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Increase in frequency of nuclear power outages due to changing climate

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Climate-related changes have already affected operating conditions for different types of energy system, in particular power plants. With more than three decades of data on changing climate, we are now in a position to empirically assess the impact of climate change on power plant operations. Such empirical assessments can provide an additional measure of the resilience of power plants going forward. Here I analyse climate-linked outages in nuclear power plants over the past three decades. My assessment shows that the average frequency of climate-induced disruptions has dramatically increased from 0.2 outage per reactor-year in the 1990s to 1.5 in the past decade. Based on the projections for adopted climate scenarios, the average annual energy loss of the global nuclear fleet is estimated to range between 0.8% and 1.4% in the mid-term (2046–2065) and 1.4% and 2.4% in the long term (2081–2100).

Climate change and energy systems have a bidirectional relationship. While the impact (and role) of emissions from energy systems on climate change and its mitigation is well understood[1–4], recent research has expanded our knowledge of how climate change exposes vulnerabilities in energy systems on the supply and demand sides[5–8]. Escalating climate-induced effects are poised to cause serious disruptions in the operation of critical energy infrastructure and, consequently, in electricity service provision[9–11].

While proponents of nuclear power advocate it as an effective means to generate low-carbon electricity[12], the debate on expanding nuclear energy on the global level has put the spotlight on trade-offs and vulnerabilities related to security and climate change considerations[13,14]. The vulnerability of nuclear power plants (NPPs) to climate change and the extreme weather conditions it creates has already been highlighted as a serious challenge[15–18].

Energy resilience, broadly defined as systems' ability to cope with, recover from and minimize the impact of various types of disruption[19], is receiving increased attention today[20,21], largely because of the extending scope of threats targeting energy infrastructure such as cyber-attacks, as well as the increased variability and unpredictability of extreme weather events driven by climate change[22]. In this Analysis, I focus on climate-driven disruptions of nuclear power operations. The term 'climate driven' or 'climate induced' refers to outages of NPPs that are caused by climatic conditions such as heatwaves, droughts, storms and so on. According to the International Atomic Energy Agency's (IAEA) definition, an outage is when the reactor's actual power is lower than the reference unit power for a period of time. Consequently, outages can be partial (power derating) or full (shutdowns). Nuclear reactors are also subjected to an array of other externally driven outages that are often linked to grid or regulatory requirements, but those are outside the scope of this paper.

Past research on this topic has focused either on the impact of the increase in the global average temperature from the perspective of its heat transfer effects on NPP cooling[17,23] or on the generalities of potential interactions between nuclear energy and climate change[14,16]. This Analysis takes a different approach by tracking climate-linked outages as they relate to the frequency and intensity of extreme weather conditions, and attempts to understand how these events impact the operations of NPPs. It is important to highlight that the term 'climate change' used in this paper implies both anthropogenic and naturally induced changes. The topic of exploring the role of human attribution to past and future climate effects has gained traction in recent years due to the 2000–2014 global warming slowdown while greenhouse gas emissions kept increasing[24].

In this Analysis, I analyse past NPP outages with focus on the decade 2010–2019, for which I use content analysis to characterize climate-linked disruptions in NPPs. The findings of the presented analysis enhance our understanding of the impact of climate change on nuclear power and its resilience on two levels. First, the analysis provides and quantifies evidence that the dramatically increased frequency of environment-linked unplanned outages over the past three decades is due to climatic effects. Under a high-emission scenario—representative concentration pathway (RCP) 8.5—the average annual energy loss of the global nuclear fleet is estimated to range between 0.8% and 1.4% in the mid-term (2046–2065) and 1.4% and 2.4% in the long term (2081–2100). Second, a mapping of climate-linked outages has shown that, although the loss of cooling quality is one of the most reported issues, NPPs face an array of other causes of disruptions that are linked to climatic variations. In addition, I find that while full outages due to hurricanes/typhoons are more frequent, disruptions caused by lower water intake levels due to droughts last longer, and thus are more consequential in terms of the loss of energy service provision, on average.

Climate vulnerabilities of nuclear power

Like other sources of energy, nuclear power is vulnerable to climate change effects. In the limited available literature on this topic, the most frequently highlighted risks are those related to increased ambient temperatures and their impact on the cooling of reactors and overall thermal efficiency[5,17]. However, unlike other thermal power plants (fossil fuels and biomass), nuclear power faces more demanding and stringent safety regulations[25]. In addition, following an unplanned outage, the reactor startup could be delayed further

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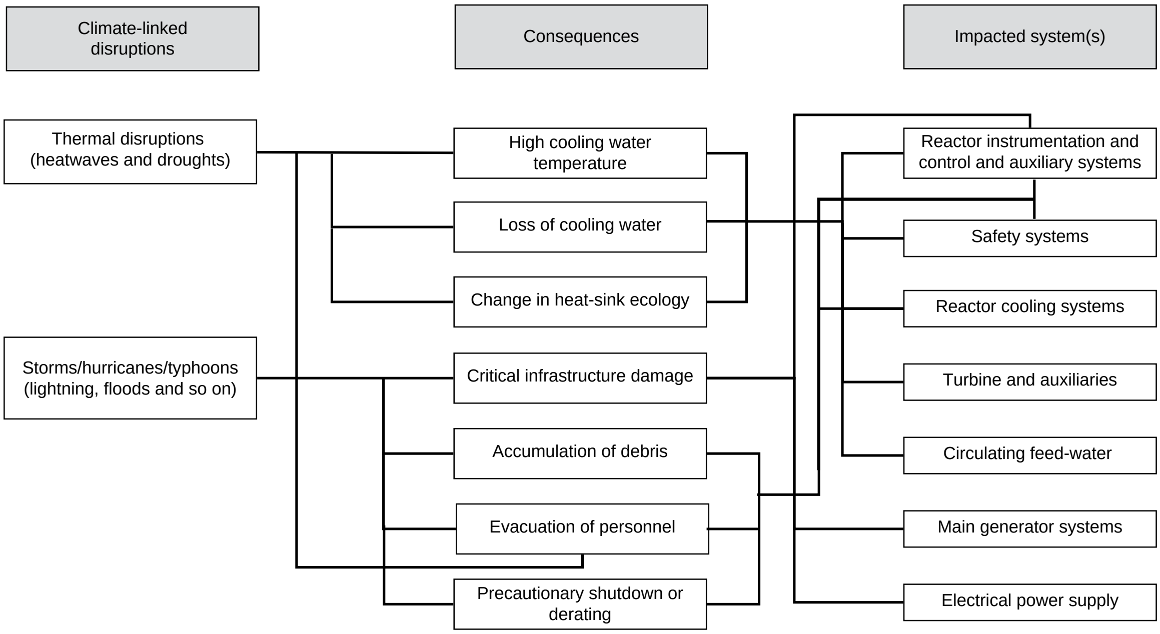

Fig. 1 | Pathways of climate-induced disruptions in nuclear power plants. This figure maps climate-linked disruptions and their respective consequences to the specific reactor system they impact. Each pathway is a potential route of a partial or full reactor outage.

until the regulatory investigation to understand the cause of the outage is completed[26].

Utilizing the collected outages data, it was possible to conduct a content analysis, which is described in Methods. The descriptive text available on the examined outages allows us to obtain a number of insights into how climate- or weather-linked conditions impact the operations of NPPs. The mapping of these conditions to their consequences and, ultimately, to the nuclear reactor systems they impact, leading to unplanned outages, is shown in Fig. 1. The reported climatic conditions can be divided into two major categories: thermal disruptions that are related to the availability of cooling water and its temperature, which include heatwaves and droughts; and storm conditions, which include powerful storms and hurricanes/typhoons.

Heatwaves and droughts affect NPP operations in direct and indirect ways. NPPs require large quantities of cooling water to extract the thermal heat. Consequently, if the heat sink (sea, river or lake) has a higher-than-usual ambient temperature, cooling effects and quality can be compromised, leading to a partial (derating) or full outage (shutdown)[23]. As an indirect effect, higher-than-usual temperatures can alter the heat sink environment, triggering new challenges. For example, a number of the examined outages involved a blockage of the water intake canal by the excessive presence of jellyfish, which have been shown to flourish in warmer waters under the effect of climate change[27,28]. In addition, heatwaves can induce wildfires, which can impact NPP operations by cutting off demand (sometimes demand is cut preemptively[29]) or through the need to evacuate NPP personnel[16]. High ambient temperatures also lead to transmission and distribution losses, which may limit the evacuation of power from centralized power stations to lower-voltage distribution networks. Sathaye et al. have estimated that a 5 °C air temperature increase diminishes the capacity of a fully loaded transmission line by an average of 7.5% (ref. [30]). Although this would affect all sources of electricity connected to the grid, NPPs have less flexibility in terms of quickly adjusting their power output compared with other sources[31].

On the other hand, stormy weather conditions can also induce partial or full outages through different scenarios such as electrical damage due to lightning strikes on nearby transformers, substations or transmission lines. Powerful storms can result in heavy rainfall, causing floods and moving debris closer to the water intake canals of the nuclear reactors, especially those located on rivers. In many cases of the examined outages, NPPs were shut down preemptively in anticipation of a coming hurricane/typhoon.

Frequency and characteristics of climate-linked outages

Over the past three decades, the frequency of NPP outages (per reactor-year) induced by external climatic events that are beyond the control of reactor operators has consistently increased, as shown in Fig. 2. In the 1990s, the average frequency of environment-induced outages (full and partial) was around 0.2 outage per reactor-year, but since then it has increased by around eightfold, reaching an average of 1.5 in the past decade. In comparison, the external outages that are not driven by climate-linked causes (blue data points) have only increased by 50% over the same period, making climate disruptions the leading cause of external outages (excluding grid-linked and load-following outages). At the same time, the average frequency of full outages (outages that required reactor shutdown) has also increased from 0.05 per reactor-year in the 1990s to 0.25 in the 2010s.

Due to data availability restrictions, only the characteristics of climate-driven full power outages that occurred between 2010 and 2019 are studied further in Fig. 3. The typology, monthly distribution and regional distribution of full climate-linked outages shown in Fig. 3a–c reveal that the largest two contributors to climate-linked full outages are hurricanes/typhoons (mainly in the United States and South and East Asia) and the increase in ambient temperature (mainly in France). In terms of the monthly distribution of outages, about 53% of all climate-induced outages occur in the months of July, August and September, mainly driven by ambient temperature issues and hurricanes. Around a third of the studied full outages do not report a specific climatic cause. One interesting observation is that full outages that are due to water intake issues are concentrated in France, where the majority of NPPs are located on lakes and rivers that are susceptible lower flow rates in the months of September, October and November (Fig. 3b).

Since its peak in the mid-1980s, the rate of building new NPPs has dramatically declined; however, in recent years, the rate of new

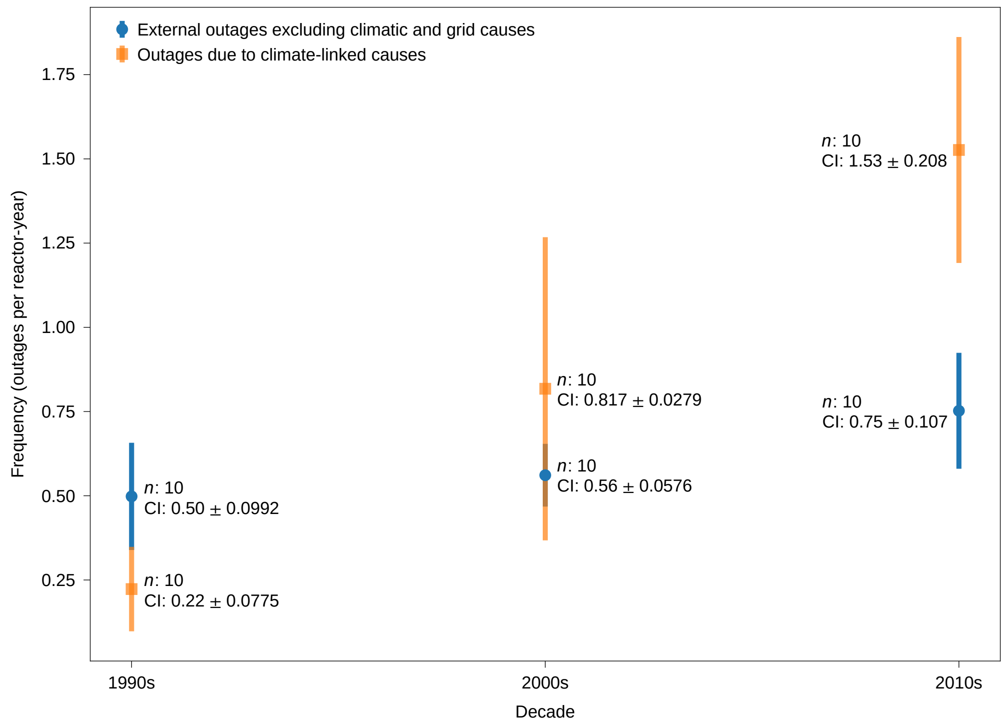

Fig. 2 | Variation of the average frequency of NPP outages per decade. The studied outages include both partial and full outages, spanning from 1990 to 2019. Orange data points represent outages induced by climatic causes; blue data points represent outages induced by non-climatic and non-grid (regulation/load-following) causes. The error bars represent the standard deviation of the outage frequency per year within each decade. Each data point represents one year. The averages and standard deviation values are calculated per decade; that is, each bar consists of ten data points (count number, $n=10$). The 95% confidence interval (CI) is shown on the chart.

reactors connected to the power grid has seen a slight recovery, mainly driven by new reactors built in China[32]. Consequently, the age of the global nuclear fleet (408 operational reactors) has been increasing since the mid-1980s, with an average age of 30.7 yr in 2020[32]. The relevance of the age of reactors on climate-driven full outages is examined in Fig. 3d, which plots the age differential between the age of the reactor where a full outage has taken place and the average age of the NPP fleet in the country of concern. Figure 3d shows that reactors of different ages, younger and older than the average fleet age, are susceptible to climate-linked disruptions, with near-zero medians of all disruption categories, except in outages caused by increase of the ambient temperature, where the median is at around 2.7 yr. The average age of reactors impacted by full outages induced by climatic causes is 30.2 yr, marginally lower than the average age of the global nuclear fleet.

NPP outages and global warming

Not all externally driven NPP outages that are induced by environmental causes can be linked to climate change effects. Non-climatic causes of outages include earthquakes, tsunamis and ingress of seaborne material or debris in the cooling water intake canal. To aggregate the outages that are solely due to effects that can be linked to climate change, a keyword list was built with all the relevant terms. Then, only the outages that includes those terms were selected by the code for further processing. The list includes the terms provided in Table 1 (or their variations).

A linear regression of the annual energy output lost (as percentage of the total energy generated by NPPs globally) with temperature deviation relative to the 1951–1980 average temperature is shown in Fig. 4a (green chart), while that of the annual frequency of climate-linked outages with temperature deviation is shown in Fig. 4b (blue chart). In both sets of data, the correlation with global warming is evident—the increase in the average global surface temperature seems to correlate with higher climate-induced outages in NPPs. The weak effect of the age of reactors as a facilitator of climate-induced outages (as shown in Fig. 3d), coupled with the presence of past research findings showing that global warming has indeed increased the frequency of extreme weather events, particularly heatwaves[33–35], reveals the increasingly prominent role of climate change as a leading cause of environment-induced outages in NPPs.

As shown in Fig. 4, the continuing global warming is increasingly disrupting the operations of NPPs, negatively impacting their role in a resilient energy system. The regression model shows that for every 1 °C temperature increase above the 1951–1980 average temperature baseline, the average share of energy output lost out of the global energy generation by NPPs is increased by around 0.5%. In 2019, the energy lost due to climate-linked outages was around 0.57% of the total nuclear electricity produced, which is around 14.7 TWh. Interestingly, as a comparison, the output of solar photovoltaic power appears to decrease by 0.45% for every 1 °C temperature increase[36]. However, ongoing material science research could offer pathways to lowering the sensitivity of the efficiency of solar modules to temperature.

Despite being based on a different methodology, the global impact of climate-induced effects on NPP outages and their corresponding energy output loss shown in Fig. 4 can still be compared with the results reported in past research, which were based on estimating the theoretical reduction of NPP power output due to higher water intake temperatures[17,23]. While the analysis presented in this paper yields a linear regression slope of 0.49, the range reported in the work of Linnerud et al.[17] and Attia[23] is between 0.30% and 0.44%. The strength of the analysis presented here is that it is based on empirical evidence generated by global outages data that reports a wider spectrum of causes beyond those linked to the loss of thermal efficiency.

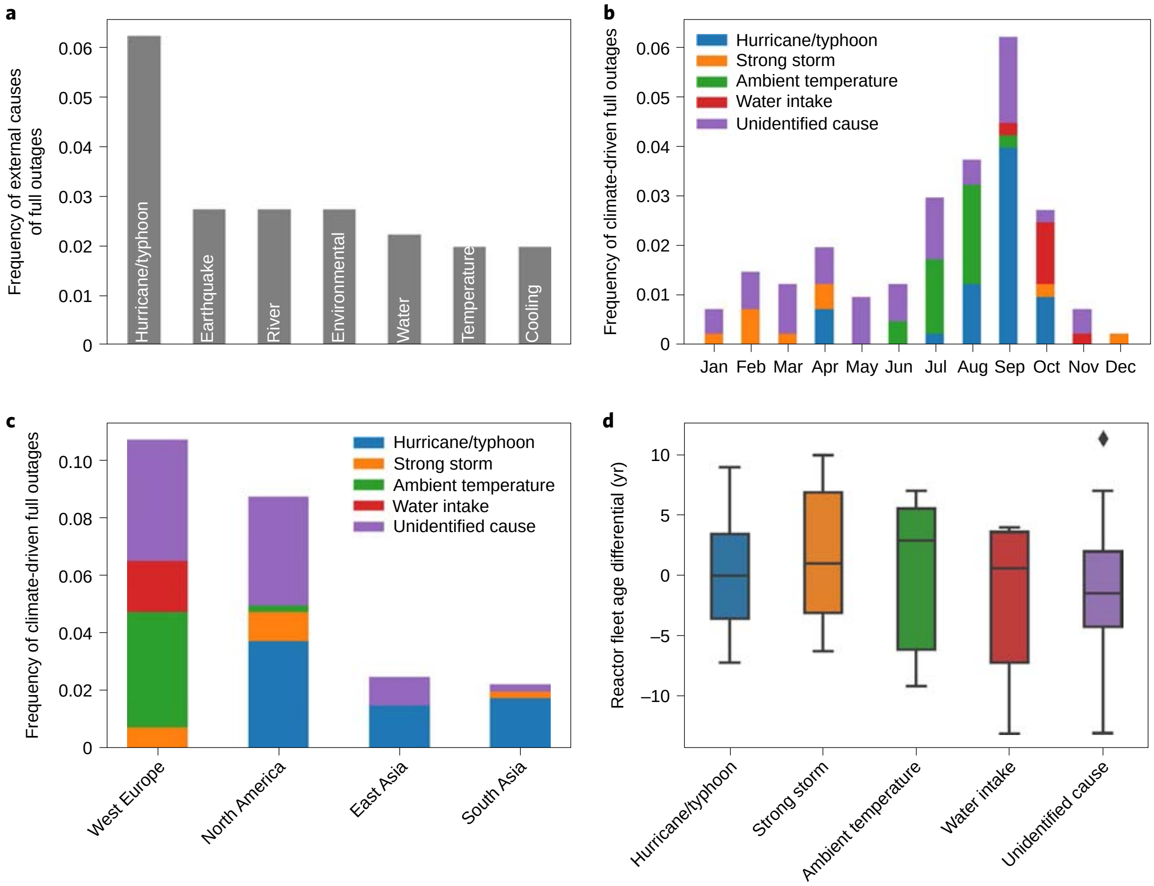

Fig. 3 | Characteristics of climate-induced full outages in NPPs between 2010 and 2019. a, The most frequent terms used to describe externally driven full outages (except those linked to the grid requirement and load following). The frequency is determined by tracking the number of mentions of each term and dividing it by the average annual reactor-year value over the period of concern. **b**, The monthly distribution of the frequency of climate-driven full outages that occurred between 2010 and 2019 based on the initiating causes. **c**, The regional distribution of climate-driven full outages that occurred between 2010 and 2019 based on the initiating causes. **d**, The variation of the reactor fleet age differential of climate-driven full outages that occurred between 2010 and 2019 based on the initiating causes. Each data point in **d** represents the age difference of the reactor where a full outage took place and the average age of the reactor fleet in the same country. The box edges indicate the 25th and 75th percentiles, the horizontal line represents the median, and the whisker edges represent the extent of the distribution with outliers indicated as points. Full data, including *n*, minima, maxima and percentiles, are included in the Source data. Note: The full outage data between 2010 and 2019 used in **b**, **c** and **d** exclude outages induced by earthquakes, including the Fukushima-linked outages, since those external outages are linked to seismic activity rather than to climatic factors.

Impact of climate-linked outages on NPP operations

To understand the impact of different climate-linked events on NPP operations, Fig. 5 examines the characteristics of the five identified categories (hurricane/typhoon, storm, temperature, water and unidentified environmental causes), averaged over the past decade (2010–2019). According to Fig. 5a,b, apart from the unidentified causes category, water intake issues such as those related to droughts and lower levels of water in rivers and lakes cause the longest outages (110 h per outage) and, consequently, are more disruptive in terms of energy service provision (135 GWh loss per outage). The impact of hurricanes/typhoons seems to be short-lived with an average outage duration of 65 h and relatively small energy disruption of 59 GWh per outage. The impact of high ambient temperature also seems to be relatively short, compared with the other categories. It is important to emphasize that partial thermal outages, driven by lowering a reactor's power output rather than shutting it down completely, are excluded from Fig. 5 and the analysis.

Besides impacting the operations of NPPs, extreme weather events can generally impact different components of the electricity value chain simultaneously, potentially compounding the disruptive effects of these events. The complex connectedness of modern and centralized energy systems magnifies the impact of climate disruptions. For example, the five identified categories of climate hazards shown in Fig. 5 could also cause indirect disruptions when they affect the power grid and transmission infrastructure as described above.

Table 1 | List of keywords used to aggregate climate-linked outages

Category	Keywords
Hurricane	Hurricane, typhoon, tornado
Storm	Storm, stormy, rain, lightning, wind, windstorm thunderstorm, flood(s)
Temperature	Temperature, cooling, heat, heatwave, efficiency
Water	Water, water level, water intake, river, lake
Other	Environment, environmental, weather

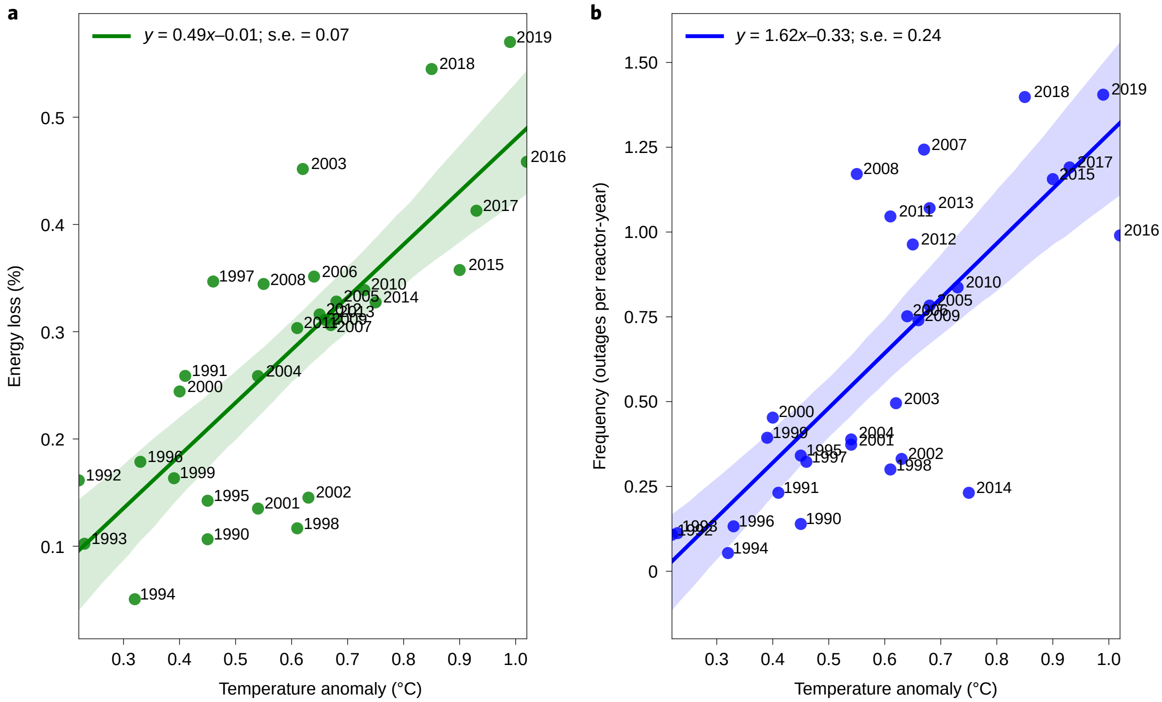

Fig. 4 | Linear regressions of the variations of energy loss and frequency of outages per reactor-year. a, The variation of the percentage loss of electric energy generated due to climate-induced outages with the temperature anomaly (°C) relative to 1951–1980 average temperatures[37] from 1990 to 2019. **b**, The variation of the frequency (outages per reactor-year) of climate-induced outages and the temperature anomaly from 1990 to 2019. The linear regression line, its equation and standard error are included in **a** and **b**. The shading in both figures represents the size of the CI.

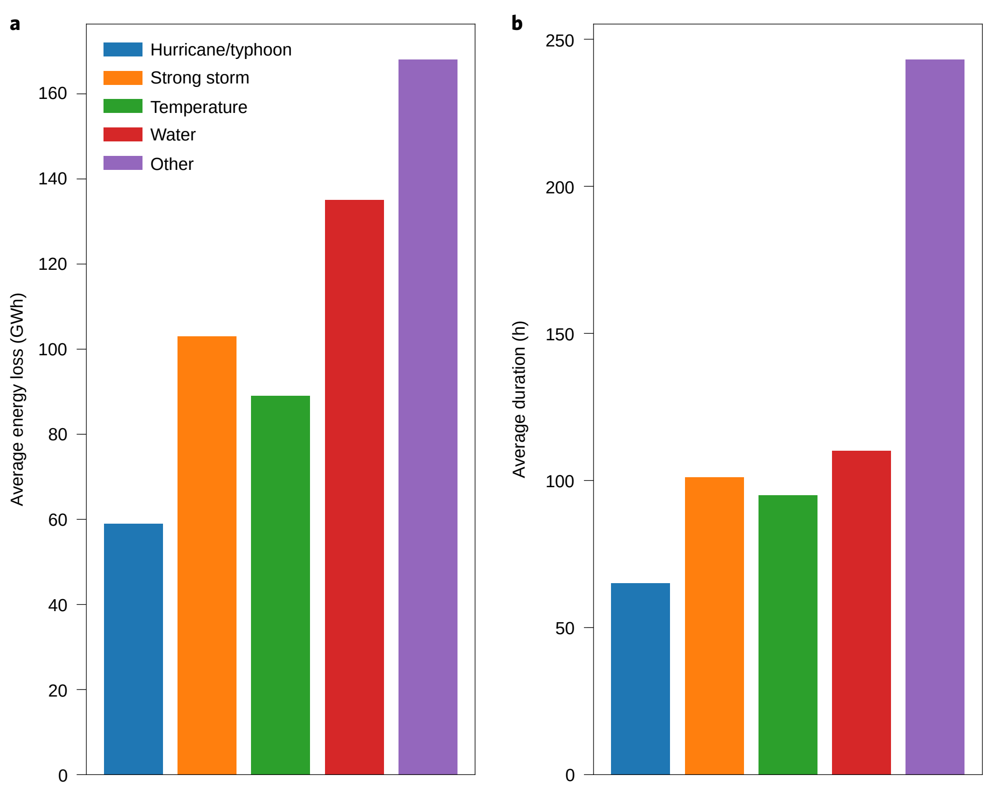

Fig. 5 | Characteristics of full outages induced by climate-linked events. The examined categories are: hurricane/typhoons, storms, temperature, water and other unidentified causes over the past decade (2010–2019). **a**, The average percentage share of annual energy loss of NPPs worldwide in GWh. **b**, The average duration (h) of the outages in the same dataset.

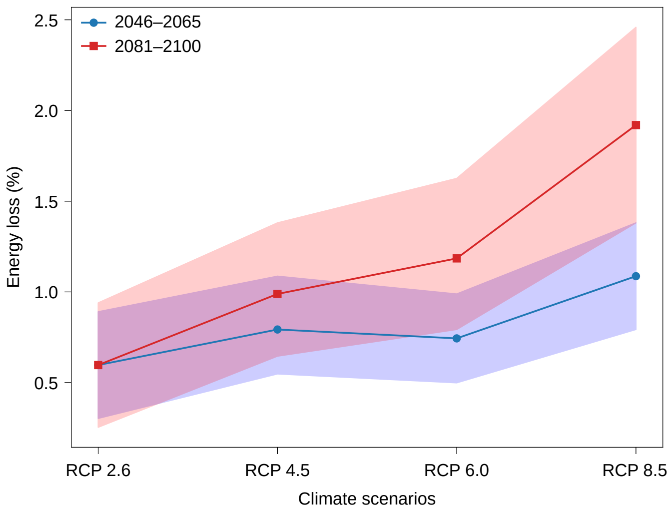

Fig. 6 | Projected variation of the annual loss of energy due to climate-linked outages. Values are percentages of the estimated energy loss by NPPs at different climate change scenarios, which represent different emissions pathways. RCP 2.6 represents a stringent mitigation scenario, RCP 4.5 and RCP 6.0 represent two intermediate scenarios, and RCP 8.5 represents a high-emission scenario. The blue markers represent the averages over the period between 2046–2065; the red markers represent the averages over the period 2081–2100. The shading represents the likely range of variation. The values of the projected global temperature and its likely range under different scenarios are obtained from the IPPC[38]. Note: since the temperature anomaly in the regression in Fig. 4 is relative to 1951–1980 average temperatures, and that of the Intergovernmental Panel on Climate Change's RCP scenarios is relative to 1986–2005 average temperatures, 0.42 °C has been added to the RCP temperatures and their likely ranges to ensure consistency with temperature values input in the regression model.

Next is 2 °C of global warming

With uncertainty surrounding our ability to mitigate or slow down climate change, it is imperative to study scenarios of how the next level of global warming could impact energy systems in general and nuclear power in particular, given its advocatory role in fighting climate change in the first place. On the basis of the regression analysis shown in Fig. 4, one can project the variation of the impact of climate-linked outages in NPPs with different climate (emissions) scenarios. Figure 6 shows the variation of the average annual percentage energy loss by NPPs due to climate-linked outages. The values in Fig. 6 were generated by feeding the projected change in global mean surface temperature, and its likely range under each scenario, to the regression formula shown in Fig. 4a.

The coupling of the growth pattern of past climate-linked outages and future climate scenarios projects the energy loss in the mid-term (2046–2065) and long term (2081–2100)(Fig. 6). In the mid-term, under a high-emission scenario (RCP 8.5), the average annual energy loss is estimated to be at around 0.8% and 1.4%. In the long term, also under RCP 8.5, the projected average annual energy loss due to climate-linked outages by the end of the century is likely to range between 1.4% and 2.4%. According to the Intergovernmental Panel on Climate Change, a 2 °C warming could even be reached before 2050, especially with high-emission scenarios[38]. Based on the regression model in Fig. 4a, a 2 °C warming would result in just below 1% energy loss across the global NPP fleet, assuming the projected impact of extreme weather events expands linearly with warming temperature.

Besides the implicit uncertainties within the RCP climate scenarios, there are two caveats in the projections shown in Fig. 6. First, the frequency and intensity of extreme weather conditions are assumed to follow the same trend that resulted from past global warming. Despite some major scientific research, this remains uncertain, and is likely to have strong regional and nonlinear variations, particularly after the 1.5 °C limit is crossed[39–41]. Second, as the issue of climate-linked disruptions becomes more pressing to power utilities and the nuclear industry, technological and/or design solutions may be deployed to mitigate the effects of extreme weather conditions on the operations of NPPs. However, unlike renewable energy sources that have a relatively short lifetime, which would allow for a faster integration of technological advances into a new generation of power plants, the long lifetime (≥60 yr) of nuclear reactors limits the integration of new technology and wider design margins in a timely manner. Current and future NPPs could be retrofitted with climate-proof parts and systems, but this itself could result in lengthy disruptions due to stringent regulatory oversight and potentially substantial costs. As a thermal source of energy, NPP technology and design interventions could naturally focus on reducing water withdrawal. For example, the US Department of Energy has recently funded a project that aims to develop advanced dry cooling techniques for thermal power plants[18].

Policy implications

In a climate-constrained world, the reported findings can have important policy implications. Governments and policymakers will have to conduct more comprehensive risk assessments of new NPPs that cover the full spectrum of projected extreme weather conditions as the climate changes, reinforcing a previous call to have a systematic and integrated risk assessment approach in which international agencies play a major role as well[16]. This will be particularly relevant for selecting sites for future plants. For existing nuclear assets, power utilities could optimize their planned outages around time periods of highest probability of climate-linked disruptions to minimize their economic impact. Such evaluations will require spatial examination of concerned contexts that is more refined than just a country-level analysis.

Current and future NPPs can adapt to climate change effects. The adaptation mechanisms will have to be context, technology and region specific and based on studying the likelihood of specific weather conditions that are relevant to the concerned regions where existing and new NPPs are located. Prediction models of extreme weather conditions need to be incorporated in assessing the risk of nuclear power assets, particularly in climate-vulnerable contexts and regions. Based on the monthly and regional distributions of outages shown in Fig. 3b,c, planned reactor outages such as those used for refuelling can be aligned with months of increased probability of climate-linked outages. For example, in the case of France, the months of September, October and November would overlap with lower river water levels.

In areas where heatwaves and droughts are common or predicted to increase, alternative cooling approaches to the 'once through' model can be implemented such as recirculating or dry cooling mechanisms[42]. However, since these mechanisms lower the thermal efficiency of NPPs and put a downward pressure on their already challenging economics[43], a detailed scenario-based economic modelling that assesses the cost–benefit of each option versus the likelihood and economic impact of disruptions would be needed. Additionally, while dry cooling mitigates cooling water vulnerabilites, it would leave NPPs vulnerable to air temperature constraints. Advanced reactor concepts that use coolants other than water (such as gases or liquid metals) could be deployed too, but these face significant deployment challenges and trade-offs[44].

In conclusion, this analysis shows that NPPs face an array of direct and indirect climate-linked disruptions associated with extreme weather conditions that are constantly increasing. Regional climate attributes add a layer of decision-making complexity when considering building new nuclear energy capacity. Although the average projected energy loss range of NPPs under a high-emission scenario is 1.4% to 2.4% in the long term (2081–2100), site-specific losses could be much higher, demanding a comprehensive economic risk modelling that integrates climate risks.

Methods

Data description. This Analysis utilizes multisource data of climate-induced unplanned outages in NPPs to assess nuclear power's resilience, with focus on the past decade (2010–2019). The main sources of the data are the IAEA's annual reports on 'Operating Experience with Nuclear Power Stations in Member States,' database on nuclear power reactors and the *World Nuclear Industry Status Report*. Other publicly available data sources have also been used in this study.

The compiled dataset consists of two parts. The first part includes only the date (yr), energy and duration characteristics of all environmentally driven outages (full and partial) between 1990 and 2019. The second part includes only full outages but has more details such as extracted descriptive text, which has been leveraged to conduct the content analysis method described below. The first part was used to generate Figs. 2 and 4, while the second part was used to generate Figs. 1, 3 and 5.

Separately, the number of operating reactors and the energy generated in each year between 1990 and 2019 have been collected. The number of operating reactors per year was taken from the World Nuclear Industry Status Report database rather than from the IAEA. The reason for this is that the IAEA data overestimate the number of operating reactors due to the presence of the 'long-term operation' classification and the choice of when to report reactor closure. In the IAEA data, the reactor closure date is the closure decision date rather than the date of last power generation.

Content analysis. Before conducting the analysis, a data-cleaning protocol was implemented. The protocol included (1) removing data entries with missing values, (2) removing duplicate entries, (3) removing outages labelled as 'extension of past outages' and (4) removing wrongly categorized outages.

Since each reported full outage is accompanied by descriptive text, exploring this text through conducting content analysis provides a powerful tool to understand why and how unplanned power outages occur and study their variation and characteristics over time. The content analysis process was automated by a Python code script that incorporates various functions that were able perform the expected tasks of a usual content analysis.

In Figs. 3 and 5, the process started with eliminating generic frequent words such as 'power,' 'reactor' and 'unit'. Short words with fewer than four letters were also removed. Since the style, spelling and abbreviations varied a lot between data entries, a matching algorithm that groups and counts words that are similar was developed. For example, words such as 'cooling', 'cool' or 'coling' would be grouped together. After the grouping of similar terms, five categories have been identified as shown in Figs. 3 and 5: hurricane/typhoon, storm, temperature, water and other. The terms used to feed each category are listed in Table 1. The climate-linked outages were selected if the data entries included one or more of keywords listed in Table 1. For example, the storm category was selected through only considering data entries that have one or more of the following keywords and their matching words: 'storms,' 'rain,' 'lightning,' 'thunderstorm' and so on. Once a category has been defined and its data rows have been selected, other data processing and analysis can be conducted. Figure 3b,c was then produced on the basis of mapping of the adopted categorization model to the monthly and geographic distributions. Figure 3d was produced by subtracting the age of the nuclear fleet in the country where the impacted reactor is located from the age of the impacted reactor itself. To check that the code worked well, the removed data entries were checked by the author. All the removed outage entries were either triggered by environmental causes that are not linked to climatic effects such as earthquakes and tsunamis, debris blocking the water intake (not due to storm/floods) or load following.

Data availability

The datasets generated and/or analysed during the current study are not publicly available due to third-party restrictions, but anonymized datasets are available from the author on reasonable request. The publicly available data that was used in this paper can be found on the IAEA Power Reactor Information System (PRIS) database (https://pris.iaea.org/pris/home.aspx), and the IAEA Operating Experience with Nuclear Power Stations in Member States (2020 version can be accessed on this link: https://www.iaea.org/publications/14782/operating-experience-with-nuclear-power-stations-in-member-states). Source data are provided with this paper.

Code availability

The Python codes that enable the reproduction of the main analysis is available upon reasonable request from the author.

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