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Fragility assessment of power grid infrastructure towards climate resilience and adaptation

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Abstract

Natural hazards pose a significant risk to the robustness of the power grid. Climate-related hazards, in particular, are growing in both frequency and severity as a result of climate change. Statistical analyses demonstrate a noticeable increase in both the frequency of accidents owed to climate related stressors and their ensuing consequences in recent years. Consequently, it becomes crucial to understand and measure the resilience of infrastructure when confronted with external challenges, which is a pivotal stage in crafting successful strategies for adapting to climate change. To accomplish this objective, the creation of sturdy fragility models is absolutely necessary. These models function as instruments for assessing the extent of damage to assets and for quantifying losses using metrics related to hazard intensity.

Within this framework, we conduct a review of the existing fragility models tailored to transmission networks, distribution networks, and substations. Our review is structured into three primary sections: damage assessment, fragility curves, and recommendations for climate adaptation. The initial section offers a brief examination of damaging hazards, modes of failure and impacts. The subsequent section provides an overview of both analytical and empirical fragility models, underscoring the need for further investigations into compound and non-compound hazards, particularly windstorms, floods, lightning, and wildfires. Finally, the third section delves into climate adaptation investments within the context of climate change. This review can contribute to the enhancement of power grid asset resilience in the face of climate change. Its findings are pertinent to various stakeholders, including risk analysts and policymakers involved in risk modelling and the formulation of adaptation investments.

Keywords: power grid; fragility curves; climate resilience; adaptation investments

1 Introduction

The European power grid is vital for modern societies, supporting critical services like water, transportation, and communication, as well as facilities like healthcare. Yet, the resilience of roughly 509,000 km transmission network and 25,400 substations are continuously threatened by natural hazards e.g. windstorms and flooding. Ensuring uninterrupted electricity supply is crucial for community safety and prosperity. Natural hazards, including climate-related ones, threaten grid functionality annually. According to the European Network of Transmission System Operators for Electricity [1], 18-22% of disruptions in Europe during 2018-2021 resulted from climate hazards, potentially higher due to under-reporting [2]. Climate hazards were the leading cause of transmission network disruptions in this period, with no outages linked to power generation plants. A World Bank study [3] estimated 37% of power outages attributed to natural hazards from 2010-2016, lasting four times longer than non-natural outages. Global trends support these findings [4], with higher percentages in some regions [5]. Notable examples of grid vulnerability include the 2021 European floods and the 2019 California heatwave, causing extensive damage and prolonged power outages [6,7].

Evidence indicates a rising trend in accidents and their consequences, driven by climate change and grid complexity. In 27 EU+UK countries, the average interruption frequency due to extreme weather events more than doubled from 2004 to 2016 [8]. The North American Electric Reliability Corporation (NERC) reported that 69 out of 70 large power transmission events in the U.S. from 2016-2021 resulted from extreme weather, challenging the electricity system [9]. The Intergovernmental Panel on Climate Change (IPCC) 2023 report [10] confirmed increasing weather extremes due to global warming, expected to persist [11]. Expanding power grids, especially in coastal Mediterranean regions [12], heightens infrastructure exposure.

To understand power grid vulnerabilities, we need robust fragility models. Fragility Curves (FCs) facilitate risk analysis and loss assessment as well as quantification of resilience [13]. However, literature on power grid fragility models against natural hazards, accounting for climate projections and multiple hazards, is limited. A review by [14] highlighted empirical, single-hazard models as predominant. Existing models focus largely on wind hazards, neglecting others like snow, lightning, floods, and wildfires [9,15]. European models remain mostly empirical, even for wind hazards [16,17]. Analytical FCs primarily target different infrastructure types [18,19].

In view of the new EU Directive [20] that intends to enhance the resilience of critical entities, accounting for all-hazards, climate change and adaptation, this study aims to conduct a review of fragility assessment models and adaptation investments for power grid assets against critical natural hazards. Before doing so, a database analysis and damage assessment to identify the most damaging hazards, failure modes and impact is carried out.

2 Previous accidents on power grid due to natural hazards

2.1 Database analyses

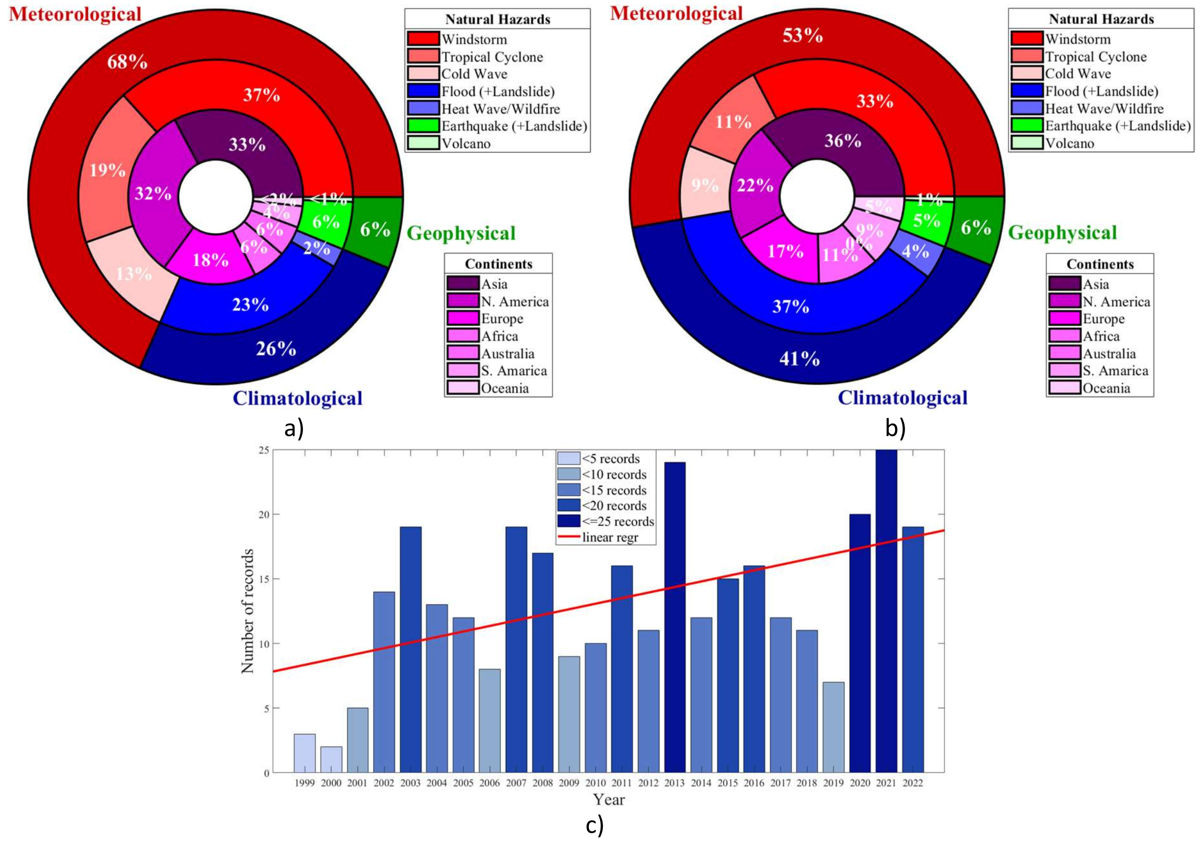
The purpose of this section is to identify the most significant natural hazards that pose threat to the power grid network as well as the potential research gaps in available damage reporting and in the consideration of natural hazards for fragility assessment. The main challenge when carrying out a statistical analysis is that databases present different level of accuracy and detail. Numerous accidents are under-reported, and there is also inconsistency with respect to the information that is reported for each accident, which introduces bias into the statistical analysis. To reduce the bias, multiple databases and cross-checking with reports and media can be employed. In this study, data is extracted from two available accident databases: the International Disaster Database (EM-DAT) and the database of the Asian Disaster Reduction Center (ADRC). These choices were made, because the data are publicly available, while the level of detail allows the categorization of accidents. The accidents included in the analysis meet one or more of the following criteria in both databases: 5-10 or more fatalities, a minimum of 100 people affected and/or an international appeal for emergency assistance. The extracted records refer to accidents that occurred between 1999 and 2022.

Out of a total of 703 accidents, 177 and 151 accidents were selected from EM-DAT and ADRC, respectively. Using keywords, the accidents were categorized per each family of hazards (meteorological, climatological and geophysical), individual natural hazards and continent where the accident occurred. In Figure 1a&b, the outer circle of the pie charts represents the family of hazards, and it can be seen that the majority of accidents were triggered by meteorological hazards, followed by climatological and geophysical, for both databases. The databases agreed regarding the most damaging hazard, which was windstorms, accounting for approximately 33% to 37% of the accidents, followed by floods and cold waves. It is important to note that windstorms are compound hazards involving both wind and lightning, which have been found to cause significant damage to the power grid. A notable discrepancy between the databases was observed on the percentage of accidents caused by floods and tropical cyclones, which can be attributed to differences in the allocation of accidents. Although one-third of accidents occurred in Asia in both databases, the number of accidents that occurred in N. America was 10% less in EM-DAT, which may introduce some bias. Nearly one-fifth of accidents occurred in Europe in both databases, which could increase to 25% if hazards affected multiple countries were considered (omitted from this analysis due to lack of data). Among the least damaging hazards were heat waves and wildfires accounting for only 2% of the accidents. This percentage may be relatively biased due to under-reporting, considering the numerous and prolonged outages in wildfire-prone areas like California [23]. Wildfires are often localized events, and this might be a reason of the under-reporting; however, the risk of power grid damage due to wildfires is expected to increase considerably in areas with Mediterranean-line climate due to climate change [8,24].

Furthermore, a linear regression model was employed to estimate the number of accidents per year, taking into account data from both databases. This approach ensured that accidents reported in both databases were considered only once. As shown in Figure 1c, an increasing trend in the annual number of accidents is observed from 1999 to 2022. This outcome further highlights the importance of conducting risk assessment of power grid assets against natural hazards. Regarding the causes of failure, it can be confirmed that the most frequent cause was fallen trees on transmission towers or utility pylons due to excessive wind or snowfall, accounting for at least

15% of failures. It is noteworthy that approximately 25% of accidents were triggered by compound events such as combination of wind with rainfall, snow or lightning. These results provide valuable insights for the current review and future studies on risk and resilience assessment. Finally, regarding the failure modes, it is important to mention that, apart from conductor failures and the collapse of towers, pylons, or substations due to flooding, limited information was available for other failure modes. Therefore, the subsequent section will delve into reviewing damage assessment studies to gain a better understanding of these failure modes as well as other resilience aspects e.g. preparedness, restoration and recovery that contributed to increased losses.

Figure 1: Database analyses: percentage of natural hazards that have triggered a power outage and the allocation of accidents to each continent from a) EM-DAT and b) ADRC databases, and c) linear regression of the number of accidents per year based on EM-DAT and ADRC



2.2 Analysing failure modes and impact in major accidents

Table 1 presents information on significant power grid accidents linked to various destructive hazards, including snowstorms, heatwaves, windstorms, floods, and earthquakes. The objective is to emphasize the most common causes of failures and the consequences of these hazards on power grid assets and the economy. The first incident documented in the table concerns the 2005 Münsterland power blackout, which was triggered by a combination of factors, including ice and wind, as well as the aging infrastructure [25]. The event unfolded as a result of strong winds and heavy snowfall, leading to the accumulation of wet snow on overhead electrical lines in the form of snow rolls. This accumulation caused the failure of 82 high-voltage transmission towers. The power company responsible for the transmission system in the region initially labeled the failure as an unforeseeable "black swan" event. However, subsequent investigations by news media [26] and a forensic analysis conducted by [25] revealed that the tower collapse resulted from a combination of excessive ice and wind loading, coupled with the reduced capacity of the towers. The consequences of this blackout were substantial, affecting more than 250,000 individuals for a duration of 4 to 6 days, with estimated repair costs surpassing €130 million. This incident underscored the necessity of upgrading or replacing aging infrastructure and establishing effective communication channels between power operators and meteorological agencies to identify hazards and implement preventive measures to avert future accidents. Indeed, a power utility company proactively shut off electricity to approximately 3 million people in response to an impending threat of deadly wildfires and potential damage to the power grid due to a forecast of extreme weather conditions, which combined heat and wind hazards [6]. High temperatures can lead to short circuits because of line sagging, and wildfires front can damage directly power grid assets. While a post-event case study demonstrated that the prior shutdown by the company prevented a catastrophic outcome, it also revealed inadequacies in the preparedness of authorities and the resilience of the power grid. This was evident in the fact that it took over one month to fully restore power in all affected regions, primarily due to extensive inspections [27].

Table 1. A summary of failure modes and impact in major power grid accidents

Natural Hazard	**Event**	**Failure mode and contributing factors**	**Impact**
Snowstorm (compound hazard)	• 2005 Münsterland power blackout • Affected country: Germany	• Transmission tower collapse due to excessive wind and ice load on the conductors	• Blackout experienced by 250,000 people for 4-6 days • Rupture of 82 transmission lines
Heat wave and wind (compound hazard)	• 2019 California shutoffs • Affected country: USA	• Pre-emptive shutdown as a response to the elevated wildfire risk • Substantial rise in California's population in wildfire-prone regions • Potential failure modes: short circuits due to line sagging and direct damage to assets from wildfire front	• Around 3 million people without power for up to a month • Disruption of rail transport services for two days
Windstorm (tropical cyclone)	• 2017 Hurricane Maria • Affected country: Puerto Rico	• Damaged power lines and inaccessibility to the sites due to fallen trees • Under-investment by the government: lack of vegetation management, redundancy and design of power lines for Hurricane Category 4	• 70% of electricity customers without power • 18 billion of dollars for power grid restoration (direct damage)
Fluvial flood	• 2021 European floods • Affected countries: Germany, Netherlands	• Failure of equipment inside substations because of flood water • Very high quantity of water (the highest in 1000 years)	• Around 800,000 people without power for up to 8 weeks
Earthquake and tsunami	• 2011 Great East Japan earthquake and tsunami • Affected countries: Japan	• Collapse of steel-lattice transmission towers by tsunami-borne debris and landslides • Design level exceedance of generation plants, substations and equipment e.g. insulators, even for the most recently constructed power grid assets	• 10 million people without power, but reinstatement of 90% of the power grid within 6 days • Collapse 42 steel-lattice transmission towers (40 by tsunami-borne debris and 2 by landslide) • Half a billion $ for restoration and demand curtailment during summer due to damage to power plants

Furthermore, tropical cyclones, with hurricanes being a notable example, rank among the most destructive threats to the power grid. An illustrative case is the impact of Hurricane Maria in 2017, which inflicted severe damage on Puerto Rico's electrical infrastructure. Power lines and towers were collapsed because of severe wind and fallen trees, as a result of under-investment. Poor maintenance, vegetation management and inadequate design for Category 4 hurricanes were the primary causes of failure. Also, lack of redundance was the main cause of prolonged outages. The endeavor to restore the power grid alone incurred costs as substantial as €18 billion, marking the highest expense among all the incidents delineated in Table 1. Owing to the grid's pronounced vulnerability, merely 20% of the transmission lines were back in operation after the initial month, and the restoration process extended over a year [28,29].

The 2021 European floods, which had a significant impact on Germany's power grid, underscored the high impact of flood hazards on numerous equipment inside substations for High Impact Low Probability (HILP) events. The power outage lasted for up to 8 weeks due to site inaccessibility and repair work [29,30]. Also, the 2011 Great East Japan earthquake inflicted extensive harm on transmission towers and substations, resulting in substantial financial losses. The earthquake and tsunami exceeded design levels even for the most recently constructed power grid assets. Transmission towers failed mostly due to tsunami-borne debris, but landslides caused damage as well. This catastrophe also had a profound impact on approximately 10 million individuals. It's worth noting that the power supply was swiftly reinstated in 90% of the affected area within a mere 6 days, underscoring the nation's commendable level of preparedness. Nevertheless, the remaining 10% of the region, where damage resulted from the tsunami and landslides, necessitated a month-long effort to fully restore the power supply [31,32]. TEPCO energy provider spent half a billion for restoration and issued summer power curtailments due to the loss of power plants.

3 Fragility models for European power grid assets

One of the requirements for assessing the resilience of power grid assets is the derivation of FCs, which are practical tools that describe the probability of exceedance of a certain level of damage given the intensity measure (IM) of a natural hazard [33,34]. As shown in the following sections, even though FCs have been derived for other critical infrastructures e.g. bridges and power plants [18,19], the literature is still scarce for power infrastructure. Dumas et al. [14] carried out a review of power grid vulnerability, which is one out of very few in the literature, and corroborated that the majority of the available models are empirical and single-hazard. Furthermore, by virtue of limitations of the lognormal distribution to capture efficiently the data that pertain to multiple-parameter or multiple-hazard events, the logit function is adopted instead [35,36]. There are four main methods for deriving FCs, namely empirical, analytical, judgmental and hybrid. Analytical methods are based on physical models or explicit demand-capacity relationships, while empirical and judgmental methods rely on observations, experiments, and expert judgments. Hybrid methods combine these approaches. The key advantage of analytical forecasting over empirical/judgmental methods is the auditability and verifiability of physical models, whereas empirical data are easier to handle. Table 2 summarizes all the available fragility models for transmission and distribution network as well as substations in the EU per natural hazard, fragility method and IM. This summary is part of a comprehensive review by [37] and relies only on peer-reviewed journal publications in the last two decades. Also, only publications that derive FCs are considered. Hence, resilience assessment studies that use FCs are not taken into account.

Table 2. Fragility models for power grid assets in the EU against different natural hazards

Power grid asset	Hazard	Fragility model	IM
Transmission network	Wind	Analytical: [17]	3-s gust wind speed
Distribution network	Wind	Empirical: [16]	Maximum wind speed
	Earthquake	Empirical: [38]	PGA
Substations	Earthquake	Analytical: [39] Hybrid: [40]	PGA: [39], [40]

It can clearly be seen in Table 2 that the available models are limited per asset and hazard. This conclusion is especially true in Europe for all power grid assets and natural hazards, which renders the evaluation of impacts at an individual asset level inconsequential for planning recovery measures in a broader, EU-level policy framework. Prior FP7 projects e.g. RAIN, AFTER, ongoing HE e.g. ReCharged, R^2D^2, HVDC-WISE, RISKADAPT and studies [41] have advanced the resilience assessment of power assets, but do not study new fragility models in a systematic way, disregarding structural- and hazard-induced uncertainties. Additionally, empirical models e.g. [16] and [38] are bound to specific regions, in contrast with numerical models, and cannot easily apply to other regions due to different typologies of assets and weather conditions e.g. multi-hazard or climate change effects. Numerical fragility functions are very limited, e.g. for the Nordic transmission power network against wind hazard [17] or for substations against earthquake hazard [39] and [40], and case-specific with regard to asset typologies, ageing and design conditions. Therefore, it is evident that additional fragility studies are needed to evaluate the resilience of the EU power grid assets against all damaging natural hazards, including wind, flood, earthquakes, wildfires, lightning as well as compound events such as windstorms and snowstorms. The new fragility models can be used to reflect the impact of different adaptation investments e.g. structural upgrade, as discussed in the following section.

4 Adaptation investments for managing risks

Current EU regulations [42] focus mainly on the generation-demand balance, without providing well-informed methods on how energy infrastructure can be incorporated into national disaster risk assessments. The new EU Directive [20] and Adaptation strategy [43] stipulate that National Authorities shall identify critical entities, receive EU support and embrace grey, green and soft investments, especially because of climate change. Table 3 quotes different adaptation investments of power grid assets against natural hazards, which may exacerbate in frequency and/or intensity due to climate change depending on the region [11]. First, grey investments refer to engineering interventions that have low environmental footprint. These investments can be reflected on fragility and risk assessment models for evaluating whether the updated risk after the upgrade is acceptable or not. However, the literature lacks of such models, as demonstrated in the Section 3. Grey investments measures include structural upgrade, underground cabling, use of high-quality insulators, “low-sag” conductors, levee protection or relocation of assets, among others [44]. Green options are based on nature-based approaches and make use of the multiple services provided by natural ecosystems e.g. land-use planning for identifying alternative network paths, nature-based wind protection barriers, configuration of smart grids based on renewables to improve resilience and adaptation capacity.

Finally, soft options include policy, legal, societal, managerial and financial measures, capable of influencing human conduct and governance practices. For example, the improvement of legal status of EU member states regarding the development of smart grids, interconnection of transmission networks among member states for building redundancy and the consideration of power operators in the decision making of power infrastructure protection are soft measures. Additionally, cost-benefit analyses can be used to examine resilience trade-offs among different adaptation investments. For instance, a cost-benefit analysis can evaluate whether underground cabling is more cost-efficient than retrofitting or replacement options e.g. with pylons of different material in the long term in regions with extreme weather conditions [45]. This will result in money saving and higher safety of citizens. Also, vegetation management, maintenance and inspection of power grid assets should be part of a long-term financial planning of power operators in EU member states to prolong the lifetime of power grid assets and increase the resilience. Vegetation management, which includes trimming, removing hazard trees and other air-borne objects near overhead power lines to minimise interference risks, was identified as the most effective option for climate resilience enhancement by [46]. Finally, soft investments can play a key role in enhancing adaptive capabilities and raising awareness of local communities about climate change matters.

Table 3. Fragility models for power grid assets in the EU against different natural hazards

Natural Hazard	Exacerbated by climate change	Adaptation measures
• Windstorm	• Yes (increase in intensity and/or frequency in some regions)	• Structural upgrade of towers/pylons, use of mechanical fuses to reduce conductor breakages and underground cabling • Exploration of alternative routes of overhead lines or ecosystem-based wind protection barriers • Establishing an efficient communication channel between power operators and meteorological agencies • Frequent inspection and maintenance, vegetation management • Effective decision-making based on cost-benefit analyses
• Lightning strikes	• Yes (increase is some regions)	• Surge arresters, high-quality insulators, shield wires and lightning musts • Vector shift protection • Load shedding with real time load assessment of feeders using telecommunications • Grid reconfiguration
• Heat waves and wildfires	• Yes (Increase in intensity and/frequency)	• Hardening, maintenance planning and vegetation management • Installation of solar panels and mobile energy storage systems to increase redundancy, accounting for weather uncertainties • Proactive generation redispatch and outage prediction modelling and shutoff due to wildfire progression • System operators in the decision-making
• Flood	• Yes (Increase/decrease in intensity and/or frequency in some regions)	• Substation relocation, equipment elevation or water-proofing • Levee protection • Shutdowns based on early warnings, surge mechanisms activation and positioning repair resources at the edge of flood zones
• Earthquakes (inc. landslides, liquefaction and rockfalls) and tsunami	• No	• Seismic retrofitting of towers and equipment e.g. anchoring or flexible coupling among equipment items, use of bushings, surge arrestors and base isolation e.g. for transformers • Installation of protection barriers all around transmission towers in tsunami run-up zones for debris protection • Implementation of scour protection measures of equipment foundations

5 Conclusions

Extended periods of power shortages and significant financial losses are evident in major accidents due to the absence of robust risk assessment models and preparedness. For transmission and distribution networks, the primary causes and contributing factors include falling trees and debris on overhead lines, wind loads surpassing design specifications and the effects of aging. Substations face challenges such as exceeding inundation levels, inadequate equipment maintenance, and the absence of protective barriers, which can lead to equipment damage and short circuits.

Hence, there is a need for new fragility models to enhance the assessment of power grid asset resilience against wind, flood, and wildfire hazards. For instance, there is a lack of analytical wind and multi-hazard models that can encompass the various types of transmission towers in different ecosystems. A similar deficiency is observed in the case of substations and flood hazards. While wildfire has been recognized as a significant threat, there is still limited research in this area. Given the aging infrastructure and the anticipated impact of climate change, particularly the intensification of wind, coastal and inland flooding, and heat waves, addressing these gaps becomes even more crucial.

Grey, green and soft adaptation investments should be considered to bolster asset resilience. The impact of climate-aware structural strengthening, wind or flood barriers, and mechanical fuses on conductors can be quantified through fragility models. Additionally, land-use planning for network relocation or expansion, emergency response planning, proactive line outages, and underground cables can significantly enhance asset resilience, all of which can be evaluated through cost-benefit analyses. However, it's important to note that the cost-benefit of these investments has not yet been quantified through resilience metrics specifically tailored to power grid assets, particularly in the case of transmission networks.

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