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# Climate Change and Nuclear Security: Assessing Risks to Nuclear Infrastructure in Vulnerable Regions

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## Abstract

This study investigates how climate change intensifies security risks to nuclear infrastructure in vulnerable regions, where rising temperatures, flooding, sea-level rise, and extreme weather events increasingly threaten operational stability and safety systems. The problem lies in the absence of integrated frameworks that simultaneously address climate projections and nuclear security planning, leaving critical infrastructure exposed to compound environmental risks. The study is guided by risk society theory and resilience theory, which together explain how modern technological systems become increasingly fragile under conditions of environmental uncertainty and cascading hazards. A mixed-methods research design is adopted, combining qualitative policy analysis with quantitative climate-risk modeling to assess exposure levels across coastal and inland nuclear facilities. The dataset includes IPCC climate projection reports, International Atomic Energy Agency safety and incident records, and global disaster databases covering extreme weather events from 2000 to 2025. Results indicate that coastal nuclear plants face heightened risks from storm surges and sea-level rise, while inland facilities are increasingly vulnerable to heat stress and water scarcity that disrupt cooling mechanisms. Furthermore, governance gaps, outdated safety thresholds, and uneven regulatory capacity significantly amplify systemic vulnerability, particularly in developing regions. Measurable outcomes of the study include the development of a Nuclear Infrastructure Climate Risk Index, enabling predictive risk scoring, prioritization of adaptation strategies, and integration of climate resilience indicators into nuclear safety and emergency preparedness frameworks.

***Keywords**: Climate change; nuclear security; infrastructure vulnerability; resilience theory; risk assessment; climate hazards; nuclear safety governance*

## 1. Introduction

Climate change is now a key challenge of the twenty first century and is transforming the risk environment in environmental, economic and security spheres globally. In this changing world, nuclear infrastructure is an especially vulnerable industry, and requires very specific conditions to operate and could have catastrophic effects if the system fails. Examining the links between climate change and nuclear security in tandem is of academic relevance because compounded and interconnected risks to critical infrastructure systems have become more common in recent years, as they are not just hazards (IPCC 2023).

Infrastructure associated with nuclear energy is highly vulnerable to climate variability, and is generally viewed as a low carbon solution for reducing greenhouse gas emissions. It is not only an environmental issue, but also one of operations issues when the global climate change caused by climate change events such as rise in temperature, extreme precipitation, and sea level rise, becomes an issue for reactor safety, cooling system and waste storage facility (IAEA 2022). Such research is of paramount importance, as it is necessary to address the vulnerabilities that are emerging and to join disciplines such as climate science and nuclear security.

Deterministic environmental assumptions have been used for centuries to guide development of nuclear infrastructure around the world, with the assumption of a stable climate. Engineering design standards have been developed based on past meteorological data and the assumption that environmental extremes would stay within known limits. The current climate science, however, shows that these are no longer valid assumptions in view of the increasing climate variability and the nonlinear changes in the environment (IPCC 2023).

Nuclear infrastructure is impacted by climate change in several ways. The effects of sea-level rise, storm surges and coastal flooding are becoming a growing threat to coastal facilities, while inland facilities are under threat from rising temperatures and the loss of freshwater required to cool reactors (World Bank 2023). Heatwaves, in particular, lower thermal efficiency and cause increased operational stress on cooling systems, and drought reduces water intake, risking shutdowns or reduced capacity operation.

The International Atomic Energy Agency (IAEA 2022) considers water availability and thermal control as one of the most important factors in the safety of nuclear power plants. Failure of these systems can result in cascading operational risk, particularly in areas where infrastructure resiliency is low.

### 1.3 Research Gap

There is a significant body of literature with respect to nuclear safety and climate change separately, but not much around combined research of the two. Traditionally, nuclear safety studies are concerned with the reliability of the internal systems, how to ensure that people do not make mistakes, and the engineering protection of the systems, whereas climate change studies are primarily aimed at the climate change impact, and not necessarily linking it to the vulnerability of nuclear infrastructure.

The majority of current nuclear risk frameworks rely on past hazard probabilities and do not include future climate projections. This poses a methodological constraint in predicting future risk in a changing environment. Moreover, pre-existing research tends to be concentrated in developed countries with more sophisticated regulatory regimes, and there is relatively little research in developing areas for global risk assessments (Roberts and Chan 2024).

A further important knowledge gap is the lack of a combined quantitative and qualitative analytical model incorporating climate data and governance or policy analysis. Consequently, the effect of institutional capacity, regulatory environments and geopolitics on the resilience of nuclear infrastructure in the face of climate stress remains not well understood.

### 1.4 Research Objectives and Questions

Research Objectives

- To assess the impact of climate change on the safety and operational stability of nuclear infrastructure.
- To compare vulnerability differences between coastal and inland nuclear facilities under climate stress conditions.
- To evaluate the effectiveness of governance and regulatory frameworks in addressing climate-related nuclear risks.
- To develop a structured framework for assessing nuclear infrastructure climate risk using integrated indicators.

**Research Questions**

1. How does climate change affect nuclear infrastructure safety, efficiency, and security?
2. Which climate-induced hazards pose the greatest operational risks to nuclear facilities?
3. How do governance structures and regulatory capacities influence vulnerability and resilience?
4. What integrated framework can be developed to improve nuclear infrastructure adaptation to climate change?

### 1.5 Scope and Significance of the Study

This study focuses on global nuclear infrastructure systems, with particular emphasis on coastal and inland nuclear facilities located in climate-vulnerable regions. It examines both physical environmental risks and institutional governance structures to provide a multidimensional understanding of vulnerability.

The significance of this study lies in its contribution to bridging disciplinary boundaries between climate science, nuclear engineering, and security governance. It responds to the growing academic and policy need for integrated risk assessment frameworks that account for climate-induced uncertainties in critical infrastructure systems. As Beck (1992) argues in risk society theory, modern technological systems produce risks that extend beyond institutional control and traditional risk management frameworks.

Furthermore, this study contributes to resilience theory by identifying how adaptive capacity can be strengthened in highly sensitive infrastructure systems such as nuclear facilities (Walker and Salt 2012). It also provides policy-relevant insights for international organizations, including the IAEA, by proposing pathways for integrating climate projections into nuclear safety governance.

## 2. Literature Review

### 2.1 Nuclear Safety and Risk Governance Literature

Engineering reliability, operational control, and accident prevention mechanisms have always been the focus points of the literature on nuclear safety. The deterministic approach to safety, redundancy and containment barriers are key features of early nuclear safety frameworks that are used to reduce radiation leakage and operational failure (IAEA 2022). These methods rely on the assumption that the main source of risk is from the internal fault of a system or human error, not from environmental conditions outside the system.

Increasingly, however, this traditional method is found to be less useful in the face of global climate change, as suggested by more recent scholarship. Brown et al. (2021) suggest that nuclear plants built in the late 20th century were built with conditions of a stable climate that have changed in the present environment. Hence, the safety margins derived from past weather data are getting increasingly out-of-date.

Nuclear operational disruptions have come to be influenced significantly by external environmental stressors, as evidenced by recent floods in Europe and heatwaves that caused shutdowns in North America (World Bank 2023). It represents a concept change from the internal containment of the risks to a vulnerability to external systems of the nuclear safety.

### 2.2 Climate Change and Critical Infrastructure Vulnerability

The literature on climate change clearly identifies the rise in extreme weather events which are becoming more frequent and intense. The IPCC (2023) states that rising temperatures has exacerbated hydrological cycles, resulting in increased flood, drought and heat wave events on a global scale. These environmental changes have direct impacts on critical infrastructure systems.

Temperature variations and available water are significant limitations for energy infrastructure, especially for nuclear energy systems. Increased temperatures decrease thermal efficiency in power generation systems and the shortage of water during drought limits cooling. Flooding and storm surges can also create other risks such as the impact on physical infrastructure and loss of operational continuity (Roberts and Chan 2024).

The World Bank (2023) classifies climate change as a “risk multiplier” as it does not create new risks, but magnifies the risks already faced by numerous interdependent systems. This idea is especially important to the nuclear industry because several subsystems need to be operating together in extreme safety conditions.

### 2.3 Nuclear Infrastructure under Climate Stress

There is increasing research focusing on nuclear infrastructure-climate change interactions. Both the short- and long-term climate risks to nuclear infrastructure are highlighted in these studies.

Extreme weather events like cyclones, hurricanes and flooding pose an immediate risk since they can directly cause damage to infrastructure or result in emergency shutdowns. Long-term risks such as rising temperatures, sea level rise and water shortage gradually lower the efficiency of operation and raise maintenance requirements (IAEA 2022).

Sea-level rise and storm surges pose increasing threats of inundation and saltwater intrusion at coastal nuclear plants. Inland facilities, however, are becoming more stressed with the decreasing flow rates in the rivers and rising ambient temperature, which impacts the cooling potential (World Bank 2023).

However, with all these results, the majority of studies are still disjointed and fail to link environmental modelling to nuclear security frameworks, hence restricting their usefulness for predicting the future risk assessment.

### 2.4 Resilience theory and adaptive capacity

A major concept in the Resilience theory is the concept of environmental disturbances. Walker and Salt (2012) define resilience as the ability of a system to withstand shocks and sustain core functions. Resilience in infrastructure systems consists of structural strength, flexibility in operation, and adaptive governance. The nuclear infrastructure is a singular challenge, however, since the focus is on high reliability and low variability instead of flexibility. This makes it difficult to adapt rapidly to environmental changes, particularly when the climate is changing in unpredictable ways.

Continuous learning, feedback mechanisms and institutional adaptability are important to the successful development of resilient systems, as noted by Comfort et al. (2019). Nuclear regulatory systems, on the other hand, tend to be less responsive to change, as they are constrained by the safety measures and lengthy approval processes involved, which can make it difficult to respond to new climate risks in a timely manner.

### 2.5 Theory of Risk society and systemic vulnerability

The theory of the risk society of Ulrich Beck offers a basic framework for the analysis of contemporary technological dangers. The modern societies are characterized by risks created by technologies and not just by natural hazards (Beck, 1992).

Nuclear energy is a high-risk technological system, in which very little failure can have devastating consequences. Climate change exacerbates these risks by adding an additional variable in the environment that is not previously accounted for in the design of systems. Besides, Beck says, risks are “manufactured uncertainties” that are part of the modern industrial systems. This view is especially significant for nuclear facilities, where technology and the environment come together.

Fragmentation of governance mechanisms regarding nuclear safety and climate adaptation is a prominent topic in the literature. Regulation of nuclear activities is generally the responsibility of a specific national agency, while climate related activities are regulated by environmental or meteorological agencies. This institutional separation is a coordination gap in responding to nuclear risks related to climate change.

IAEA (2022) has emphasized the importance of including climate projections in the assessments of nuclear safety, which is not consistently adopted between nations. While developed countries have already started to integrate climate resilience into infrastructure planning processes, the technical capacity and funds of many developing countries are not adequate to effectively do so. Roberts and Chan (2024) also point out that current climate regulations are based on old climate baseline data, which are not reflective of future climate variability. This leaves a gap in the system of nuclear risk governance.

### Research Gap

The literature reviewed has yielded three points of interest. First, research is mostly focused on internal nuclear safety issues and not much attention is given to external environmental risks. Second, Climate Change Literature emphasizes vulnerability of infrastructure, without incorporating nuclear-specific operational constraints. Third, governance is still not well-integrated, and coordination of risk-reduction measures is not strong.

Consequently, there is a clear need for an integrated analytical framework that brings together aspects of the climate model, nuclear infrastructure assessment, and governance analysis together. This gap is the basis of the current research, which aims to delve deeper into understanding the nuclear security risks of climate change.

## 3.2 Research Methodology

This study adopts a mixed-methods approach to investigate the impact of climate change on nuclear infrastructure located in environmentally vulnerable regions. The integration of quantitative and qualitative methods enables a comprehensive assessment of both physical climate risks and institutional preparedness measures. The methodology is designed to examine how climate-related hazards affect nuclear facilities and how governance frameworks respond to these emerging security challenges.

## 3.1 Research Desig

The current study uses a mixed-methods research design that combines qualitative and quantitative methods, and analyzes the climate risks to nuclear infrastructure. Mixing the methods are more useful in comprehensively understanding measurable environmental impacts and institutional governance mechanisms. Mixed-method designs are especially useful in studies which involve multiple disciplines and are difficult to analyze using either qualitative or quantitative methods, as discussed by Creswell and Creswell (2018).

The quantitative component deals with climate-risk modelling and environmental trend analysis, and the qualitative component concerns the analysis of policy documents and thematic interpretation of nuclear governance frameworks. This dual method allows for triangulation of results and so increases the validity and reliability of the results.

## 3.2 Data Sources and Dataset Composition

The study relies on secondary data collected from globally recognized and authoritative databases. These include:

- Intergovernmental Panel on Climate Change (IPCC) assessment reports
- International Atomic Energy Agency (IAEA) safety and incident databases
- EM-DAT international disaster database
- World Bank climate vulnerability datasets
- National nuclear regulatory authority reports

According to IPCC (2023), these datasets provide standardized climate projections and hazard indicators that are widely used in infrastructure risk modeling. The IAEA (2022) database provides detailed records of nuclear facility safety performance and incident reports, which are essential for assessing operational vulnerability.

## 3.3 Sampling Strategy

A purposive sampling technique is used to select nuclear facilities based on geographic exposure and climate vulnerability. Facilities are categorized into:

- Coastal nuclear plants
- Inland nuclear plants
- High-risk developing region facilities

This classification allows comparative analysis across different environmental and governance contexts. Patton (2015) argues that purposive sampling is appropriate in qualitative-driven mixed-method studies where the focus is on information-rich cases rather than statistical generalization.

### 3.4 Variables and Analytical Framework

The study uses a structured risk assessment model:

**Climate Risk = Hazard × Exposure × Vulnerability**

- **Hazard:** Climate-induced events such as floods, heatwaves, sea-level rise
- **Exposure:** Geographic location and environmental sensitivity of nuclear facilities
- **Vulnerability:** Infrastructure design, governance strength, and adaptive capacity

This framework aligns with UNDRR (2022) disaster risk reduction models, which emphasize the interaction between physical hazards and institutional resilience.

### 3.5 Quantitative Analysis Methods

Quantitative analysis includes climate trend assessment and risk scoring models. Temperature anomalies, precipitation changes, and sea-level rise projections are analyzed using IPCC (2023) datasets.

A normalized Nuclear Infrastructure Climate Risk Index (NICRI) is developed to compare facility-level vulnerability. The index incorporates weighted variables such as:

- Temperature deviation index
- Flood exposure score
- Water scarcity index
- Cooling dependency factor

This approach follows methodologies used in infrastructure vulnerability studies by the World Bank (2023), which integrate multiple environmental indicators into composite risk indices.

### 3.6 Qualitative Analysis Methods

Qualitative analysis focuses on policy documents, regulatory frameworks, and institutional reports. Thematic analysis is used to identify recurring patterns related to governance gaps, regulatory inefficiencies, and adaptation strategies.

Braun and Clarke (2006) highlight that thematic analysis is effective for identifying patterns across large textual datasets, particularly in policy-oriented research. In this study, themes include:

- Climate integration in nuclear policy
- Emergency preparedness frameworks
- Regulatory adaptability
- Institutional coordination gaps

### 3.7 Reliability and Validity

To ensure reliability, data triangulation is applied across multiple datasets (IPCC, IAEA, EM-DAT). Validity is enhanced through cross-verification of climate projections with observed disaster events.

According to Yin (2018), triangulation strengthens construct validity in case study and mixed-method research by reducing bias and increasing consistency across data sources.

### 3.8 Limitations of Methodology

This study relies on secondary data, which may limit access to facility-level proprietary information. Additionally, climate projections involve inherent uncertainty due to model variability. However, using multiple datasets reduces the impact of these limitations and improves robustness of findings (IPCC 2023).

## 4. Results

### 4.1 Overview of Climate Risk Exposure

The analysis of integrated datasets (IPCC 2023; IAEA 2022; EM-DAT 2025) reveals that nuclear infrastructure is increasingly exposed to multi-layered climate risks. These risks are not uniform but vary significantly based on geographic location, environmental conditions, and governance capacity. The results demonstrate a clear pattern of increasing vulnerability across both coastal and inland nuclear facilities, although the nature of risk differs between the two categories.

Overall, climate stressors have intensified operational instability in nuclear systems, particularly through disruptions in cooling mechanisms, structural stress, and emergency preparedness limitations.

### 4.2 Coastal Nuclear Facilities: High-Intensity Hazard Exposure

Coastal nuclear plants demonstrate the highest exposure to acute climate hazards. Facilities located in low-lying coastal zones face escalating risks from sea-level rise, storm surges, and coastal flooding. According to IPCC (2023), global sea levels have continued to rise at an accelerating rate, increasing the probability of coastal inundation events affecting critical infrastructure.

The results indicate that coastal facilities such as “Plant A,” “Plant C,” and “Plant E” experience recurrent exposure to extreme weather events. Flooding incidents and storm surges have the potential to disrupt external power supply systems and cooling water intake structures, both of which are essential for reactor safety (IAEA 2022).

Roberts and Chan (2024) emphasize that compound coastal hazards where storm surge coincides with high tide and extreme rainfall significantly amplify nuclear risk. The findings of this study support this observation, showing that coastal facilities exhibit the highest composite risk scores in the Nuclear Infrastructure Climate Risk Index (NICRI).

### 4.3 Inland Nuclear Facilities: Chronic Thermal and Hydrological Stress

Inland nuclear facilities face a different but equally significant risk profile. Rather than acute flooding events, these facilities are increasingly affected by chronic environmental stressors such as rising temperatures and water scarcity. The results show that “Plant B” and “Plant D” experience reduced cooling efficiency during prolonged heatwaves. According to the World Bank (2023), inland regions are projected to experience higher frequency and duration of heat extremes, which directly affects thermal power systems. Reduced river flow and groundwater depletion also limit the availability of cooling water. The IAEA (2022) identifies cooling water availability as a critical determinant of nuclear operational safety, and this study confirms that inland facilities are becoming increasingly constrained in this regard. Unlike coastal risks, inland vulnerabilities develop gradually but persistently, creating long-term operational stress that increases maintenance demands and reduces system efficiency.

### 4.4 Comparative Risk Analysis: Coastal vs Inland Facilities

A comparative analysis reveals distinct risk profiles between coastal and inland nuclear facilities:

- **Coastal Facilities**: High-intensity, low-frequency catastrophic risks (flooding, storm surges)
- **Inland Facilities**: Low-intensity, high-frequency chronic risks (heat stress, water scarcity)

IPCC (2023) suggests that compound climate hazards are becoming more frequent globally, meaning coastal and inland risk patterns may increasingly overlap in the future.

The Nuclear Infrastructure Climate Risk Index (NICRI) shows that coastal facilities generally score higher in acute hazard exposure, while inland facilities score higher in operational stress indicators. This dual vulnerability pattern indicates that no nuclear facility type is exempt from climate-related risks.

### 4.5 Governance and Regulatory Vulnerability Findings

The results highlight significant disparities in governance capacity across regions. Facilities located in developing countries show higher vulnerability scores due to weaker regulatory frameworks, limited climate adaptation planning, and outdated safety standards.

IAEA (2022) reports that many national nuclear regulators still rely on historical climate data rather than predictive climate models. This study confirms that such reliance leads to underestimation of future risks.

Roberts and Chan (2024) argue that governance fragmentation between climate authorities and nuclear regulators creates institutional blind spots. The findings of this study support this claim, showing that facilities with integrated governance structures demonstrate lower vulnerability scores compared to those with fragmented oversight systems.

### 4.6 Composite Risk Index (NICRI) Findings

The Nuclear Infrastructure Climate Risk Index (NICRI) developed in this study provides a comparative vulnerability score across facilities. Results indicate:

- Highest risk scores: Coastal facilities in high-storm regions
- Moderate risk scores: Inland facilities in arid and semi-arid regions
- Lower relative risk: Facilities in temperate, well-regulated regions

World Bank (2023) findings on infrastructure vulnerability align with these results, confirming that climate exposure combined with governance strength determines overall risk levels.

### 4.7 Key Result Summary

The major findings of this study can be summarized as follows:

- Climate change significantly increases both acute and chronic risks to nuclear infrastructure.
- Coastal facilities face high-impact episodic hazards, while inland facilities face persistent operational stress.
- Governance capacity plays a decisive role in determining vulnerability levels.
- Integrated climate-security frameworks are lacking in most nuclear regulatory systems.

## 5. Dataset Description

### 5.1 Overview of the Dataset

The dataset used in this study is constructed from multiple authoritative global sources to ensure reliability, comparability, and analytical depth. It combines climate projections, nuclear safety records, and disaster databases to evaluate climate-related risks to nuclear infrastructure.

According to IPCC (2023), multi-source datasets are essential for capturing the complexity of climate-driven system risks, particularly when assessing critical infrastructure.

The dataset integrates secondary data rather than primary field surveys due to the sensitivity of nuclear facility information and security restrictions (IAEA 2022). This approach ensures ethical compliance while maintaining analytical rigor.

### 5.2 Data Sources

The dataset is compiled from the following globally recognized repositories:

- Intergovernmental Panel on Climate Change (IPCC AR6 climate projections, 2000–2025)
- International Atomic Energy Agency (IAEA) nuclear safety and incident reports
- EM-DAT International Disaster Database (extreme weather events)
- World Bank climate vulnerability indicators
- National nuclear regulatory authority summaries

World Bank (2023) emphasizes that combining environmental and infrastructure datasets improves predictive accuracy in risk assessment models, especially in climate-sensitive sectors.

### 5.3 Dataset Structure and Variables

The dataset includes both quantitative and qualitative variables structured across environmental, infrastructural, and governance dimensions.

#### Environmental Variables

- Temperature anomalies (°C deviation from baseline)
- Sea-level rise (mm/year)
- Frequency of extreme rainfall events
- Duration of heatwaves (days/year)

#### Infrastructure Variables

- Reactor cooling dependency index
- Plant age and design classification
- Backup system capacity
- Geographic elevation

#### Governance Variables

- Regulatory strength index
- Climate integration in nuclear policy
- Emergency preparedness score
- Institutional coordination level

According to IAEA (2022), governance indicators are increasingly important in nuclear safety assessment due to the growing complexity of external risk environments.

### 5.4 Nuclear Facility Sample

To ensure confidentiality and maintain ethical research standards, nuclear facilities are assigned pseudonyms.

| Pseudonym | Region | Type of Facility | Primary Climate Risk |
|---|---|---|---|
| Plant A | Coastal East Asia | Large Pressurized Water Reactor | Sea-level rise & typhoons |

| | | | |
|---|---|---|---|
| Plant B | South Asia Inland | Thermal reactor system | Heat stress & water scarcity |
| Plant C | Western Europe Coastal | Advanced Generation III reactor | Storm surges & flooding |
| Plant D | Sub-Saharan Africa Inland | Small modular reactor | Drought & cooling limitations |
| Plant E | North America Coastal | High-capacity nuclear plant | Hurricane-induced flooding |

Roberts and Chan (2024) highlight that regional classification is essential for identifying differentiated risk patterns in nuclear infrastructure systems, particularly under climate stress conditions.

### 5.5 Climate Data Coverage (2000–2025)

The dataset spans a 25-year period (2000–2025), allowing for longitudinal analysis of climate trends. This time range captures both historical climate variability and recent acceleration in extreme weather events.

IPCC (2023) reports that this period includes significant increases in global temperature anomalies and a measurable rise in the frequency of extreme hydro meteorological events. These trends are directly incorporated into the dataset to evaluate their impact on nuclear infrastructure exposure.

### 5.6 Data Normalization and Index Construction

To ensure comparability across variables, all dataset components were normalized using a standardized scaling method. This allowed the construction of the Nuclear Infrastructure Climate Risk Index (NICRI), which aggregates multiple indicators into a single composite score.

The NICRI follows a weighted structure:

- Climate hazard weight: 40%
- Infrastructure sensitivity weight: 35%
- Governance capacity weight: 25%

World Bank (2023) supports the use of weighted composite indices in infrastructure vulnerability studies to capture multidimensional risk interactions.

### 5.7 Data Reliability and Limitations

While the dataset is robust and multi-sourced, certain limitations remain. Nuclear facility-specific operational data is partially restricted due to security concerns. Additionally, climate projections contain inherent uncertainty due to variability across models (IPCC 2023).

However, triangulation across multiple datasets (IAEA, IPCC, EM-DAT) improves reliability and reduces bias in risk estimation. Yin (2018) emphasizes that such triangulation strengthens internal validity in complex interdisciplinary studies.

### 5.8 Summary of Dataset

The dataset provides a comprehensive foundation for analyzing climate-induced risks to nuclear infrastructure. It integrates environmental, infrastructural, and governance variables, enabling a multidimensional assessment of vulnerability. The use of pseudonymized facilities ensures ethical integrity while maintaining analytical depth.

## 6. Ethical Considerations

### 6.1 Protection of Sensitive Infrastructure Information

This study involves analysis of nuclear infrastructure, which is classified as critical and sensitive due to its potential implications for national security. Therefore, strict ethical standards were applied to ensure that no identifiable operational details of nuclear facilities were disclosed. All facility names were replaced with pseudonyms (Plant A–E) to prevent any security risks or misuse of information. According to IAEA (2022), research involving nuclear systems must prioritize non-disclosure of sensitive operational data to maintain global safety standards.

### 6.2 Use of Secondary and Publicly Available Data

The study relies entirely on secondary datasets obtained from publicly accessible and internationally recognized sources such as IPCC reports, EM-DAT disaster records, and World Bank climate indicators. No classified, restricted, or proprietary nuclear operational data was accessed. IPCC (2023) emphasizes that secondary climate datasets are widely used in academic research due to their transparency and standardized validation processes.

### 6.3 Data Anonymization and Confidentiality

To ensure confidentiality, all nuclear facilities were anonymized using coded identifiers. This approach prevents direct association between findings and specific locations or operators. Yin (2018) highlights that anonymization is a key ethical requirement in case-based infrastructure studies, particularly when dealing with high-risk sectors such as energy and nuclear systems.

### 6.4 Risk-Free Interpretation and Responsible Reporting

The study carefully avoids presenting any technical details that could compromise nuclear operational security or be misinterpreted for harmful purposes. All findings are presented at an aggregated analytical level focusing on climate vulnerability trends rather than operational vulnerabilities.

Furthermore, interpretations are framed within academic and policy contexts to ensure responsible communication of risk-related findings. This aligns with ethical research principles outlined by the World Bank (2023), which emphasize the importance of responsible dissemination in infrastructure vulnerability studies.

## 7. Theoretical Analysis

### 7.1 Risk Society Theory and Nuclear Infrastructure Vulnerability

The theory of risk society was established by Ulrich Beck, which offers a starting point for interpreting how contemporary technological systems produce systemic and, often uncontrollable, risks ( Beck 1992). This theory is important to nuclear infrastructure as nuclear energy is a high consequence technological system, meaning that although it is rare, if failures do occur, they can lead to catastrophic consequences.

The results of this research are very much in line with Beck's thesis, that modern risks are becoming more and more “manufactured uncertainties,” in the same manner as modernization and industrial progress. Climate change, as a systemic phenomenon affecting the entire globe, adds to these uncertainties through the change in environmental baseline conditions on which nuclear infrastructure has been designed.

The results demonstrate that the environmental conditions to which both coastal and inland nuclear plants are subjected today are now beyond the scope of past design assumptions, in line with Beck's proposition that technological systems are now part of growing risk environments (IPCC 2023).

### 7.2 Climate Change as a Risk Multiplier

Climate change is a risk multiplier and not just a hazard, in the context of risk society theory. It enhances and exacerbates existing vulnerabilities of nuclear systems by increasing the frequency, intensity and unpredictability of environmental stressors.

In coastal areas, floods for instance, do not cause new risks but greatly amplify already existing operation risks; similarly, in inland areas heat waves do not cause new risks but they significantly intensify already existing operational vulnerabilities. Climate change has nonlinear interactions with infrastructure systems, causing cascading failures in interconnected networks, according to the World Bank (2023).

This study's results show that nuclear infrastructure is not vulnerable to a single stressor, but rather a combination of stressors, including heat stress, water scarcity, and storm surges, all happening at the same time.

### 7.3 The Resilience Theory and System Adaptation

Resilience theory, on the other hand, emphasizes the ability of systems to withstand shocks and remain operational. Walker and Salt (2012) describe resilience as the capacity of a system to persist, adapt and change in response to an outside disturbance.

While high reliability and safety margins are required in nuclear infrastructure, the infrastructure structure should not be too rigid to be flexible in adapting to changes. The findings of this study show that nuclear plants have difficulties adapting to the highly dynamic climate, particularly in countries with low governance in political institutions.

Comfort et al. (2019) conclude that resilience in infrastructure systems is not just identified through engineering capabilities, but also by institutional adaptability and feedback. This is confirmed by the results, as facilities with high governance scores have lower vulnerability scores in the Nuclear Infrastructure Climate Risk Index (NICRI).

### 7.4 Risk and Resilience Interconnection

Risk society theory and resilience theory can be integrated to develop a comprehensive understanding of the sensitivity of nuclear infrastructure in the face of climate change. Risk society theory is a theory which explains how vulnerabilities are increasing (systemic production of risk through modernization). The theory of resilience is used to understand the reactions of systems to these vulnerabilities (adaptive capacity and institutional response). This dual-theoretical approach emphasizes the fact that the risk of nuclear infrastructure is not just a function of environmental hazards, but also of institutional capacity and system adaptability.

As highlighted by IAEA (2022), modern nuclear safety frameworks should ensure that external environmental risks are taken into account alongside internal adaptive mechanisms, further highlighting the importance of integrated theoretical approaches.

### 7.5 Governance and Institutional Theory Perspective

The theoretical analysis also is consistent with the theory of governance, which focuses on institutions in the management of complex risks. Disaggregated governance systems limit the effectiveness of climate adaptation in nuclear systems.

Roberts and Chan (2024) have suggested that the institutional split between climate and nuclear policies generates a significant coordination gap. This study corroborates this argument by showing that facilities rated as more vulnerable have lower institutional coordination scores in regions with lower institutional coordination scores.

As a result, governance structures serve as a mediating variable between exposure to climate change and infrastructure resilience.

### 7.6 Theoretical Synthesis

Combining the three theoretical perspectives produces a unified analytical model:

- **Risk Society Theory**: Explains systemic expansion of technological risk
- **Resilience Theory**: Explains adaptive capacity of infrastructure systems
- **Governance Theory**: Explains institutional effectiveness in risk management

Together, these theories explain that nuclear infrastructure vulnerability under climate change is a multi-layered phenomenon shaped by environmental, technological, and institutional factors.

### 7.7 Summary of Theoretical Insights

The theoretical analysis demonstrates that nuclear infrastructure is increasingly embedded in a global risk environment shaped by climate change and technological interdependence. Risk society theory explains the structural production of vulnerability, resilience theory explains system response capacity, and governance theory explains institutional performance differences. These combined insights provide the conceptual foundation for interpreting the empirical results of this study.

## 8. Discussion / Analysis

### 8.1 Interpretation of Core Findings

The results of this study highlight the fact that climate change is not an environmental issue anymore, rather it is a direct threat to the operational and security of nuclear infrastructure. The findings show that both coastal as well as inland nuclear plants are facing increasing risks, but the ways they are vulnerable are quite different. This is consistent with the projections of IPCC (2023) for increasing frequencies, intensities and spatial variability of climate hazards.

There are high-impact, acute risks for coastal nuclear plants, including flooding, storm surges and sea-level rise. Chronic stress occurs in inland facilities due to heatwaves and water scarcity. The dual risk structure reinforces the World Bank's (2023) argument that climate change is a “risk multiplier, that it exacerbates existing infrastructural risks and does not create standalone risks.

### 8.2 Vulnerability Dynamics in Coastal and Inland Areas

The comparative results indicate that coastal nuclear infrastructure is mostly vulnerable to episodic but catastrophic hazards. Power systems can be quickly damaged by events like storm surges, coastal flooding and emergency back-up systems. Even a short interruption in the cooling system can drastically raise the operational risk in a nuclear plant, as stressed by IAEA (2022).

However, there are slow onset but enduring stressors for inland nuclear plants. With warmer temperatures come a drop in cooling efficiency, and less river flow and groundwater helps to limit operational stability. These results are consistent with Roberts and Chan (2024), who state that the climate stress of inland regions is becoming a long-term structural problem for energy systems in arid and semi-arid areas. The analysis shows that there is no such thing as a safe category, rather, they are two forms of climate vulnerability.

### Governance and Institutional Fragility

One of the key analytical results is that the ability of the government to govern has a significant impact on nuclear infrastructure resilience. The vulnerability scores in the Nuclear Infrastructure Climate Risk Index (NICRI) are much higher for facilities in low regulatory capacity areas that are less integrated into climate change.

IAEA (2022) states that in addition to engineering design, regulatory oversight and institutional coordination are also essential to nuclear safety. This study finds that many regulatory regimes still use historical climate assumptions and not predictive climate models to this day. Roberts and Chan (2024) also contend that weak institutional linkages and coordination between climate authorities and nuclear regulators result in institutional blind spots. The current study backs this up as it has found that non-coordinated exposure to climate risks are directly linked.

### 8.4 Climate Change as a Systemic Stress Multiplier

The findings provide strong evidence that climate change is a systemic stress multiplier in infrastructure systems of nuclear facilities. Climate change does not act as just one hazard, but as a combination of several interrelated infrastructural vulnerabilities, including cooling systems, power networks and water supplies. An example of this is that in a heat wave both electricity demand and cooling capacity can be affected and thus the dual stress scenario is created. Flooding can also have an impact on both the physical and digital monitoring infrastructure. The cascading effects are defined by IPCC (2023) as an important aspect of climate related systemic risk.

This phenomenon can be described with the help of the risk society theory developed by Beck (1992), which focuses on risks created by modern technological systems, risks which are interlocked and cannot be kept in the traditional boundaries.

The other significant discovery is that older nuclear facilities are more susceptible to climate stress. Older facilities were designed using historical climate data which underestimated present environmental extremes. According to World Bank (2023), aging infrastructure systems are typically not adaptive, and are therefore more vulnerable to environment changes. This study validates that the older facilities have greater NICRI scores because they have not been as modernized and lack flexibility in system design.

A compounding effect of the ageing of infrastructure and climate change exposes, especially in developing areas, a high level of systemic risk exposure in the context of investments in modernization.

### 8.6 Regional Inequality in Climate Risk Exposure

Significant regional differences in nuclear climate vulnerability are noted in the analysis. Risk levels are higher in developing areas, where governance structures are less effective, the technological capacity is less developed and resources are limited.

The IPCC (2023) also highlights the unequal global exposure to climate impacts, in the sense that the developing regions are more exposed than developed regions, even though they are less responsible for the global emissions. This work argues that the vulnerability is not just environmental, but institutional and economic as well in the context of nuclear infrastructure.

Roberts and Chan (2024) also call attention to the fact that, in today's world, the disparity in infrastructure resilience is increasingly a central issue in energy security.

### 8.7 Integration with Theoretical Framework

The results of the empirical research fully substantiate the theoretical framework employed in this research. Risk society theory (Beck 1992) is one theoretical approach that can account for the growing systemicization of nuclear vulnerability. The differences in adaptive capacity between facilities can be explained using the resilience theory (Walker and Salt 2012). Institutional Coordination Shapes Vulnerability Outcomes: Governance Theory. This holistic view is echoed by IAEA (2022), which emphasizes that nuclear safety should include environmental forecasting and institutional preparedness.

### 8.8 Summary of Discussion

The overarching message of the discussion is that the climate change impacts on nuclear infrastructure risk profiles are significant. Vulnerability can be broken down into coastal and inland vulnerabilities, and governance capacity is identified as playing a pivotal role in resilience. The findings validate the recognition of nuclear security as a dynamic system – shaped by environmental, technological and institutional conditions and influenced by climate change – and not a static engineering challenge to be solved.

## 9. Conclusion

### 9.1 Summary of the Study

The study explored the emerging linkage between climate change and the security of nuclear infrastructure, specifically the potential impacts of environmental stressors like sea-level rise, flooding, heatwaves, and water scarcity on the operating stability of nuclear plants. The results show that nuclear facilities are suffering from acute and chronic climate risks, and that there are different vulnerabilities of coastal and inland facilities.

Episodic high impact hazards like storm surges and coastal flooding are most threatening to coastal plants, and increasing temperatures and decreasing water supplies are most threatening to inland facilities. The findings are congruent with IPCC (2023) projections for a more intense climate extremes globally in all regional areas.

### 9.2 Key Findings

The study yielded a number of significant results:

Climate change is a major increase in both the operations and construction risks of nuclear infrastructure. Vulnerability patterns are unique but just as critical along the coast and in inland facilities. Governance capacity is a critical factor to deciding infrastructure resilience. Older infrastructure is more vulnerable to climate change disruption. Risk is exacerbated when climate hazards compound vulnerabilities stemming from existing technological reliance. In support of the IAEA (2022) assertion, that nuclear safety is no longer a technical matter but also an environmental and institutional challenge, this study robustly confirms that.

### 9.3 Theoretical Contributions

This research adds to the debates taking place in the theoretical literature, by linking risk society, resilience, and governance theory into a single analytical framework. There is evidence that nuclear infrastructure risks are more systemic, and driven by external forces, which is confirming Beck's risk society theory from 1992. The results confirm findings related to the importance of adaptive capacity and institutional flexibility and are consistent with the resilience theory (Walker and Salt 2012). This relationship between regulatory strength and vulnerability reduction is observed, supporting governance theory. These frameworks in combination give a holistic picture of the changing technological risk landscapes caused by climate change.

### 9.4 Policy Implications

The findings of this study have important implications for policymakers and nuclear regulators:

- Climate projections must be fully integrated into nuclear safety design standards.
- Regulatory frameworks should be updated to include future climate scenarios rather than historical data alone.
- International cooperation through organizations such as the IAEA should be strengthened to ensure uniform safety standards.
- Investment in adaptive cooling technologies and infrastructure modernization is essential, particularly in inland regions.
- Developing countries require targeted financial and technical support to improve nuclear resilience.

World Bank (2023) emphasizes that infrastructure resilience requires proactive investment rather than reactive disaster response, which is especially relevant for nuclear systems.

### 9.5 Academic Contribution

This study contributes to academic literature by bridging a significant gap between climate science and nuclear security studies. It introduces a multidimensional approach that integrates environmental hazards, infrastructure sensitivity, and governance capacity into a unified risk assessment framework.

Additionally, the development of a Nuclear Infrastructure Climate Risk Index (NICRI) provides a structured tool for comparative analysis of nuclear vulnerability across regions. This contributes to both methodological advancement and policy relevance in infrastructure risk research.

### 9.6 Limitations of the Study

Despite its contributions, the study has certain limitations. The reliance on secondary data restricts access to detailed operational-level nuclear facility information. Furthermore, climate projections inherently involve uncertainty due to variability across models (IPCC 2023).

However, triangulation of multiple datasets (IAEA, IPCC, EM-DAT) improves the reliability and robustness of findings.

### 9.7 Recommendations for Future Research

Future research should focus on:

- Developing real-time climate monitoring systems for nuclear facilities.
- Conducting country-specific case studies for deeper regional insights.
- Integrating artificial intelligence-based predictive risk models.
- Exploring socio-political dimensions of nuclear climate governance.

These directions will help improve predictive accuracy and policy responsiveness in nuclear infrastructure management.

### 9.8 Final Conclusion

In conclusion, climate change represents a significant and escalating threat to nuclear infrastructure worldwide. The increasing frequency and intensity of environmental hazards are reshaping the operational landscape of nuclear energy systems. Without integrated climate-security governance frameworks, nuclear facilities will continue to face rising levels of systemic risk.

This study demonstrates that nuclear infrastructure resilience depends not only on engineering robustness but also on adaptive governance, climate-aware planning, and international cooperation. Addressing these challenges is essential to ensuring the long-term safety and sustainability of nuclear energy systems in a changing global climate.

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