclusions of their study were that i) climate change-induced external events have primarily caused minor incidents, such as temporary shutdowns, rather than significantly compromising the safety of nuclear power plants, ii) location-specific measures are vital in order to face the potential impacts of climate change on the safety and operation of nuclear facilities because intensity and frequency of the external events may vary locally, iii) accidents related to climate change are likely to origin from failures in lower-grade safety systems that may propagate to highergrade safety systems, and iv) relying solely on historical data may not suffice due to the dynamic nature of climate change.

In Finland, Jylhä et al. (2018) summarized research topics, methods and materials related to extreme weather and marine phenomena potentially dangerous for the Finnish nuclear power plants. They examined both single and combined external events. They identified altogether 11 combined hazards: high temperature and humidity; heavy snowfall with high wind speed; snow load with high wind speed; frazil ice or pack ice with strong wind; organic material in sea water with strong wind; frazil ice or pack ice with strong wind and heavy snowfall; organic material in sea water with strong wind and heavy snowfall; high peak current of flashes with strong wind, downburst or tornado; heavy rain with strong wind; high air and sea water temperatures; and low air temperature and strong wind.

For constructing scenarios for compound hazards in the future, climate model data are needed for two or more weather variables. As is well-known, however, information provided by climate models is typically biased with respect to observations. Therefore, there is a need for multivariate bias-adjusting methods that should possibly also consider potential bias nonstationarity (see, e.g., Olsson et al. (2015); Van de Velde et al. (2022)). However, this topic is beyond the scope of the present report.

3 Examples of compound hazards

3.1 Compound flooding

All the Finnish NPPs are located on the coast. For this, knowledge on the behavior of sea level is of importance. Extreme sea levels are hazardous for NPPs as flooding exceeding the design values of an NPP would be a risk for safety-critical compartments, in particular electric power supply and control systems. Coastal flooding on the Finnish coast has been investigated recently in several studies in the MAWECLI initiative. These studies primarily address individual drivers of coastal flood risk rather than compound flooding events. Räty et al. (2023) estimated return periods of extreme sea levels using Bayesian hierarchical modeling approach, Rantanen et al. (2024) examined how clustering of cyclones correlate with extremely high sea levels, and Särkkä et al. (2024) studied the highest plausible limits of extreme sea levels in the Baltic Sea caused by synthetic cyclones. In addition, Pellikka et al. (2023) made projections for the Finnish coast for mean sea level, which is a crucial component when assessing risks of coastal flooding in the future climate. Below, we summarize two articles on compound flooding events where oceanographic driver(s) (sea level and/or waves) are involved.

Nasr et al. (2021) pointed out that coastal areas located at low altitudes are exceptionally prone to flooding because these areas are exposed to effects of multiple drivers. They examined compound flooding along the United States coastline using both observations and reanalysis data sets (ERA5). With the help of Kendall's rank correlation coefficient (τ) and tail (extremal) dependence (χ), they analyzed dependence between oceanographic (storm surge and waves), fluvial (excessive river discharge), and pluvial (direct surface runoff) drivers. The study revealed the highest dependence between surges and waves, and after that by surge and precipitation, surge and discharge, waves and precipitation, and waves and discharge. The authors also conducted a dependence analysis for the pairs of drivers (discharge – precipitation, surge – precipitation, surge – discharge, surge – waves, precipitation – waves, discharge – waves) for the tropical season (June–November) and extra-tropical season (December–May), and discovered that the dependence values are principally stronger in the tropical season. Regional differences in the strength of dependence was found: along the Gulf of Mexico and parts of the East Coast a stronger dependence between drivers during the tropical season was found, and on the West Coast, stronger dependence during the extra-tropical season was found. This outcome is important as the seasonal differences in the strength of dependence between the different flooding drivers indicate in which season certain locations are more likely to be affected by compound flooding.

By utilizing ERA5 reanalysis and by conducting a bivariate analysis of the dependence between flooding drivers, Camus et al. (2021) examined compound flood potential in Europe and surroundings (including the North Atlantic, Baltic, Mediterranean, and Black Sea coastlines). They focused on flooding events caused by four different drivers: precipitation, river discharge, storm surge, and waves. The study had two goals: 1) examining sensitivity of the compound flooding potential to multiple factors, for example to sampling method (annual maxima vs. peak over threshold approach) and 2) exploring the dependence between pairs of the four flooding drivers (river discharge – precipitation, river discharge – storm surge, river discharge – waves, river discharge – storm surge and waves). Regarding the effect of sampling method of the first goal, the analysis showed higher correlation coefficients using annual maxima than peak over threshold approach. In terms of the second goal, significant differences in the dependence between the pairs of drivers were observed. The study revealed also that hotspots of compound flooding potential locate along the southern coast of the North Atlantic Ocean, the western coasts of France and the UK, and the northern coast of the Mediterranean Sea. In these hotspots, the compound events are driven by the combination of the four drivers. In addition to the hotspots, the study revealed that regions with relatively high compound flood potential locate in the eastern coast of Italy and the southern Mediterranean Sea. In these regions, combinations of precipitation and sea level were the main reason for compound flooding.

With the help of the approaches used in the studies presented above, it is possible to identify places with the highest potential for compound flooding, as well as to determine driver combinations that are more likely to contribute to compound flooding. The results highlight that coastal flood risk cannot be assessed by considering individual drivers in isolation, as their dependence can substantially amplify impacts relevant for critical infrastructure such as nuclear power plants.

3.2 Precipitation and wind speed extremes

Both very heavy precipitation and strong winds caused by low pressure areas, i.e., extratropical cyclones, are single external events that need to be taken into account in safety considerations of NPPs. First, very high accumulation of precipitation might result in pooling of water near buildings, thereby posing a potential risk to safety equipment, especially electric power supply and control systems (Jylhä et al., 2018). Second, offsite power might be lost due to objects carried by wind to the switchyard or due to structural damage of power line pylons (Jylhä et al., 2018). Accordingly, also their combination is of relevance for nuclear safety.

Owen et al. (2021) quantified the co-occurrence of extreme precipitation and wind gusts over Europe during the extended winter season (October to March) of years 1980-2018. The 99th percentile was used to define an extreme. As an empirical measure of extremal dependency, the conditional probability χ was used, indicating the probability of precipitation (or wind) exceeding the selected threshold given that wind (or precipitation) is also extreme. Besides exploring spatial distribution of the compound events for different time scales (a maximum of 24 h lag and lead was allowed), also their relationship to extratropical cyclones was investigated. The cyclones were identified and tracked using an objective feature tracking algorithm (Hodges, 1999). In addition to ERA5, three observational data sets were used.

According to the results, the probability of co-occurring extreme precipitation and extreme wind is largest along Europe's western coasts, the northeastern coast of the Mediterranean and south of the Alps. In contrast, eastward facing coasts in Europe showed lower co-occurrence. In Finland, the probability was in general slightly higher in the south than in the north, and twice as high for 1-hour than for 48-hour precipitation accumulation period. Furthermore, the findings of the study suggested that cyclones moving through regions on hourly or 6 hourly timescale are the main cause of the co-occurrence. The probability of a cyclone occurring nearby (within 1110 km) at the same 6-hour time period as an extreme compound event was estimated to be around 80 per cent in Finland.

Rather than examining climatological patterns of co-occurring heavy precipitation and strong winds, Zscheischler et al. (2021) introduced a method to evaluate how applicable output data provided by weather modelling is for the analysis of highly extreme compound weather events. Noting that two weather variables can be dependent at normal levels but asymptotically independent in the extremes, the authors focused on the dependency structure in the tails of bivariate distributions of daily precipitation sum and daily maximum wind speed in a reanalysis product (ERA5) and a set of simulations by a high-resolution regional weather model (WRF). Two tail dependence parameters and a metric called Kullback–Leibler (KL) divergence were considered, and the method was demonstrated for a region in central Europe, including the Alps, during November-March in 1980-1999. It was found that during the study period the high-resolution WRF simulations performed better than ERA5 in realistically capturing precipitation and wind extremes as well as their response to orographic effects. The authors also pointed that because the selected model settings appeared to strongly affect the simulated dependence structure of compound precipitation and wind speed extremes, a range of different climate and weather model combinations are needed in order to make robust compound-risk assessments for future climate conditions.

3.3 Freezing rain and strong wind gusts

Within the Finnish Research Programmes SAFIR2018 and SAFER2028, the occurrence of freezing rain and strong wind gusts as separate events have been studied by Kämäräinen et al. (2017) and Kämäräinen et al. (2018) and by Laurila et al. (2025a), respectively. As mentioned above, offsite power might be lost due to strong winds. Furthermore, ice coating formed by freezing rain may lead to severe power outages, transportation disruption, and delays in emergency responses (Kämäräinen et al. (2017) and references therein). Because both weather phenomena can thereby be relevant for safety considerations of nuclear installations, of interest is also their potential combination, here referred to as “FZG” (Freezing Rain + Gusts).

The occurrence of FZG, and associated ice accumulation due freezing rain, in USA has been studied by Coburn et al. (2024) for the period 2005-2022. While Kämäräinen et al. (2017) applied a precipitation-typing algorithm for estimating the occurrence and amounts of freezing rain, Coburn et al. (2024) used meteorological data at almost 900 in-situ observing stations as input to an energy balance model in order to derive hourly estimates of ice accumulation. The outcomes of the method were then combined with gust observations to produce a geospatial atlas of FZG hazards in USA. To quantify damage associated with FZG, a specific index was used, and the results were validated and integrated with National Oceanic and Atmospheric Administration (NOAA) Storm Reports. Particularly severe or impactful FZG were described in more detail in terms of their meteorological drivers and associated socio-economic impacts (damage, disruptions). 50-year return level estimates provided by the study for each US state suggested that the joint FZG hazard may have been underestimated in earlier analyses, as the new results appeared to be comparable to past estimates for 500-year events.

Regarding nuclear installations in Finland, it is worth noting that as a hazard metric, the study used an index that has been originally designed for radial ice accumulation on e.g., power lines. The hazard-to-impact relationship may differ for other kinds of infrastructure.

3.4 Atmospheric heatwaves and drought

Compared to high air temperatures and heatwaves that affect ventilation and room cooling systems of NPPs, drought as a single external event is of minor influence for the Finnish NPPs, since their need for cooling water is satisfied by sea water. Nonetheless, prolonged dry spells combined with heatwaves form favourable weather conditions for the spread of wildfires, possibly posing risks to, e.g., transmission line connections of NPPs (Kim et al., 2024). Besides, smoke related to the wildfires might enter ventilation air intakes in NPPs (Jylhä et al., 2018).

The occurrence of drought and the occurrence of heatwaves are strongly correlated (positively in summer and negatively in winter). Moreover, compound drought and heatwave (CDHW) events yield an example of a hazard combination for which its individual components may differ from each other in their temporal or spatial scale and are both affected by global climate change. Therefore, such a compound hazard is not easy to define unequivocally.

Shan et al. (2024) considered CDHW events in Belgium in 1901-2020 and proposed a multi-phase method for identifying them on a daily scale across the four seasons. The indices used by the authors described dry (hot) spells according to the probability of occurrence in 30-year moving window baseline periods. The moving window approach was adopted to account for non-stationarity, and the probabilities of the component spells (hot or dry) were defined after making a choice from ten commonly used distribution functions. The indices were calculated for various accumulation periods that were longer for dry and shorter for hot spells. Minor dry or warm spells were removed, and mutually dependent compound events were merged in order to focus on statistically extreme and temporally separate combinations of droughts and heatwaves. The authors then retrieved CDHW events and estimated empirically their probabilities of occurrence. In addition to a simple overlap of drought and heatwave days, three alternative definitions for CDHW were explored, such as drought periods that overlap with at least one heatwave or heatwaves that overlap with at least one drought.

To demonstrate the method, it was applied to daily observations at a Belgian weather station. Although not statistically significant, an increase in the number of days in CDHW events between the former and latter halves of the 100-year study period was found, mainly due to a statistically significant increasing trend in the frequency of heatwaves.

According to the authors, the proposed identification method makes it possible to more precisely identify the start and end dates of CDHW events. They pointed out that further studies are needed to confirm whether the method works well in different climatic zones.

3.5 Marine and atmospheric heatwaves

High temperatures in the sea are of interest to NPPs, as they affect the intake of seawater and the temperature of outlet water. Sometimes the environmental permit of the NPP limits the temperature of outgoing water, causing limitations to the operation of NPP during a period of high seawater temperatures.

As stated in the preceding Section, high temperatures affect ventilation and room cooling in NPPs. In case atmospheric heatwave occurs simultaneously with a marine heatwave, the combined effects might lead to reduction of the energy production in the NPP.

The high temperatures of sea surface layer and deeper layer are affected by atmospheric temperatures over the sea. In coastal regions, upwelling and downwelling may cause rapid changes in sea temperatures. For example, during an atmospheric heatwave, upwelling may bring cold water from deeper layers to surface, causing rapid decrease in the sea surface temperature.

A period of high sea temperatures above the statistically expected values is called a marine heatwave. In the Baltic Sea, the winter mean temperature is considerably lower than summer mean temperature. Therefore, the heatwave during winter does not have effects on NPP operation, whereas summer heatwaves have higher temperatures that are of interest to NPPs.

In the Mediterranean Sea, Paredes-Fortuny et al. (2025) studied how concurrent atmospheric heatwaves intensify marine heatwaves in the Mediterranean Sea. They found that during an atmospheric heatwave, wind speeds are small, which leads to a warm surface layer that does not mix with deeper layers that are colder. When the atmospheric heatwave ends, stronger winds mix the layers and the surface layer releases latent heat to the atmosphere through water vaporization. This might lead to a strengthening feedback loop, which may further amplify Mediterranean atmospheric and marine heatwaves.

In the Baltic Sea, the drivers of marine heatwaves were investigated using a coupled numerical atmosphere-ocean model (Gröger et al., 2024). Using hindcast simulation data 1980-2016, they found that in the summer marine heatwaves are caused by atmospheric blocking (high pressure) over Scandinavia. Winds above the sea area are weak and vertical mixing with colder sub-thermocline waters is low. During the simulation period, no clear trends of marine heatwave extent, frequency or duration were found. This is partly explained by the large natural climate variability in the Baltic Sea region, which makes it difficult to detect underlying trends.

Another source for information for marine heatwaves are the satellite-derived sea surface temperatures. Bashiri et al. (2024) studied satellite data 1982-2023 to study marine heatwaves in the Baltic Sea. They found that the area affected by the marine heatwaves has increased during this period. In summertime, the marine heatwave areas are mainly offshore, but they extend to the coast in the eastern Gulf of Finland, the Bothnian Bay and the southeastern Baltic Sea. The marine heatwaves are correlated with two Northern Hemisphere teleconnection patterns: the Scandinavia patterns and the East Atlantic pattern. Scandinavia teleconnection corresponds to Scandinavian blocking in Gröger et al. (2024), whereas the East Atlantic teleconnection describes a southward shifted NAO pattern with low pressure over the North Atlantic and high pressure over Europe, leading to transport of warm air from south to northern Europe that causes high temperatures in the Baltic Sea region.

There have been summers recently in the Baltic Sea region with warm spells leading to marine heatwaves. One such example was the summer 2022, when extreme positive anomalies of sea temperatures were observed. These extreme circumstances are studied by Lindenthal et al. (2024). Based on reanalysis data, they found that sea surface temperatures in the Bothnian Bay exceeded the 90th percentile of climatologically expected value by 9 °C during the summer 2022. Based on sea surface temperature observation data from Kiel lighthouse (1989-2022) and Northern Baltic Proper wave buoy (1997-2022), the number of marine heatwave events has increased by 0.6-0.7 events per decade. This is influenced by the global warming of the atmosphere.

Similar marine heatwaves have been observed in the neighboring coastal seas, as was case in June 2023. Then the European North-West Shelf (North Sea and other sea areas surrounding UK and Ireland) experienced a marine heatwave of unprecedented magnitude. The probability of this event was studied by Atkins et al. (2025) by pooling an ensemble of initialized climate model simulations to generate a large distribution (n = 2520) of marine heatwave events. They found that the probability of such an event is approximately 10 % in the present-day climate. The probability of this event has increased by over 12 times in the central North Sea since 1993.

The modeling of sea surface temperatures via coupled atmosphere-ocean models needs considerably computational resources. An alternative approach has been used by Zhu et al. (2022) to model sea surface temperature on the Polish coast in six separate locations. They use a physical-statistical model to describe the energy balance of the surface layer. The time derivative of the sea surface temperature depends on the sea surface temperature, the air temperature and time via eight parameters. These model parameters are estimated through calibration and validation, using sea surface temperature measurements 2009-2016 for calibration and 2017-2019 for validation of the model. They found that with the increasing air temperature, sea surface temperature presents a clear warming trend (0.13 to 0.17 °C/year), and air warms faster than sea surface for the studied stations. This modeling approach can be applied to other sea areas than the Polish coastal region, but then model parameters have to be tuned separately for the studied region.

For the Finnish NPPs, the high sea temperatures are relevant in the summer. Especially the Loviisa NPP is situated in a coastal region affected by marine heatwave in the summer (Bashiri et al., 2024). Where as sea surface temperatures can be detected from satellite data, temperatures in deeper layers can only be studied from ocean model data, as the measurements in of the vertical temperature profiles are limited to a number of fixed stations and infrequent soundings from research vessels. The increasing availability of satellite data and novel data processing methods will also help with analyzing the sea surface temperature in higher detail in the Baltic Sea.

4 Final remarks

A part of the MAWECLI project (2023-2025) has been dedicated to multi hazards, aiming at enhancing reliability of estimates about the likelihood of exceptional co-occurring events in the vicinity of the NPP sites. Three multi hazards have been considered: i) cyclones + high sea level + waves (Rantanen et al. (2024); Särkkä et al. (2024)); ii) convective storms + meteotsunamis + lightning (Laurila et al., 2025b); and (iii) high winds + intense snowfall (Olsson et al., 2025).

The current review report provides additional examples of combinations of atmospheric and atmosphere-marine hazards relevant for nuclear power plant safety. It also briefly describes some methodological approaches to investigate them. We found that studies of compound weather events require using statistical methods to examine the dependence of compounding phenomena via copula methods and other multivariate extreme value methods that are often complex.

The warming of the global climate affects the probability of compound events. For the purpose of getting new knowledge and deeper understanding about them, a spectrum of data sources is available. High-quality reanalyses data enable more detailed studies of past compound events and how the already realized climate change has affected them. The use of most recent climate model projections with statistical analysis methods, like those referred to in the literature review given here, will provide information on the projected changes in the extent, duration and intensity of the compound events in the future. Furthermore, the development of very-high resolution convection-permitting climate models allows improved studies of intense small-scale compound phenomena.

Although not all compound events or drivers discussed in this report are directly relevant to Finland, the approaches used in the studies might be useful for the evaluation of multi-hazards potentially affecting the Finnish NPPs, especially in the changing climate. Accordingly, our plan is to further examine and potentially utilize various methodologies referred to in this report for conducting state-of-the-art research on compound external hazards relevant for nuclear power plant safety in Finland.

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