Critical Infrastructure Security: An Extreme Events Risk Assessment Approach for On-shore Wind Farms

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Abstract

Modern critical infrastructures encompass facilities and systems vital to societal functions, in sectors such as health, transportation, food and energy. The matter of security in critical infrastructures, particularly renewable energy assets, is increasingly important nowadays in the context of extreme weather events and natural hazards, as it translates to safety threats and green energy production impediments. Focusing on wind farms, their strategic deployment in areas with favorable wind conditions has the potential to significantly reduce greenhouse gas emissions, limit the reliance on fossil fuels and mitigate the impacts of climate change. This paper presents the framework of a risk assessment approach for on-shore wind farms, focusing on their vulnerability to extreme weather and environmental phenomena, including lightning strikes, ice formation, seismic activity, floods, high winds, and hurricanes. The framework identifies the most significant risks threatening onshore wind farms and their impacts, while simultaneously conducting a risk assessment that considers specific parameters such as the likelihood, frequency and severity of the risks. These elements will form the basis for evaluating the effects on the operation and overall performance of the energy system. At the same time, existing risk mitigation strategies that have been effectively implemented are proposed, aiming to further enhance the safety and resilience of wind farms. This work stresses the importance of risk-informed decision-making in safeguarding critical renewable energy infrastructures against the increasing frequency and severity of extreme natural events. While this paper covers the design aspects of risk assessment, the conclusions and products of this research contribute to a broader framework of an ongoing project concerning the development of an on-shore wind farm digital twin, which will facilitate real-time monitoring and control.

Keywords

Wind farm, onshore, energy, sustainability, resilience, risk, natural hazard

1. Introduction

Technological developments in the utilization of renewable energy sources have brought significant changes to energy production, contributing to the enhancement of sustainability and resilience on a global scale. Within this established situation, onshore wind farms represent a key element of the modern energy chain, as they offer a more environmentally friendly alternative solution for energy production compared to existing energy systems that rely on fossil fuels. Besides, with the use of wind energy, greenhouse gas emissions are reduced and the negative impacts of climate change are mitigated.

The onshore wind farms, apart from their environmental and economic benefits, face several risks associated with extreme weather events, such as lightning strikes, hurricanes, floods and ice formation [1]. The timely management of these risks is essential for ensuring the continued uninterrupted operation of wind farms, while simultaneously enhancing their resilience and operational reliability. For this reason, the risk assessment of extreme weather events is a valuable tool for the protection of critical infrastructure. By evaluating the likelihood, frequency and severity of various environmental hazards, this approach enables a systematic identification and understanding of potential vulnerabilities and supports decision-making processes. Such methodologies not only enhance operational resilience, but also help mitigate economic losses caused by disruptions.

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This paper aims to present a risk assessment framework for onshore wind farms, which can be integrated as a key component in the development of a Digital Twin. By utilizing Digital Twins, real-time monitoring of the operation and performance of wind farms is achieved, while at the same time, there are capabilities for predicting potential risks and issues, facilitating their proactive management [2].

The first section of this paper refers to the importance of critical infrastructure for the functionality of states at both national and international levels. The second section presents the most common extreme weather events that threaten the operation of onshore wind farms, while in the next section of the paper, risk management methodologies are presented. In the final section, proposals are provided for the proactive mitigation of risks and the enhancement of the resilience of onshore wind farms.

2. Defining and Protecting Critical Infrastructures: A Global Perspective

One of the critical challenges governments face globally in today's era is the protection of Critical Infrastructures (CI). Such infrastructures are defined as systems or parts which are essential for maintaining vital societal functions, public health, safety, economic stability and social well-being [3]. A potential disruption or failure of these systems' operations could have a severe impact on the population's life and health [4]. The critical infrastructures of a state can be likened to the vital organs of the human body, whose proper functioning is essential for its survival [5].

The European Union defines critical infrastructures as those "located within Member State territory, whose disruption or destruction would have a significant impact on one or more Member States". In Greece, according to Presidential Decree 39/2011, Article 2, paragraph (a), critical infrastructures are defined as:

"Assets, systems or parts that are essential for maintaining the vital functions of society, the health, safety, and economic and social well-being of its members and whose disruption or destruction would have a significant impact on the country due to the inability to maintain these functions" [6].

In the United States, the general definition of critical infrastructures is: "Assets and systems, whether physical or virtual, so vital to the United States that their failure or destruction would have a debilitating impact on security, the national economy, public health or any combination of these factors". In Australia, critical infrastructures are defined as: "Those facilities, supply chains, information technologies and communication networks which, if destroyed or rendered unavailable for an extended period, would have a significant impact on the social or economic well-being of the state or affect the country's capability in matters of national defense and security." Finally, in the United Kingdom, critical infrastructures are described as: "Those infrastructures, services and systems that underpin the economic, political and social life of the United Kingdom, the loss of which would result in: 1. Large-scale loss of life, 2. Significant impact on the national economy, 3. Major consequences for society and 4. National security issues [6].

Based on the above, the infrastructures classified as critical may vary from country to country, but, generally, they include networks and services, as illustrated in Figure 1 below.

Critical Infrastructures can include networks and services that can be categorized as shown below in Table 1 on the next page.

Table 1
List of critical sectors and related critical services [8].

Critical Sector	Critical Subsector	Critical Services
Energy	Electricity	Generation (all forms, including wind farms) Transmission / Distribution Electricity Market
	Petroleum	Extraction Refinement Transport Storage
	Natural Gas	Extraction Transport / Distribution Storage
Information, Communication Technologies (ICT)	Information Technologies	Web services Datacentre / cloud services Software as a Service
	Communications	Voice / Data communication Internet connectivity
Water	Drinking water	Water storage Water distribution Water quality assurance
	Wastewater	Wastewater collection & treatment
Food		Agriculture / Food production Food supply Food distribution Food quality/safety
Health		Emergency healthcare Hospital care (inpatient & outpatient) Supply of pharmaceuticals, vaccines, blood, medical supplies Infection/epidemic control
Financial services		Banking Payment transactions Stock Exchange
Public Order and Safety		Maintenance of public order and safety Judiciary and penal systems
Transport	Aviation	Air navigation services Airports operation
	Road transport	Bus / Tram services Maintenance of the road network
	Train transport	Management of public railway Railway transport services
	Maritime transport	Monitoring and management of shipping traffic Ice-breaking operations
	Postal / Shipping	Document & Parcel transport services Payment transactions
Industry	Critical industries	Employment / GDP /supply of goods sustaining activity
	Chemical / Nuclear Industry	Storage and disposal of hazardous materials Safety of high-risk industrial units
Civil Administration		Government functions
Space		Protection of space-based systems
Civil protection		Emergency and rescue services
Environment		Air pollution monitoring and early warning Meteorological monitoring and early warning Ground Water (lake/river) monitoring and early warning Marine pollution monitoring & control

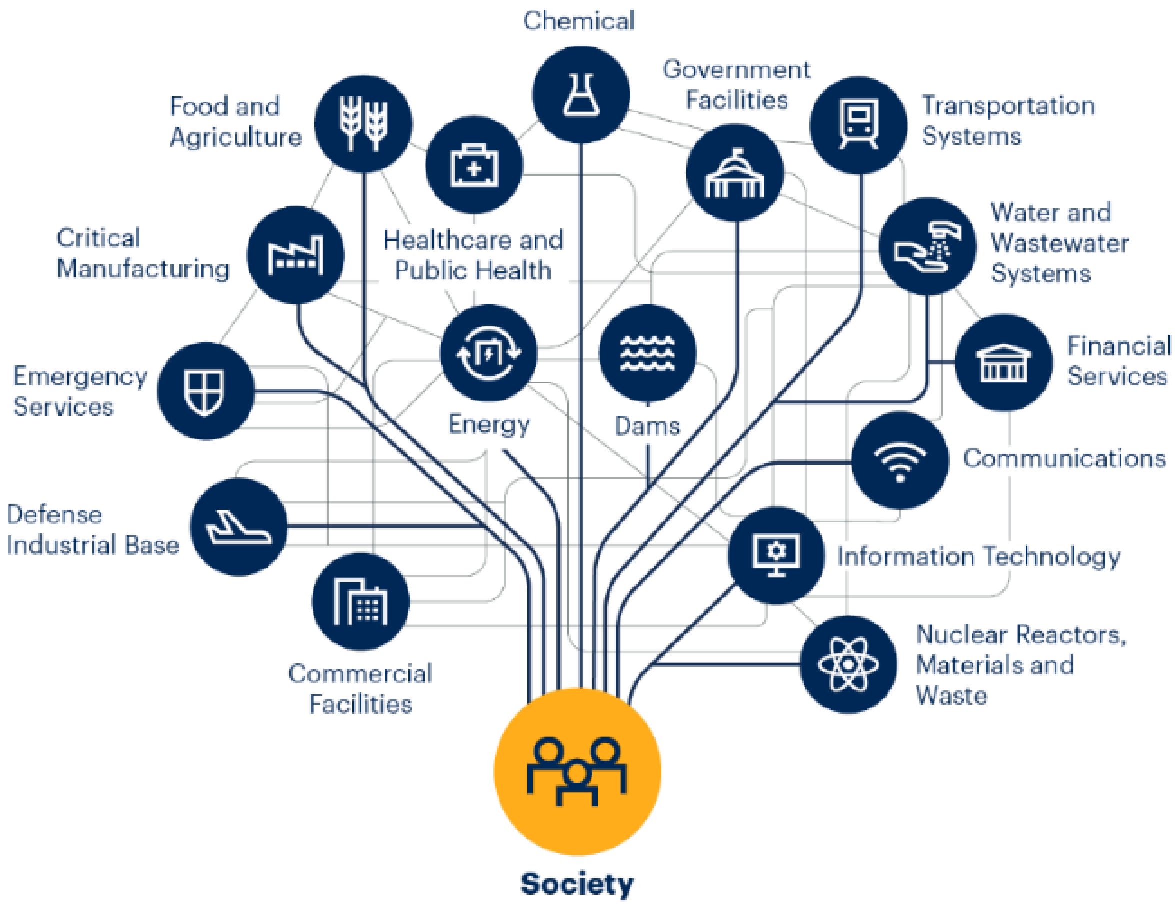

Figure 1: Most Critical Infrastructure sectors [7].

3. The Role and Resilience of Wind Farms in Modern Energy Systems

Based on the points mentioned in the previous section, wind farms are considered critical infrastructure due to their contribution to energy production. The current need for a transition to cleaner and more sustainable energy forms makes wind energy a critical factor in the effort to enhance and develop renewable energy sources. This aims to reduce greenhouse gas emissions and strengthen energy security at both national and global levels [9].

3.1. Challenges Posed by Extreme Environmental Events

One of the most significant challenges faced by wind farm operators are extreme weather events, specifically strong winds, severe storms, flooding and ice formation, which affect the functionality, structural integrity and maintenance of wind turbines [10]. The above-mentioned phenomena not only reduce efficiency but also increase repair and restoration costs due to potential damages they may cause [11].

Understanding risks is the basis for developing risk management systems, which may include modern energy storage systems capable of ensuring the effective operation of wind farms even under adverse conditions. Additionally, by utilizing IoT technologies, improved monitoring of both the operation of wind farms, as well as their energy management and sustainability can be achieved [12].

4. Extreme event identification and impact

The deployment of on-shore wind farms is a process that involves careful planning and selection of strategic locations, in order to maximise their efficiency in harnessing the wind and provide green energy. Many times, though, the same selected installation sites offering ample energy generation, are also vulnerable to extreme natural effects affecting not only the seamless operation, but also the structural integrity of wind turbines. These diverse environmental challenges can disrupt operations, compromise safety, and incur significant economic costs. Understanding the nature of these vulnerabilities is a critical first step in risk assessment [13]. This section identifies and analyzes the most severe environmental phenomena that can have a major impact on on-shore wind farms, extending to potential repercussions. Each type of natural hazard is analysed separately, taking into account its consequences in wind farm safety and performance.

4.1. High winds and hurricanes

Although the design characteristics of a wind turbine are exactly those to harness the power of wind, excessive speeds of the latter can be overwhelming, leading to significant structural fatigue and component failure or damage. High winds are an extreme event with frequent occurrence in on-shore sites over the world. Some of its damaging consequences include blade overloading, tower buckling, and nacelle misalignment, resulting in both mechanical failures and safety hazards. Therefore, turbine design innovations and shutdown protocols are vital, in order to mitigate the effects of these challenges. Additionally, current research has focused on the aerodynamic design of wind turbines to withstand high wind loads as much as possible, while also highlights the importance and moves towards the direction of more advanced and accurate wind speed monitoring and forecasting [14].

4.2. Lightning

Lightning strikes are -similarly to high winds- among the most frequent and disastrous natural events affecting wind farms. The height and metallic structure of turbine towers with large blade spans constitute a very tall, highly conductive medium, with extreme susceptibility to lightning. Depending on the intensity of the strike, the repercussions on a wind farm may vary from structural damage on the turbine blades to disruptions or failures of the electrical system or even the causing of catastrophic fires [15]. As mentioned above, the most vulnerable components to lightning are the turbine blades, with damage caused on their surface or their internal structure that can frequently result in prolonged operational downtime and costly repairs.

4.3. Ice formation

Depending on location, whether in regions of cold climate, high altitude, or both, the accretion of ice, due to freezing rain, wet snow or frost on the wind turbine blades presents significant assessment and operational challenges. Thus, with ice formation, it is common to receive errors in measurements from anemometers, wind vanes and temperature sensors, which complicates assessment and planning endeavours. Furthermore, the accumulation of ice alters the aerodynamic shape and increases the load on the blades, which may result in reduced power generation, as well as (in case of prolonged ice conditions) mechanical wear or even failure in some extreme cases. Finally, there is a potential safety hazard to personnel, equipment, or the surrounding infrastructure, due to ice shedding from the blades' rotation [16].

4.4. Seismic activity

Other region-depended extreme natural events include earthquakes. They are not very commonly associated with wind farms, since most major installations of the latter have so far been deployed in northern Europe, which has very small seismic activity. However, as wind farm interest has been spreading to many more areas in recent years, a revisited approach might be necessary for a natural phenomenon whose effects should not be underestimated. Seismic events, depending on intensity and duration, are capable of structural damage to turbine tower foundations, deformations, or even total tower collapsing, as well as disruptions to power transmission infrastructure and resulting downtime. Moreover, vibrations of seismic waves could potentially wear and stress wind turbine components, especially those with moving parts, to the point of failure. According to current resilience studies, in regions more prone to seismic activity, wind turbine towers may require retrofitting and detailed structural analysis beyond the current standards [17].

4.5. Floods

Onshore wind farms are most commonly placed on the top of a hill or in other high places to exploit wind intensity for higher power generation. There are cases, though, where wind farms are deployed on lowlands, valleys or coastal areas, facing an inherent risk of flooding. Whether from heavy and continuous rainfall, rising sea or river water levels or other geological phenomena, floods are considered a significant risk. The most affected parts of the installation are the turbine tower foundations that can be severely damaged, as well as land-level systems and equipment, risking corrosion effects if the water is left unchecked. Another important risk is the flooding of roads and access points leading to vital maintenance or control areas, potentially compromising the safety of the infrastructure. As extreme weather events increase in frequency, meticulous planning is required, on site location selection, introducing design options of an elevated infrastructure, as well as implementation of drainage systems, in order to mitigate flood damage [18].

Understanding in detail the specific impacts of the above extreme environmental events is considered vital for the design of onshore wind farms with reliable operational performance. The increasing frequency and severity of extreme natural events witnessed all around the globe due to the effects of climate change, stress the need for application of continuous risk assessment and adaptive strategies. In the following sections, a comprehensive risk assessment framework is presented, in order to evaluate these hazards in detail and propose some effective mitigation strategies to enhance the safety and resilience of onshore wind farm installations.

5. Risk Assessment for Onshore Wind Farms: Ensuring Safety, Efficiency and Sustainability

Risk assessment is a crucial tool for ensuring the safety, efficiency, and environmental sustainability of onshore wind farms. When potential risk factors are systematically identified and evaluated, operators are able to implement more effective mitigation strategies, thus, preventing accidents and minimizing environmental impacts. This process is vital at all stages of the project from construction to operation, in order to safeguard personnel, optimize resources and ensure compliance with regulatory standards.

5.1. Introducing factors of likelihood and severity

Risk likelihood and risk severity are known to be fundamental components of any comprehensive risk assessment framework. Their thorough evaluation provides a solid foundation for identifying potential threats, prioritizing mitigation measures, and ensuring reliability in operation of onshore wind farms. When dealing with certain types of critical infrastructures, which are exposed to diverse and sometimes extreme environmental phenomena, these factors should be analyzed meticulously, in order to account for varying hazard profiles [19]. This section discusses the application of likelihood and severity assessments to the extreme natural hazards described above.

5.1.1. Risk Likelihood Assessment

The factor of likelihood in any given risk is translated as the probability of the hazard occurring within a set time interval and geographical location. In the case of onshore wind farms, likelihood is determined by historical data analysis, environmental conditions analysis of the specific region, as well as investigating local meteorological or geological patterns. The likelihood factor is typically represented on a scale, incrementing from "very unlikely" to "almost certain" or from very low to very high. The following paragraphs present the likelihood dimension for each hazard discussed previously:

The likelihood and/or frequency of high winds and hurricanes occurring in an area is heavily influenced by regional wind patterns, storm formations and also, climate shifts. The utilization of wind speed data statistical modeling, combined with climate repercussions, provides a good estimation of extreme wind events' likelihood.

The probability of lightning is calculated based on regional existing or newly acquired information, regarding thunderstorm frequency, ground flash density, and local atmospheric conditions. These crucial factors often obtain values using meteorological data from various sources and also lightning detection networks.

The hazard of ice accretion on turbine blades is noticed to happen mostly in certain geographical locations closer to the poles and under specific meteorological conditions, such as sub-zero temperatures and high humidity, occurring simultaneously. A likelihood assessment of ice accumulation, besides regional information, depends heavily on historical temperature measurements and precipitation data, especially during winter months. The probability of seismic events is generally derived from geological surveys and seismic hazard maps, which can indicate fault lines and also, a regional history of earthquake repeatability.

For the estimation of flood likelihood, hydrological modeling can be implemented, which takes into account various precipitation patterns, water table levels and proximity to rivers or coastal areas. Climate change effects, responsible for increased rainfall and water level rise are also taken into consideration.

5.1.2. Risk Severity Assessment

Risk severity is defined as the estimation of the potential impact a hazard may have on a wind farm's infrastructure, operational performance, and safety. Severity is evaluated based on factors such as the intensity of the hazard, the vulnerability of components and the consequences of failure. The dimension of severity scales from very low to catastrophic. This section briefly outlines the potential severity effects associated with each hazard: Severe wind events can cause structural damage to turbine towers, blade deformation, or complete system failure. The severity depends on wind speed intensity, exposure duration and the design specifications of the turbines. Hurricanes may also disrupt grid connections and maintenance operations.

Lightning strikes pose a high risk of electrical damage to turbines, including damage to blades, control systems, and transformers. The severity is amplified if grounding systems or lightning protection measures are inadequate.

Ice accumulation on blades reduces aerodynamic efficiency, leading to power output losses and increased mechanical stress. Detached ice fragments can also pose safety hazards to nearby infrastructure and personnel. Severity escalates with prolonged ice events or inadequate de-icing systems.

Earthquakes can result in foundation instability, structural misalignment, or damage to grid interconnections. The severity is determined by the magnitude and proximity of seismic events, as well as the adequacy of structural reinforcements.

Flooding can damage electrical systems, foundations, and access roads. Wind farms located on lowlands or along a coastline are particularly vulnerable to inundation. Severity depends on water depth, flow velocity, and the duration of the flooding event.

Likelihood \ Impact	Negligible	Minor	Moderate	Significant	Severe
Very Likely	Low Med	Medium	Med Hi	High	High
Likely	Low	Low Med	Medium	Med Hi	High
Possible	Low	Low Med	Medium	Med Hi	Med Hi
Unlikely	Low	Low Med	Low Med	Medium	Med Hi
Very Unlikely	Low	Low	Low Med	Medium	Medium

Figure 2: Example of a risk matrix (heat map) [20].

5.1.3. Integration of Likelihood and Severity

In assessing overall risk, likelihood and severity (or impact) are integrated into a risk matrix, as the figure below suggests. For example, a high-likelihood, low-severity event might require precautionary measures, while a low-likelihood, high-severity event (an earthquake for instance), could demand extensive prevention and mitigation efforts. Utilizing this integrated approach enables wind farm operators to prioritize foreseeable risks and allocate project resources effectively.

The simultaneous evaluation of both likelihood and severity factors, offers the opportunity for onshore wind farm operators to implement targeted strategies, in order to address high-risk scenarios [19]. For example, installation sites prone to lightning may require enhanced grounding systems and special blade coating, while high wind regions could benefit from reinforced turbine designs and cutting-edge shutdown technologies. This fundamental dual-factor approach to risk assessment is deemed essential to protect wind farms against devastating effects induced by extreme weather and environmental phenomena.

5.2. Comprehensive Risk Assessment Techniques for Onshore Wind Farms: Methods and Applications

One of the key priorities for the smooth operation of wind farms is the assessment of risks related to personnel safety, environmental protection and operational efficiency. Specifically, by minimizing the likelihood of workplace accidents, a safe environment is created for workers in wind farms. Additionally, through the assessment and evaluation of both risks and their consequences, the impact on biodiversity and local ecosystems in the broader operational area of a wind farm can be reduced [21]. Furthermore, the timely identification of technical and economic risks facilitates the optimization of operational and economic efficiency of wind farms [22]. In the literature, there are various methodologies for approaching risk assessment related to onshore wind farms. The most common are the following:

Risk Identification Workshops involve stakeholders from all categories associated with wind farms, such as wind turbine and wind farm manufacturers and designers, energy managers, consumers and representatives of local communities near wind farms, among others. The purpose of these workshops is the proactive identification of potential risks that wind farms may face and the adoption of preventive mitigation measures. However, the conclusions of these workshops are often subjective, for this reason, it may be necessary to quantify risks using Failure Mode and Effects Analysis (FMEA), FMEA is a proposed methodology that focuses on potential failures of wind turbine components and assesses their impact on the overall performance of the energy system. This methodology assigns a Risk Priority Number (RPN) to each potential failure by considering the following parameters: severity, likelihood of occurrence and detectability. This facilitates wind farm operators in focusing on the most critical risks. FMEA is primarily applied during the operational phase of wind farms [23].

Simulation-Based Risk Assessment utilizes Monte Carlo simulations and the Critical Path Method to quantify risks directly associated with schedules of the projects to be implemented, their costs and the allocation of available resources. This methodology is particularly suitable during the construction phase of wind farms, when there is uncertainty regarding their construction times and costs [24].

Fuzzy-Based Risk Assessment is the most suitable methodology for risk assessment under conditions of uncertainty or incomplete data regarding the construction and operation of wind farms. This methodology takes into consideration certain risk parameters that are difficult to estimate in advance (fuzzy parameters), such as the acceptance of wind farm construction and operation by local communities, potential changes in the regulatory framework for their construction and operation, etc. The most accurate possible determination of these parameters is a critical guarantee for the successful implementation of this methodology and for making informed decisions concerning the construction and the operation of wind farms [25].

Geographic Information Systems (GIS) Analysis utilizes available spatial data to evaluate the suitability of areas intended for wind farm development and the environmental risks present in those areas. By mapping critical parameters such as the topographical and meteorological characteristics of the reference area, proximity to other transportation infrastructures (e.g., roads, ports, airports), and potential environmental constraints (such as proximity to environmentally protected areas), this methodology establishes a framework that supports decision-making, particularly during the planning phase of each wind farm [26].

Multi-Criteria Decision Analysis (MCDA), as a proposed methodology, considers a range of parameters (economic, environmental, technical, and social) related to positioning and operational aspects of wind farms. Specific weight values are assigned to these parameters, and various combinational scenarios are examined to enable stakeholders to arrive at the optimal decision-making design throughout the entire lifecycle of a wind farm (from construction to the end of its operation) [27].

All the aforementioned risk assessment methods can also be used in combination at various stages of the construction and operation of onshore wind farms, enhancing the accuracy and reliability of decision-making.

6. Innovative Mitigation Strategies for Environmental and Operational Risks in Wind Farms

Mitigation strategies are essential for onshore wind farms and critical infrastructures in general, to address the vulnerabilities created by extreme natural hazards, such as seismic activity, hurricanes, and lightning. These hazards are mainly analyzed through the use of mathematical models, while supported by historical data, in order to estimate event frequency and intensity (impact). Structural failures in wind turbines, caused particularly after lateral loads are applied from various natural forces, are often discovered from tower or foundation failures, since these components are proved to show greater vulnerability than blades, as the latter are designed for higher wind forces [15]. Considering the critical role of wind farms in renewable energy production and their constant exposure to extreme environmental events, it seems that the implementation of mitigation measures and contingencies are absolutely critical to enhance structural resilience, ensure continuous operations and minimize produced energy disruptions.

- Flooding or heavy rainfall: To address these weather phenomena, either elevated platforms or modern drainage systems can be used. Elevated platforms provide protection for the electrical

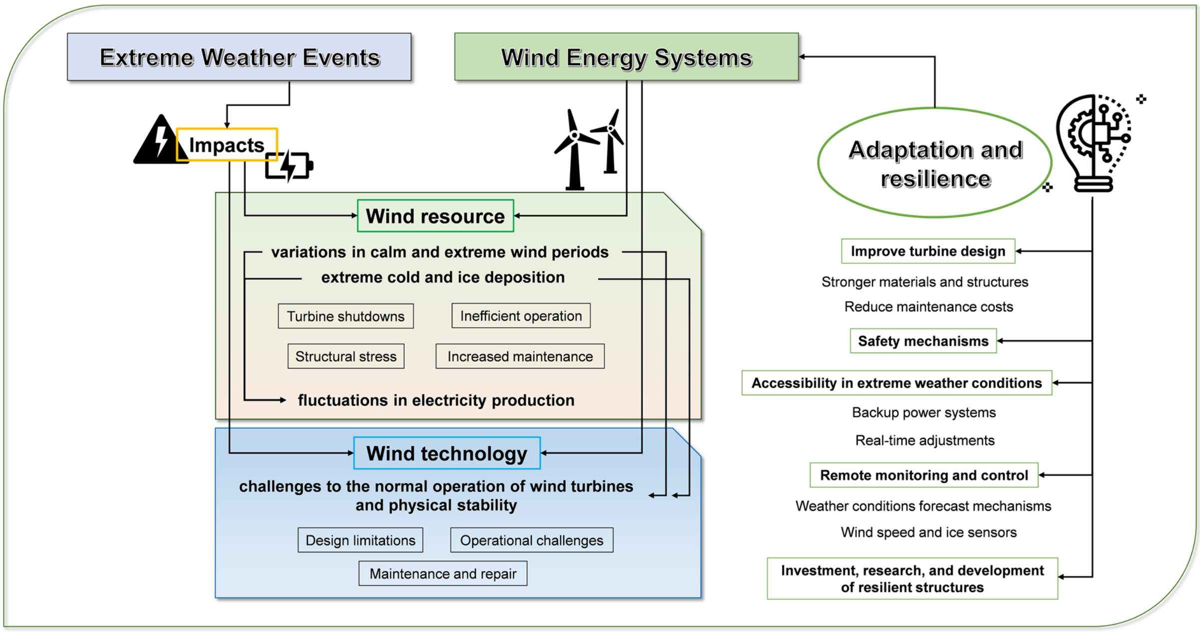

Figure 3: Extreme weather events, impacts and resilience solutions on wind energy systems [28].

and mechanical components of wind turbines from water, while drainage systems ensure the rapid removal of water, preventing the formation of standing water that could affect the stability of the foundations [28].

- Lightning: To mitigate the effects of lightning, grounding systems are used to effectively disperse electrical discharges. This enhances the protection of wind farms by reducing transient overvoltages.
- Ice accumulation: De-icing methodologies are incorporated into the design of wind turbines. Specifically, heating elements can be applied to the blade coatings of wind turbines, such as $MoS2/ZnO$ coatings, which have proven effective under cold conditions [29].
- Strong winds and hurricanes: Structural reinforcement measures, such as the aerodynamic design of wind turbine blades and dynamic braking systems, are implemented. These systems ensure the safe shutdown or limitation of the rotational speed of wind turbines [16].
- Earthquakes: The foundations of wind turbines are constructed using seismic-resistant materials and shock-absorbing systems. Additionally, soil reinforcement techniques, such as the use of micropiles, are employed to reduce the potential risks of ground settlement during seismic events [30].

In general, the utilization of prediction and protection measures through sensors, certain backup options in emergency turbine shutdowns, as well as the research and development of highly resistant components to withstand adverse natural phenomena tailored to each geographical location requirements are meant to reduce costs in installation and maintenance. This will ultimately result in minimizing energy production costs and bolster the security and lifespan of the installation, as presented in the figure above [28].

7. Conclusions

Considering the rapid expansion of wind energy as a significant contributor to green energy production worldwide, indicates the need for development of more efficient and sustainable systems to further improve operational stability and financial gain. Wind turbines are frequently up against numerous challenges from environmental hazards, as well as mechanical failures, amplified by devastating weather consequences. These vulnerabilities can result in substantial interruptions to energy generation, leading to major economic losses. In order to address these raised issues, it is essential to identify and evaluate the risks involved, pushing towards the creation of more resilient wind energy systems. This requires a comprehensive approach, including meticulous site evaluation, bespoke design methodologies, and risk analysis with strategic planning and contingency solutions, to ensure long-term efficiency and economic viability for wind farm installations [15].

As mentioned above, the increasing reliance on renewable energy sources, particularly onshore wind farms, suggests the necessity to provide methods and strategies to safeguard these critical infrastructures against environmental hazards. This paper has outlined a comprehensive risk assessment framework tailored to the extreme challenges posed by weather and other environmental phenomena. By systematically evaluating extreme natural events such as lightning strikes, ice formation, seismic activity, floods, high winds, and hurricanes, the approach presented provides a mechanism to identify vulnerabilities and assess their potential impacts on operational performance and overall system reliability.

A centerpiece of this framework is the integration of risk assessment fundamental parameters, such as likelihood and severity, in order to offer a thorough demonstration of how specific hazards could compromise the functionality of a wind farm. Additionally, the implementation of mitigation strategies and safety protocols tailored to each extreme event, combined with predictive maintenance approaches, are set to enhance the resilience of such critical energy systems. This ensures not only the unhindered production of green energy, but also the continuous contribution of wind farms towards global decarbonization.

Finally, this research stresses the importance of risk-informed strategies and specifically, the implementation of specialized risk assessment techniques in enhancing and protecting renewable energy critical infrastructures. Extreme natural events with devastating effects are noticed to appear ever more frequently, thus requiring a shift towards resilience planning and management. Future work applications will -most definitely- be able to refine and implement the proposed framework, with an emphasis on validating its effectiveness in operational level and further integrating digital technologies, in order to boost resilience, reliability, and profitability throughout the whole lifecycle of onshore wind farms.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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