Gonçalves *et al. Sustainable Energy Research (2024) 11:4*
https://doi.org/10.1186/s40807-023-00097-6

Sustainable Energy Research

REVIEW **Open Access**

Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures

Ana C. R. Gonçalves[1,2*], Xurxo Costoya[1], Raquel Nieto[1] and Margarida L. R. Liberato[2,3*]

Abstract
Energy systems (ES) are seriously affected by climate variability since energy demand and supply are dependent on atmospheric conditions at several time scales and by the impact of severe extreme weather events (EWEs). EWEs affect ES and can cause partial or total blackouts due to energy supply disruptions. These events significantly impact essential infrastructures and are considered one of the main causes of wide-area electrical disturbances worldwide. A comprehensive review is carried out based on 210 published studies using searches from Scopus and Google Scholar databases, to assess the impacts of EWEs—such as extreme storms, wind, and lightning events, heat, or cold waves, and freezing—on ES and their associated infrastructures—production, transmission, and distribution—worldwide, with a particular focus on wind energy systems (WES). Strategies and measures are critically reviewed and synthesized to minimize and mitigate the impact of EWEs, protect, and adapt the systems to maintain regular operations even when these events occur. Finally, physical modifications to systems and the incorporation of new technological solutions such as energy storage systems (ESS), distributed energy systems (DES), and microgrids, can enhance the network resilience and mitigate the EWEs effects.

Highlights

- Extreme weather events (EWEs) have a major impact on energy systems (ES).
- Wind energy systems are particularly affected by EWEs.
- Measures and new solutions are needed to minimize the impacts of EWEs on the ES.
- ES need to be adapted to maintain normal operation during the occurrence of EWEs.
- EWEs are now a great challenge to researchers and engineers.

Keywords Energy sector, Renewable energy, Wind energy, Severe cyclones, Windstorms, Resilience measures

*Correspondence:
Ana C. R. Gonçalves
ana.redondo.goncalves@uvigo.es
Margarida L. R. Liberato
mlr@utad.pt
Full list of author information is available at the end of the article

Introduction

Energy systems (ES)—that is, infrastructures for electricity production, transmission, and distribution—are exposed to natural disasters and extreme weather events (EWEs), such as tropical and extratropical cyclones, windstorms, floods, landslides, lightning, and earthquakes (Waseem & Manshadi, 2020; Hewitt, 1983; Peduzzi, 2019). Heatwaves, droughts, and wildfires may also cause damage to ES and all associated infrastructures. These events foremost affect the physical components of the systems (Bompard et al., 2013; Brás et al., 2023; Jasiunas et al., 2021) and lead to heavy socioeconomic impacts on vulnerable populations (Gonçalves et al., 2023; Liberato, 2014; Otto et al., 2020; Stojanovic et al., 2021; Zscheischler et al., 2020). ES, which include the design and operation of energy infrastructures such as production and distribution systems, are called energy-critical infrastructures. These infrastructures are crucial for vital societal functions, including the health, safety, security, economic and social well-being of people (Kyriakides & Polycarpou, 2015; Mikellidou et al., 2018; Nik et al., 2021). Therefore, the energy supply sector includes all energy extraction, conversion, storage, transmission, and distribution processes (Bruckner et al., 2014; Martinez et al., 2019; Qazi, 2017).

Extreme weather events (EWEs) are rare occurrences that deviate from normal weather patterns in frequency and intensity. These events typically fall within or exceed the statistical rarity thresholds, ranking at or beyond the 10th or 90th percentile on a probability density function derived from observed data. When an extended period of extreme weather lasts, spanning a whole season, it might be categorized as an extreme climate event, particularly if it results in notably high or low average or total (IPCC, 2022a; McPhillips et al., 2018). Thus, certain climate extremes, such as droughts or floods, may result from multiple non-extreme weather or climate events accumulating over time, leading to extreme conditions (Leonard et al., 2014). Additionally, weather or climate events, even if not considered extreme based on statistical measures, can cause severe conditions or consequences. This could happen by surpassing a crucial limit within a societal, ecological, or physical system or by co-occurring with other events (IPCC, 2018). Furthermore, there is an understanding that climate change results in an increased occurrence and intensity of EWEs, which include extreme precipitation events, strong winds, and snowstorms, as well as intense heatwaves and droughts. These events cause extensive adverse effects on ecosystems, populations, and infrastructure, leading to consequential damage that goes beyond that attributed to natural climate variability (IPCC, 2018, 2022b). Consequently, an increase in EWEs can have a direct impact on energy demand in key end-use sectors (Damm et al., 2017; IEA, 2022; Panteli & Macarella, 2015) and affect the energy systems (ES) in the most vulnerable areas (Mikellidou et al., 2018; Otto et al., 2020; Panteli & Macarella, 2015). ES are severely affected by EWEs, which are considered a serious risk for the energy sector and its facilities—implications for the reliability and performance, and the resilience of energy supply systems (Brás et al., 2023; Gonçalves et al., 2023, and references therein, Panteli & Macarella, 2015; Holtinger et al., 2019; Perera et al., 2020) but also in the sectors of production, transmission, distribution infrastructures (Waseem & Manshadi, 2020), and other economic sectors that depend on the energy supply. Moreover, EWEs can also have implications for the reliability and performance of renewable, such as wind energy systems (WES), and non-renewable energy systems (Cronin et al., 2018; Perera et al., 2020; Schaeffer et al., 2012).

Acknowledging the growing occurrence and impact of EWEs in the energy sector, the present paper aims to assess and systematize the impacts caused by extremes of the different atmospheric parameters on energy systems (such as thermal and solar power plants, hydropower plants, power grids), the impacts of these events on energy production systems, on power transmission and distribution systems worldwide. Additionally, this study focuses particularly on wind energy systems through a comprehensive review of the effect of EWE on wind resources and wind technology. Furthermore, a review of measures and recommendations for the mitigation of impacts on energy storage systems, distributed energy systems, and smart grids and microgrids is presented. Adaptation measures and new strategies to mitigate the impacts of extreme events and to maintain the normal operation of the systems and associated infrastructures are described and finally, conclusions are drawn. Thus, the main novelty of this study, in comparison with existing literature, is the fact that it presents a comprehensive review of the impacts of extreme events on different energy systems worldwide, with a special focus on wind energy systems, together with the identification and analysis of measures and solutions that allow to minimize those impacts and increase the resilience of systems to these events.

This study proceeds in the following order: (i) to assess the real impact of the EWEs on ES worldwide; (ii) to focus particularly on the WES; (iii) to identify and assess the need to adapt the WES systems to maintain their normal operation and the stability of the network, even during the occurrence of EWEs; and (iv) to critically review and suggest measures and solutions to minimize the impacts of EWEs on the systems. Therefore, the article's structure is as follows: the background is presented in section two;

section three describes the data and methods used to perform this review. Section four identifies and evaluates EWEs and their impacts on energy systems. In section five the impacts on WES are specifically assessed. Section six analyzes and synthetizes the strategies, measures, and solutions. The results and conclusions are presented in the final section.

Background

Energy systems are heavily impacted by climate variability since the energy availability and supply are dependent on atmospheric conditions (Gonçalves et al., 2021; Jerez & Trigo, 2013; Liberato, 2014; Staffell & Pfenninger, 2018; Trigo et al., 2004) and/or climate change impacts (Damm et al., 2017; Devis et al., 2018; Jasiunas et al., 2021; Lledo et al., 2019; Otto et al., 2020; Santos et al., 2015; Tobin et al., 2016). ES are susceptible to diverse types of events, including EWEs, natural hazards, and climate change as summarized in Fig. 1.

The concept of vulnerability is used to measure the challenges a system faces in supporting its function during and after an unwanted event (Doorman et al., 2006; Sperstad et al., 2020). Power system vulnerability consists of two aspects: susceptibility to threats and the system's ability to cope with such events. It involves the power system operator's technical, human, and organizational factors (Sperstad et al., 2020). Several types of vulnerability, such as in power generation infrastructure, transmission, distribution, and supply chains, are studied by Schweikert and Deinert (2021).

Abedi et al. (2019) further define the concept of vulnerability by dividing it into physical vulnerability, systemic vulnerability, systemic and physical, and measurement-based assessments. These authors discussed vulnerability analysis methods, differentiating between analytical and simulated approaches. Analytical methods provide accurate solutions for simplified problems and are efficient for evaluating similar systems. Simulations, like Monte Carlo methods, generate accurate solutions to more complex, real-world problems, particularly when deriving equations becomes challenging. While analytical methods rely on mathematical solutions for simplified models, simulations replicate actual system behaviors, becoming the preferred choice as systems become more complex (Abedi et al., 2019, and references therein). Moreover, the authors detailed various vulnerability analysis approaches, dividing them into two primary categories: analytical methods and Monte Carlo simulations. The analytical methods include complex network methods (pure complex network method and extended complex networks methods), flow-based methods (deterministic flow-based approach and probabilistic flow-based approach), logical methods (game theory and hierarchical method), functional methods (agent-based

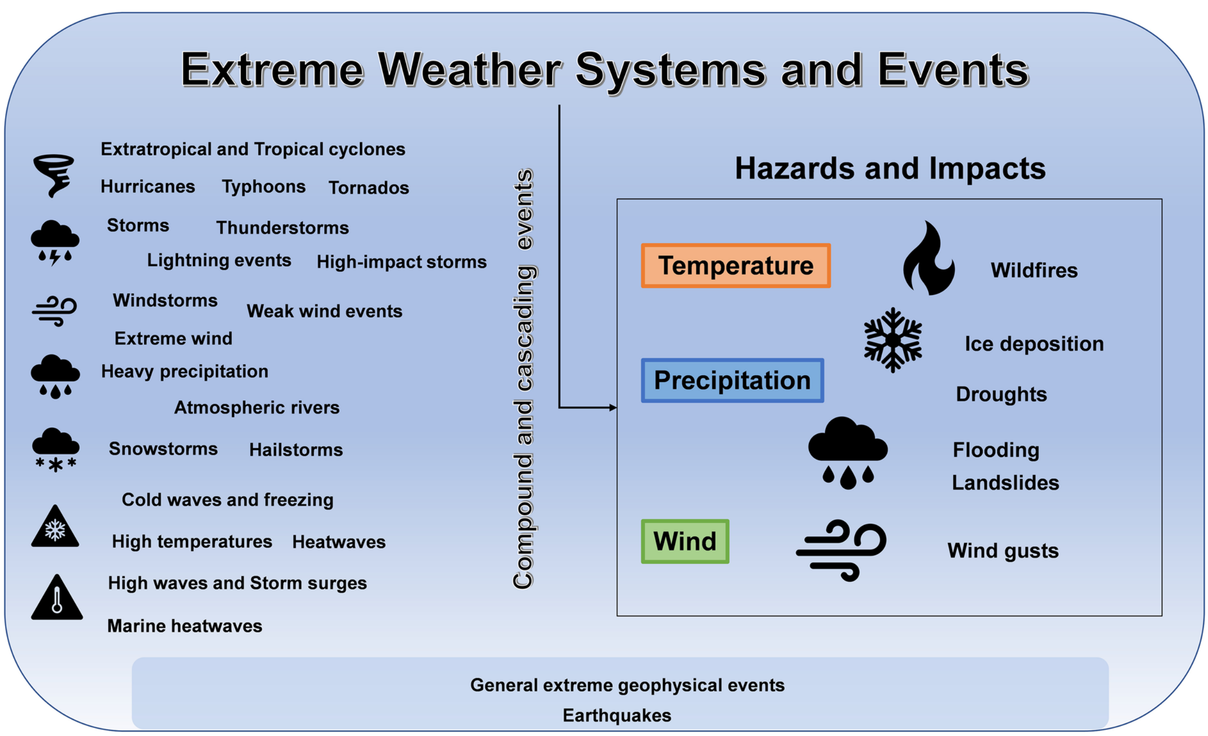

Fig. 1 Extreme weather systems and events that impact energy systems

modeling, dynamic modeling, and multi-objective optimization) (Abedi et al., 2019, and references therein).

The assessment of electrical grid component vulnerability under extreme weather and climate conditions is also considered in the work of Dumas et al. (2019). The authors investigated the impact of extreme weather and climate conditions on different electrical grid components. They identify hazards like temperature changes, water availability issues, storms, flooding, wind pattern variations, and other extreme events such as wildfires. These hazards are assessed within the context of electricity generation, transmission, distribution, and demand. The study employs engineering approaches, including fragility curves, damage functions, and dose–response functions, to evaluate the vulnerability of grid components to environmental threats. Fragility curves and damage functions predict the probability of system or component failure in response to a single extreme event, while dose–response functions quantify how a component reacts to climate stress exposure. These tools help energy planners quantify the climate vulnerabilities of their assets, enabling better risk assessment and mitigation.

In this sense, the rise of power outages caused by EWEs has led to the study of system and grid resilience (Brás et al., 2023; Chen et al., 2022; Dumas et al., 2019; Gonçalves et al., 2023). Resilience refers to a network's ability to rapidly recover from disturbances (Holling, 1973). Energy system resilience depends on the occurrence of severe weather incidents and includes the system's capacity to predict, tolerate, restore, and respond to challenges (Gosh & De, 2022; Panteli & Mancarella, 2015). Various organizations and researchers define resilience with characteristics such as resourcefulness, robustness, adaptability, and rapid recovery, and other features associated with resilience include redundancy, capacity, flexibility, and tolerance (Mahzarnia et al., 2020 and references therein). Standardized definitions, metrics, and evaluation methods for resilience are being developed, and research is ongoing to address gaps and challenges (Bhusal et al., 2020; Bie et al., 2015, 2017). Grid resilience involves anticipating, absorbing, restoring, and adapting to impacts caused by EWEs, to return the grid to normal operation swiftly (Hossain et al., 2021; Jufri et al., 2019). Therefore, developing strategies to enhance ES and grid resilience is crucial for power system planning and operation, considering the significant impact of EWEs on power supply reliability and socioeconomic factors (Bhusal et al., 2020; Jufri et al., 2019; Panteli & Macarella, 2015; Panteli et al., 2017).

Although diverse types of systems are examined, the main emphasis is on renewable energy systems, specifically on wind energy systems (WES), which are particularly vulnerable to the impacts of climate change and the increasing frequency of EWEs (Fernández-Alvarez et al., 2023; IPCC, 2022b; Nogueira et al., 2019; Tobin et al., 2018). Wind resources are extremely sensitive and dependent on weather conditions (Davy et al., 2018; Gonçalves et al., 2021; Ravestein et al., 2018) since wind energy depends on the cube of the wind speed. The changes in the intensity and frequency of extratropical cyclones (Catto et al., 2019; Karremann et al., 2016), for example, can result in varying frequencies of calm or strong wind periods, leading to fluctuations in electricity production (Costoya et al., 2022; Gonçalves et al., 2021; Moemken et al., 2018). Moreover, wind energy is currently experiencing the highest growth rate among renewable energy sources and is projected to have the largest installed capacity by 2030 (IEA, 2022; Wind-Europe, 2023).

Thus, EWEs pose significant challenges to the secure and reliable operation of energy systems (thermoelectric production technologies) (Panteli & Mancarella, 2015; Zhou et al., 2023), especially renewable energy systems (RES), such as hydroelectricity, photovoltaic, and wind energy systems (Sims et al., 2011; Panteli & Mancarella, 2015; Zhang et al., 2019; Zhou et al., 2023).

In this sense, measures and solutions are needed to adapt these systems and to minimize their impacts which are analyzed in the following sections.

Data and methods

A comprehensive and objective analysis of the current knowledge on the research question "The impacts of extreme weather events on energy systems" is carried out in this article using an interdisciplinary approach. This type of review focuses on contextualization and interpretation, presenting a broad overview and critical analysis of the literature within a subject area, with a more qualitative synthesis of information (Cronin et al., 2008; Grant & Booth, 2009; Green et al., 2006; Machi & McEvoy, 2016; Onwuegbuzie & Frels, 2016). This comprehensive literature review follows the next steps:

- Definition of the research question/objective and selection of the topic: define and narrow the research topic or question; clarify the scope and objectives of the review to guide the literature search.
- Literature search/research strategy and information collection: develop a comprehensive search strategy using relevant keywords and terms; explore multiple reliable sources (databases, journals, books) to gather literature.
- Selection criteria: establish criteria for including or excluding sources based on relevance, publication date, and research quality.

- Screening and selection: review and select collected literature to identify relevant articles, studies, and sources; delete irrelevant material that does not contribute to the review's focus.
- Data extraction: extract key information from selected literature, including key ideas, methodologies, and key findings.
- Synthesis and analysis: analyze and synthesize extracted information to identify patterns, themes, or gaps in the literature.
- Organization and structuring: develop a logical structure for presenting the review, organizing information into themes or categories, or chronologically; synthesize findings to develop a coherent narrative that addresses the research question.
- Critical evaluation: assess the quality, strengths, and limitations of the reviewed literature; discuss conflicting findings, gaps in research, biases, or areas in need of further exploration.
- Writing the review: structure the narrative review by introducing the topic, logically presenting synthesized information, and offering interpretations derived from the literature.
- Conclusion and recommendations: summarize main findings and conclusions drawn from the review; discuss implications for practice, policy, or future research based on the insights gained.
- Revision and finalization: review and revise the review for clarity, coherence, and accuracy before finalizing; make sure arguments are supported by evidence from the literature and the narrative flows logically.

These steps provide a structured method to carry out a narrative literature review, offering a comprehensive presentation and critical analysis of the information collection currently available on the topic in question (Cronin et al., 2008; Green et al., 2006; Pautasso, 2019).

For this review, the information and literature consulted are publications searched from scientific sources available on the internet of scholarly literature—databases Scopus (Scopus, 2022) and Google Scholar (Google Scholar, 2022) and based on research topics and keywords considered representative of the topic under study, and that are summarized in Table 1.

The publications data include multiple reliable sources, such as scientific articles, reports, books, and doctoral theses available and published worldwide in the English language. Selection criteria were established for inclusion or exclusion of sources based on relevance and research quality. With the results obtained in the search screening and selection were made through an analysis to understand whether the collected literature is applicable. That is, deciding whether it fits with the topics under study, by reading the main objectives and conclusions of each document and excluding irrelevant material that does not contribute to the focus of the review. Then, only the documents of interest, consistent with the object of the study, were downloaded. As a result, 210 relevant scientific documents published between 1973 and 2023 were selected and used to review the scientific literature on EWEs and their effects on ES, especially on WES.

From these documents, the main objectives, methods, and conclusions were extracted, which were subsequently synthesized and analyzed to identify a pattern in

Table 1 Topics and keywords of the research

Topics	Research keywords
Extreme weather events (EWEs)	Weather variables EWEs Impact of EWEs on ES
Energy systems (ES)	Vulnerabilities of ES The resilience of ES Renewable and non-renewable ES Energy production and distribution systems Impacts of EWEs on electricity production technologies Impacts of EWEs on energy transmission and distribution infrastructures
Wind energy systems (WES)	Impacts of EWEs on WES Solutions to minimize the impacts of EWEs on WES
Measures and solutions	Mitigation of EWEs impacts on ES Energy storage systems (ESS) Distributed energy systems (DES) Smart grids and microgrids

the type of information collected. That said, the information was organized considering the topics under study, and a coherent narrative was developed. Concerning the impacts of EWEs on electricity production systems, these can be divided according to the type of events that gave rise to them. The studies were analyzed on extreme wind and lightning events, storms, hurricanes, heat waves, and drought events, weak wind events, cold waves and freezing, high temperatures resulting from climate change, floods, compound flood events, and general extreme events. The variation, frequency, and intensification of this type of event significantly affect electricity production. At this point, studies on the most varied impacts on ES were analyzed, such as thermoelectric production technologies, nuclear energy, hydroelectricity, and photovoltaic and wind energy systems. In addition, energy transmission and distribution systems that constitute the energy production system itself are analyzed, as well as energy storage systems, distributed energy systems, and smart grids and microgrids.

During the process of writing the review, it was structured, and the information was presented logically, as well as the results and conclusions of this review. Furthermore, limitations and gaps in the reviewed literature were also identified, and proposals for future work were also identified. Finally, the narrative was revised, to present a clear and precise text, with arguments supported by evidence from the literature and figures were conceived to better systematize the most relevant findings.

Extreme weather events' impacts on energy systems

In this section, the impacts of different atmospheric parameters such as temperature, precipitation, and wind are described to understand their impacts on the energy systems (ES). Then, diverse impacts of extreme weather events (EWEs) on energy production, transmission, and distribution systems are presented in the following points, using a critical analysis of several case studies.

Importance of different atmospheric parameters on energy systems

The atmospheric temperature, precipitation, and wind are extremely important in the power production, the functioning of electricity production systems and their associated infrastructures, since the systems are dependent on their values for efficient functioning and on the resource availability (water, wind, solar radiation), and power demand, as mentioned in the following paragraphs.

Temperature—high temperatures impact the effectiveness of thermal and solar power plants, influencing their cooling needs (Rubbelke & Vogele, 2011; Schaeffer et al., 2012), as well as affecting biomass production, including factors like the duration of the growing season, water availability, and crop diseases (DOE US, 2013; Panteli & Macarella, 2015). Moreover, decreased temperatures can result in ice forming on equipment, such as wind turbines, or on the sea surface, significantly impacting offshore activities (Pryor & Barthelmie, 2010). Conversely, elevated temperatures in permafrost regions can lead to instability in the foundations of sizable structures. Additionally, rising temperatures can decrease the efficiency of power transmission capacity, as well as the grounding efficiency of electricity transmission and distribution lines (DOE US, 2013; Panteli & Macarella, 2015). Heating and cooling needs are greatly influenced by temperature fluctuations, affecting not only overall energy use but also seasonal consumption patterns and the preferred primary fuels for each (e.g., electricity is used primarily for cooling, while heating mainly depends on other energy sources) (Dowling, 2013; Jasiunas et al., 2021). Thus, thermal, and hydroelectric power generation are particularly vulnerable to risks arising from heatwaves and droughts, while transmission, distribution systems, and other renewable technologies are more susceptible to risks associated with cold spells (such as heavy snowfall, ice storms), windstorms, floods, and wildfires (Gonçalves et al., 2023; Panteli & Macarella, 2015; Perera et al., 2020; Yalew et al., 2020).

Precipitation—the precipitated water is used for generating power in hydroelectric facilities, helping in the cooling processes of thermoelectric plants, and cleaning solar panels. However, this dependence on precipitation for energy production undergoes substantial yearly fluctuations, with drought periods posing a significant energy security risk for nations heavily dependent on hydroelectric power (Liberato et al., 2021; Trigo et al., 2004). Thermal energy generation depends significantly on water for cooling purposes (for instance, 43% of the European Union's water consumption is attributed to the cooling needs of energy production). (Jasiunas et al., 2021; Rubbelke & Vogele, 2011). Water is essential for the maintenance and cleaning of solar panels, presenting a significant challenge in arid regions. Furthermore, the presence of clouds impacts the amount of solar radiation, consequently influencing the overall production of solar energy (Dowling, 2013). In addition, most of the capacity for storing electrical energy (more than 99%) relies on pumped hydro storage, which depends on the availability of water in accessible reservoirs. Substantial energy amounts are consumed in the processes of transporting and treating water. With a growing trend towards desalination in energy system applications, water demand could increase if naturally occurring water sources are substituted by transported water (Jasiunas et al., 2021, and references therein).

Wind—severe winds pose one of the most significant threats to electrical grid systems (Rubbelke & Vogele, 2011). The predicted increase in wind speed attributed to climate change is a pressing issue, especially considering the projected expansion of wind energy (Davy et al., 2018; Jasiunas et al., 2021; Santos et al., 2015). These changes have the potential to significantly impact economic aspects, site viability, plant design, operational approaches, and overall system stability (Pryor & Barthelmie, 2010). However, when extreme variations in the availability of these resources occur, resulting from the occurrence of EWEs, energy systems are severely affected (e.g., Gonçalves et al., 2021, 2023). Thus, the energy sector and the respective ES are extremely impacted by EWEs.

The occurrence of compound events, such as wind and snow and/or freezing or high temperatures, heatwaves, and droughts, may constitute a multiplying disruptive factor, as described in the following sections.

Impacts on energy production systems

Overall, EWEs have a significant impact on both electricity demand and generation. These events can manifest as droughts, leading to reduced hydropower output in countries like Brazil and increased reliance on liquefied natural gas imports. Heatwaves can also affect electricity generation by reducing the availability of nuclear power, as observed in France and other regions. Additionally, lower-than-average wind speeds can affect wind generation in Europe. Furthermore, events like Hurricane Ida can disrupt the offshore production of electricity in the United States (Beven et al., 2022; U.S. Energy Information Administration (EIA), 2021; IEA, 2022).

Concerning EWEs affecting energy production systems (renewable and non-renewable), several studies address the topic, including those mentioned in the following paragraphs.

Rocchetta et al. (2015) introduce a multi-objective distributed energy systems (DES) that accounts for extreme wind and lightning events. Their assessment of associated risks considers both regular environmental conditions and extreme scenarios. Environmental variations significantly affect the operation and performance of DES, and security and reliability are key concerns for their future. Panteli and Macarella (2015) investigate the impact of weather and climate change on the dependability and operation of energy system components. They propose a comprehensive modeling framework aimed at understanding and simulating the effects of severe weather on energy systems, offering potential strategies for prevention or mitigation in the future.

EWEs pose challenges to the reliability of power systems, and disruptions in power generation highlight the vulnerability of the systems (Abdin et al., 2019). The recent study of Brás et al. (2023) analyzed the impact of EWEs on European power technologies, emphasizing the substantial increase in hydroelectric energy capacities during floods and storms, contrasted with a decrease in fossil fuel-based technologies. The study reveals that although floods and storms positively influence hydroelectric energy, droughts, and heat waves neutralize these gains. Additionally, the results highlight the varying impact of wind and solar photovoltaic technologies, underlining the need for strategic planning to manage these risks as Europe strives to amplify renewable energy use while maintaining a reliable power supply.

In addition, the study of Van der Wiel et al. (2019) explores meteorological conditions associated with increased risks related to European energy security in a renewable energy-dependent energy system that relies on wind and solar sources. They conducted large ensemble experiments using data from two global climate models (EC-Earth and HadGEM2-ES) to calculate 3 sets of 2000-year daily records of energy production and demand. The weather data reveal extreme events of low renewable energy production and high energy shortfalls, primarily caused by high-pressure systems and atmospheric blocking. These events occur in winter and summer, and redesigning renewable energy distribution or importing energy cannot prevent these high-impact events and it is not enough to mitigate them. Climate change impacts are smaller compared to the interannual variability of these events, emphasizing the need to design future power systems considering their unpredictability.

Storms (Liberato, 2014; Pinto et al., 2010; Priestley et al., 2018) and particularly hurricanes (Che et al., 2014) contribute significantly to power disruptions in the U.S. electrical sector, primarily due to damage inflicted on transmission systems (Gonçalves et al., 2023; Reinoso et al., 2020; Rezaei et al., 2016; Tomaszewski & Ruszczak, 2013), as discussed on the following section. The study by Gonçalves et al. (2021) assessed the high-impact storms that affected Southwestern Europe in the December months of 2017 to 2019, and it was concluded that these events had a positive effect on wind energy production, with the highest values of energy production occurred on the stormy days.

However, solar photovoltaic (PV) systems can supply power to local loads during transmission system restoration. In this way, the study by Cole et al. (2020) conducted research examining the projected energy production from PV systems and storage during 18 hurricanes that hit landfall in the US between 2004 and 2017. The findings indicated that solar PV generation during hurricanes varied between 18 and 60% of its potential under clear skies, while post-hurricane conditions allowed PV systems to produce between 46 and 100% of their clear-skies potential. When combined with storage systems, PV can provide a minimum level of energy during and after a hurricane, thus improving the resilience of the PV system.

Another question is the floods and the work of Najafi et al. (2021) introduces a network-oriented framework designed to characterize compound flood risks in coastal areas. This integrated framework, focusing on the complex connections between infrastructure systems, offers a means to analyze risk across multiple global regions. It incorporates these interdependencies into a comprehensive assessment tool to model failures and subsequent cascading impacts.

Heatwaves can affect the operation of power grids by increasing peak loads, reducing generation and transmission capacity, and reducing the thermal capacity of transmission lines. This can reduce gas turbine and combine-cycle gas turbine efficiency and cause severe power shortages and large price spikes. Ke et al. (2016) researched the potential effects of heatwaves on the operation of power grids. Their findings underscore the importance of accurately assessing the capacity of thermal power plants concerning ambient temperature. This assessment is crucial to avoid underestimating capacity reduction during periods of heatwaves. Hourly consideration of derating effects during heatwave periods is also crucial. The study of Abdin et al. (2019) proposes a modeling and optimization framework designed for power systems planning. This framework considers operational flexibility and the ability to withstand extreme heatwaves and droughts, intending to increase resilience within the power system. The results show that implementing a resilient planning framework can lead to substantial enhancements in load supply during extreme events. Although this approach involves higher investment and operational costs, the savings derived from reducing load loss during such events completely offset these expenses (Abdin et al., 2019).

Concerning climate change impacts on energy systems, a comprehensive analysis of how climate change directly impacts the production of solar photovoltaic (PV) energy across the electric grids of European regions, considering a future scenario with high-capacity installed of PV was carried out by Jerez et al. (2015). The results suggest that by the end of the century, the change in solar PV output, compared to current estimations, could range from a decrease of 14% to an increase of 2%. The most significant declines are anticipated in Northern countries, and the consistency of power generation over time might even display a slightly positive trend in Southern countries. So, this indicates that while there might be minor reductions in solar energy production in specific parts of Europe, the European PV sector is unlikely to face substantial threats from climate change.

In the same way, the study of Bloomfield et al. (2016) highlights the need to consider the impact of long-term climate variability on power systems, especially as climate change mitigation policies lead to increased weather-dependent renewable energy generation. By analyzing multi-decadal meteorological records and a simplified power system model for Great Britain, the study shows that inter-annual climate variability affects all aspects of the power system, with the most significant impact on baseload generation. In a 2025 wind-power scenario, the inter-annual range of operating hours for baseloads like nuclear power increases fourfold, indicating the importance of long-term planning. This research suggests that renewable integration studies used in policy and system design should adopt a more robust approach to climate data and expand consideration of climate variability, as this issue is likely to be relevant for power systems in regions with strong climate variability, such as Western Europe.

Periods of high temperatures have resulted in cutbacks in generation, raising concerns about the stability of the power supply. As thermal power generation relies heavily on water for cooling purposes, the potential impact of climate change across the European Union was analyzed on 1326 individual thermal power plants and 818 water basins in 2020 and projected conditions for 2030 (Behrens et al., 2017). Despite efforts aligned with policy objectives and a decrease in the withdrawal of water for electricity production, the results indicate an increase in the number of regions experiencing reduced power availability due to water stress, rising from 47 basins in 2014 to 54 basins by 2030. The most at-risk basins are primarily situated in the Mediterranean region, with additional vulnerable areas identified in France, Germany, and Poland. Additionally, there are plans for constructing more plants in these stressed areas (Behrens et al., 2017).

Moreover, high temperatures can result in reduced efficiency in thermoelectric and nuclear power generation. This decrease in efficiency stems from factors such as decreased access to cooling water, reduced biomass production, limited hydroelectric resources, and decreased effectiveness of renewable electricity technologies (Auffhammer & Mansur, 2014; Nik et al., 2021). Additionally, the higher temperatures caused by climate change can reduce the efficiency of PV cells (Feron et al., 2021; Schaeffer et al., 2012).

The study of Perera et al. (2020) suggests that computations relying on standard weather patterns might capture gradual changes. Nonetheless, their findings highlight that accurately measuring the consequences of climate change and adjusting energy system designs accordingly could potentially increase the renewable energy fraction by up to 30%. This adaptation is crucial to ensure robust and reliable operation. So, increasing resilience to extreme weather is crucial for designing electrical systems with intermittent renewable energy sources (RES).

Thus, providing support to increase the strength of ES components such as structures, conductors, and poles, represents a viable approach to minimize the impact of EWEs (Tari et al., 2021). Additionally, assessing the viability of system functionality during extreme events involves implementing adaptation measures and system control (Tari et al., 2021; Zhang et al., 2019), consequently increasing the resilience of the grid (Panteli & Macarella, 2015).

Impacts on power transmission and distribution systems

The transmission lines are a major part of the ES and are greatly affected by EWEs that cause important power transmission grid interruptions—Hurricane Sandy in 2012, and Hurricane Katrina in 2005—have caused critical blackouts and heavy damages (for example, hurricane Sandy left about 7.5 million customers without power across 15 states in the US) (Che et al., 2014). In Europe, extratropical cyclones stand out as major contributors to insured losses, where individual storms possess the potential to generate billions of EUR in damages (Pinto et al., 2010; Priestley et al., 2018). Notable examples of severe windstorms, characterized by extreme wind speeds associated with intense cyclones, include storms Lothar and Martin in December 1999. These storms resulted in losses of US$8 billion and US$3.3 billion, respectively. Storm Kyril in January 2007 also caused insured losses of more than US$6.7 billion (Roberts et al., 2014), with significant impacts on buildings, utility infrastructure, as well as transport, forestry, and agricultural sectors (Pinto et al., 2010). In addition, storm Klaus, in January 2009, with over US$6 billion in total losses reported in Spain and France (Liberato et al., 2011), and storm Xynthia, in February 2010, with 64 reported casualties, and a total economic loss estimated at least US$4.5 billion over the Iberian Peninsula and France (Liberato et al., 2013), were considered the most expensive weather risk event in the world during 2009, and the 2nd insured loss event in 2010, respectively. Windstorm Gong, in January 2013, caused considerable socio-economic damage and huge insured losses in the Iberia Peninsula. The extreme winds caused transportation disruptions, and structural damage to infrastructures due to the uprooting and downfall of thousands of trees. More than 11,000 km of wires within the national power grid were affected, causing power cuts in numerous areas. Approximately 2.6 million people were left without access to electricity and communication services for several days. Insured losses amounted to over 100 million EUR (Liberato, 2014).

Consequently, several studies discuss these issues and expose their research and results.

Extreme winds, ice storms, and wet snow deposition on overhead power lines (OPL) are some of the major causes of structural failures in transmission and distribution lines (Reinoso et al., 2020; Rezaei et al., 2016; Tomaszewski & Ruszczak, 2013). These events have the potential to surpass the mechanical capacity of even recently constructed and well-engineered lines, leading to overloads. While numerous studies qualitatively assess the influence of climate change on various elements of the energy system, quantitative assessments are scarce regarding the effects of climate change and EWEs on the dependability of structures, particularly on power transmission and distribution lines (Matko et al., 2017; McMahan & Gerlak, 2020; Panteli et al., 2017; Rezaei et al., 2016; Tomaszewski & Ruszczak, 2013; Ward, 2013). Gonçalves et al. (2023) present a risk analysis methodology focusing on EWEs' impact on OPL in Portugal. Their study found that extreme winds are the main factor disrupting OPL, accounting for approximately 28 to 40% of the examined events linked to windstorms. In instances of compound events—wind and rain—the probability of damage to the OPL varies from 21 to 30%, while for wind and ice events, it fits between 3 and 5%. Consequently, the development of effective solutions is essential to mitigate these impacts. Guo et al. (2020) present a model that evaluates the probability of transmission line failures during typhoon weather conditions. This model considers both the wind speed and the load of the lines. Their findings reveal that the Monte Carlo simulation and the DC model based on OPA can simulate the fault propagation path and identify the crucial components of the power grid during a typhoon. The work of Waseem and Manshadi (2020) discusses the impact of various natural disasters on the operational planning of the electricity grid. They examine the challenges that arise during such events and explore the strategies to mitigate and ideally prevent any negative effects on the grid's operation. Zimba et al. (2020) described the tropical cyclone Idai which hit on March 14th, 2019, on the power grid across southern Africa. Their findings underscore the significance of reinforcing electric power infrastructure during design and planning phases. In addition, the authors advocate the implementation of multifaceted emergency preparedness protocols within power utilities and emphasize the need for coordinated preparedness efforts with other sectors such as transportation, telecommunications, meteorology, and security. Scherb et al. (2019) propose an efficient procedure to assess component importance and network reliability in wind-exposed power grids. Their method accounts for cascading failures and islanding caused by load redistribution after the first failures caused by windstorms. Applied to the Nordic Grid, the results prove its effectiveness in planning network enhancements to mitigate wind impacts and enhance line abilities to limit cascading failures. In the same way, Caro et al. (2019) propose an advanced methodology to enhance grid resilience during severe events by employing flexibility tools. A real case study in northeast Italy proved the potential of demand response policies to mitigate cascading outages during a severe weather event. This method strategically reduces the cascade effect of numerous outages on a power network when faced with severe weather conditions. It achieves this by making minimal adjustments to market, load, and generation programs, effectively resolving an optimization problem. Gunduz et al. (2017) conducted a comprehensive analysis of Sweden's power system reliability, addressing climate change-related natural disasters. They proposed updating the power policy and investing in underground cables to mitigate the severe impacts of EWEs, such as the Gudrun storm of 2005, which caused significant economic damage. Chen et al. (2022) developed a hybrid simulation approach to model the connection between strong wind and power grid faults. The approach considers line galloping uncertainty and trajectory complexity, using adaptive simulation strategies to simulate cascading fault scenarios during extreme wind conditions. Omogoye et al. (2021) study hurricane impacts on the electric power system, particularly the distribution network. They suggest reviewing resilience enhancement techniques for the distribution network and proposing a statistical model for predicting line outages during hurricanes to improve short-term operational planning.

Another relevant topic is the oil and gas supply which can be disrupted by EWEs leading to production shutdowns, such as hurricanes in the Gulf of Mexico in 2004 and 2005 (Schaeffer et al., 2012). Shao et al. (2017) present an integrated approach to electricity and natural gas planning aimed at enhancing the power grid's resilience against adverse events. They suggest supporting the OPL with underground natural gas pipelines to achieve improved resilience and cost-effectiveness. Additionally, this integrated solution helps mitigate the considerable damage caused by extreme events on interconnected infrastructures. In 2021, the more recent example of supply disruption includes the natural gas shortage of 31 GW of power production capacity due to freezing in Texas (IEA, 2021; Mann et al., 2021; Shrestha et al., 2023).

Therefore, the infrastructures of transmission and distribution such as the OPL, are greatly affected by EWEs, where the main cause of the infrastructure disruption is the extreme wind resulting from extreme storms such as hurricanes, typhoons, tropical and extratropical cyclones, and snowstorms (with ice deposition). On the other hand, fires caused by high temperatures during heat wave events and drought events, combined with those caused by human error, pose a serious risk to energy transmission and distribution infrastructures, such as overhead power lines, leaving studies lacking about these impacts in this work. As mentioned in the different studies analyzed above (e.g., Gonçalves et al., 2023; Liberato, 2014), these events caused destruction and serious damage to the components of the electrical lines, leading to the interruption of electrical supply to populations for several days.

Thus, Fig. 2 highlights the connections between extreme weather events and the impacts caused by weather variables (precipitation, wind, and temperature) on energy systems and electrical infrastructures that jeopardize the resilience of the electrical grid.

From this review, the wind energy sector is one of the most affected by EWEs, so, an analysis of these impacts on the wind energy systems (WES) is presented in the next section.

Wind energy systems

Wind resource

Wind resource is a renewable, efficient, and clean energy source, offering substantial potential to reduce greenhouse gas emissions. (Ahmed et al., 2020; Davy et al., 2018; Schaeffer et al., 2012). In recent years, wind energy has become increasingly attractive and presents a successful economic development, and it is one of the fastest-growing technologies to produce renewable energy (Khchine et al., 2019; Nogueira et al., 2019). The potential of wind energy relies on near-surface winds, which can be influenced by various factors such as circulation patterns, terrain, and EWEs (Hueging et al., 2013; Pryor & Barthelmie, 2013; Tobin et al., 2016). These factors can lead to fluctuations in wind power generation, resulting in variations in the availability of electric power. Changes in the intensity and frequency of extratropical cyclones, for example, can affect wind patterns, leading to variations in calm and strong wind periods (Catto et al., 2019). Additionally, understanding the impact of climate change on wind resources is crucial for assessing energy availability (Carvalho et al., 2021; Davy et al., 2018; Devis et al., 2018; Fernández-Alvarez et al., 2023; Lledó et al., 2019; Martinez et al., 2023; Nogueira et al., 2019; Tobin et al., 2018), as they are a potentially high risk for

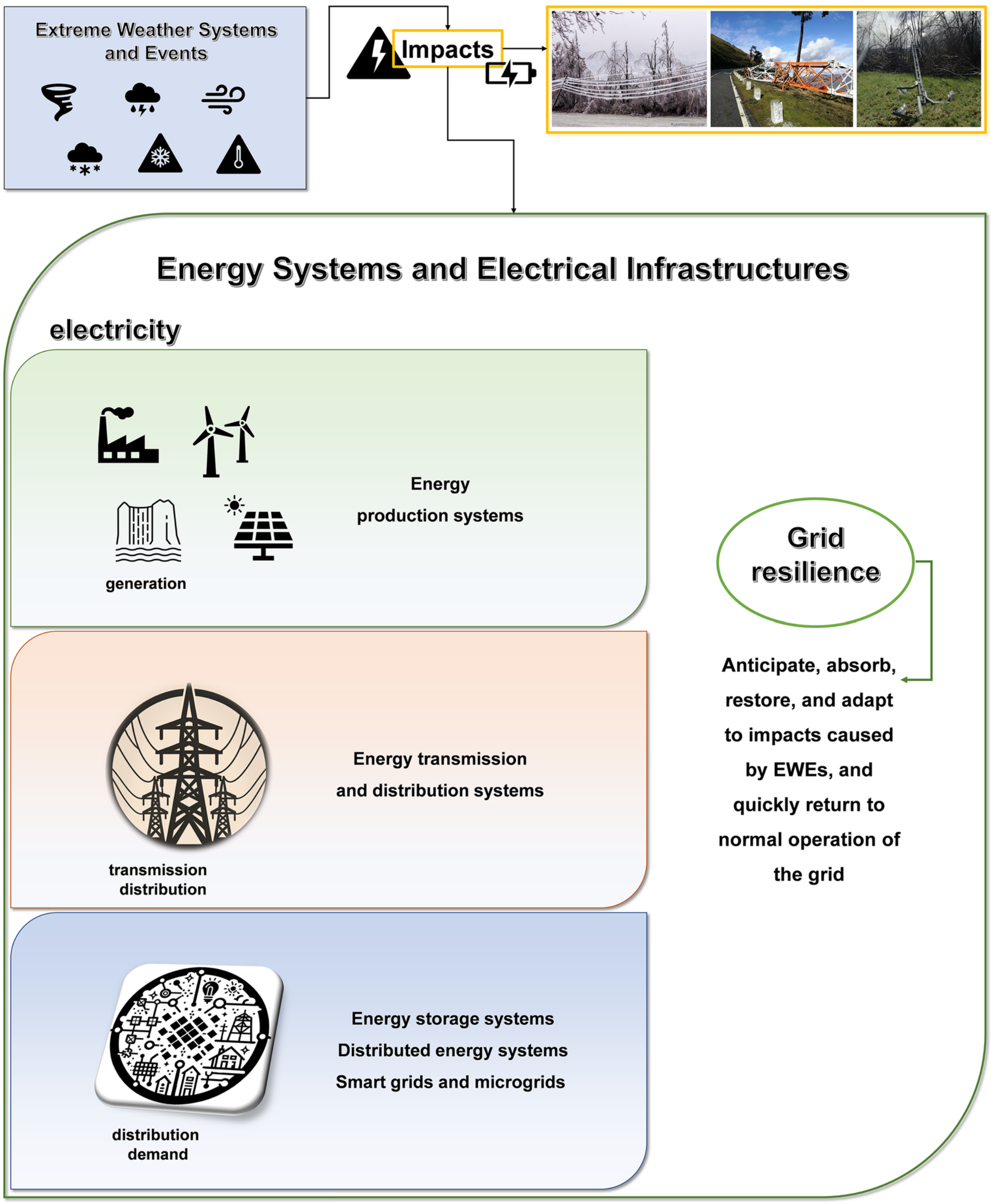

Fig. 2 Impacts of extreme weather events on energy systems and electrical infrastructures, and grid resilience (photographs courtesy of Agostinho Fernandes and Sílvia Loureiro)

investors (Modaberi et al., 2023; Solaun & Cerdá, 2019). Numerous studies have explored the influence of climate change on Europe's electricity sector (e.g., Dowling, 2013; Wenz et al., 2017) and its impact on wind speeds and wind energy potential across the continent (Hueging et al., 2013; Reyers et al., 2016; Tobin et al., 2016). In most of these investigations, results consistently indicate a small increase in wind energy potential annually across northern Europe, while there is a small decrease projected for southern Europe under future climate scenarios (Devis et al., 2018; Liberato et al., 2015; Moemken et al., 2018; Santos et al., 2015; Tobin et al., 2016). These events would entail more pronounced fluctuations in electricity production (Costoya et al., 2022; Moemken et al., 2018; Nogueira et al., 2019; Ravestein et al., 2018; Tobin et al., 2016) which poses challenges to the reliable functioning of wind turbines, especially in Europe, where wind energy plays a significant role in the energy mix due to the substantial installed capacity of onshore and offshore wind, with further expansion expected in the coming years (WindEurope, 2023; Zhang et al., 2019). In the context of the IPCC (2021) report, it suggests a probable decrease in global mean wind speeds. This decline is expected to be most pronounced in regions where prominent wind power facilities are currently installed, such as the western United States, northern Europe, and East Asia. Consequently, alterations in wind patterns might lead to reduced wind energy production, potentially resulting in disruptions to electrical grids. Conversely, along with the predicted decrease in mean wind speeds, there is a projected increase in cyclone intensity. These intensified cyclones could surpass the operational limits of wind farms, temporarily interrupt their operation, and cause physical impact to turbines and associated energy infrastructure (IEA, 2022). However, some studies highlight that the increase in storminess during specific periods may contribute to an increase in wind power generation, as occurred during the December months of 2017 to 2019 in Southwestern Europe (Gonçalves et al., 2021, and references therein). Therefore, it is crucial to implement measures and solutions to adapt WES and minimize the impacts of EWEs on their safe and dependable operation.

Wind technology

Wind farms can be based onshore with turbines that are located on land or more rural areas, as these are usually built in less-populated areas where buildings and obstacles do not interrupt the air; or offshore when turbines are typically installed on the ocean. Offshore systems, in contrast to onshore wind farms, are considered more efficient due to the higher wind speeds, increased consistency, and lack of impediments presented by landmasses or human-made structures (Whittlesey, 2017; Eriksson et al., 2008; Watson et al., 2019; Roga et al., 2022; Kiwi Energy, 2019; National Grid, 2022).

As wind turbines (WTs) continue to grow in both capacity and size, their susceptibility to various factors intensifies. However, there remains a lack of research focusing on elements that impact WTs, such as extreme wind events, gusts, blade icing, sea ice, permafrost, and air density. These variables are influenced by numerous factors that are considerably more difficult to predict but with great influence on WES (Modaberi et al., 2023; Solaun & Cerdá, 2019).

In the following paragraphs, some studies that discussed important aspects related to WES are presented and analyzed.

The study of Couto et al. (2021) uses weather type classification to analyze wind power generation in Portugal, and the results show cyclonic regimes that present high variability, while anticyclonic regimes present more low-generation events. Therefore, these results allow the enhancement of the predictability of wind resources and, so, minimize impacts on the electricity production and systems. In this sense, the work of Zhang et al. (2019) discusses the importance of considering extreme weather and climate change in wind power deployment to improve global sustainability, security, economics, and resilience. The results found that if extreme wind speed increases by 20%, the first capital cost of wind unit installation by the end of the century could increase by 12% due to the higher strength of tropical cyclones. Additionally, rising sea levels due to storm surges and sea ice pose higher risks to inland and offshore wind tower structures and foundations. On the other hand, increasing the hub height and rotor diameter in wind turbine technology leads to an increase in annual energy production and turbine capacity factors, which can limit the use of fossil-based power generation. So, Martin et al. (2020) show that increasing the turbine hub height from 80 to 160 m and the rotor diameter from 90 to 130 m increased the average annual energy production and capacity factors by 19% and 45%, respectively. Advancements in wind turbine technology, specifically in the rotor diameter and hub height, are the main drivers of cost reductions in wind power. Larger rotors decrease specific power, which boosts capacity factors and allows for wind power to be generated in low-wind areas.

Moreover, as the WTs undergo continuous improvements, it becomes imperative to establish updated standards that include the latest designs, especially for offshore wind conditions. The first offshore wind markets emerged in Europe and there is a need to adapt systems, documents, and standards to suit diverse markets such as Europe, Japan, and the US. This adjustment is crucial as the natural and climatic conditions in Europe do not reflect the extreme conditions, such as typhoons, hurricanes, earthquakes, and icing, prevalent in other global regions (IRENA, 2019).

Thus, EWEs are a necessary consideration for wind energy systems operators because of the vulnerability of these systems. In addition, more studies are needed to support normal operation, stability, and security of electricity demand and to adapt the WES during extreme events (Clarke et al., 2021). Progress in climate research allows the characterization of potential changes in extremes over time. Consequently, taking advantage of this improved predictive capability is imperative when considering changing benchmarks for power disruptions and other effects on ES (Perera et al., 2020). The adoption of cutting-edge technology will thus reinforce safety measures and maintain the stability of WES and distributed energy systems. This emphasis on technological innovation is crucial as wind energy plays a key role in shaping the future landscape of global energy structures.

WTs, onshore or offshore, have built-in mechanisms to lock and feather the blades (reducing the surface area pointing into the wind) when wind speeds exceed 55 miles per hour (25 m s^{-1}) (U.S. Department of Energy, 2018). The National Renewable Energy Laboratory (NREL) and the University of Miami developed WT simulation software (FAST) and a forecast model to optimize WTs for hurricane resiliency and structural efficiency. They use a downwind orientation, allowing the blades to bend without hitting the tower and reducing structural damage during an extreme event (Kim et al., 2016; U.S. Department of Energy, 2018 and references therein). Zhou and Yang (2020) propose a wind turbine with sensors on the turbine itself, on the blades, and on the tower to monitor its operation. So, the inclusion of a wind speed detector improves power generation efficiency by allowing the turbine to predict wind conditions. Additionally, sensors on the wind blades can detect the degree of damage, preventing accidents and minimizing losses for the company and surrounding people due to blade breakage. This is crucial for typhoon scenarios, which can cause offshore wind power ramp events and impact power system stability.

Another issue is analyzed by Wang et al. (2019) which proposed a framework to mitigate the impact of wind power ramping caused by typhoons on offshore wind farms. Their strategy optimizes curtailment, considering generator adjustments, demand response, and grid resilience. This approach efficiently utilizes system adjustments, maintains supply–demand balance, and minimizes costs while ensuring security and stability. WTs need backup power systems during hurricanes. This allows them to adjust their direction and face the wind. The Philippines already uses this technology (Han et al., 2014; Worsnop et al., 2017). In Japan, turbines must withstand strong winds and lightning storms. Thus, investment to expect every possible scenario that affects wind energy is required (Fortune, 2021). Vestas developed the V136-4.2 MW Extreme Climate turbine, optimized for extreme weather and low to medium wind speeds. It withstands up to 53 m s^{-1} winds and 74–78 m s^{-1} gusts. With a full-scale converter, it operates in low-grid capacity areas, increasing winter storm energy production by 56%. This WT model is suitable for onshore/offshore sites, it targets projects in Japan, Asia, the Caribbean, and the UK (Vestas, 2019, 2022). Siemens Gamesa also has a model of WTs suitable for extreme weather conditions and typhoon resistant (Siemens Gamesa, 2022), while Enercon modifies turbine components for performance in extreme climates, without limiting the operation of the turbines (Enercon, 2022). These robust technologies can withstand typhoon winds [over 33 m s^{-1} (119 km h^{-1})] by adjusting blade pitch to support safe spinning while generating sufficient power. A backup system allows the turbine to align with the wind even when the power grid shuts down. MHI Vestas Offshore Wind will deploy over 30 typhoon-strength turbines at the Akita Noshiro Offshore Wind Farm Project in Japan, boosting the growing sector (Spectra, 2020; Vestas, 2020).

A different solution to mitigate EWE impacts offshore is the floating platform with reduced steel usage which is being developed. These platforms use a central counterweight and pulley system to respond to waves, increasing wind generator effectiveness and reducing maintenance costs. The design minimizes wear and tear on turbines, enabling greater energy capture during EWEs (Popular Lin et al., 2019; Science, 2021).

The WindFloat Atlantic project in Viana do Castelo, Portugal, is a significant achievement in offshore wind energy (WindFloat Atlantic, 2023a). It features the largest turbine ever installed on a floating platform, situated 20 km offshore in waters 100 m deep. Using Principle Power's advanced technology, the project enables the installation of floating platforms in deep waters, tapping into abundant wind resources. The project's innovation lies in its design, inspired by the oil and gas industry, to support multi-MW floating wind turbines in deep waters (over 40 m). The semi-submersible floating structure is anchored to the seabed and maintains stability through water entrapment plates and a ballast system. WindFloat Atlantic is versatile, compatible with any offshore floating wind turbine, and can be fully assembled onshore, reducing the need for marine resources. The project's resilience was tested during the record-breaking storm Ciaran in November 2023, withstanding extreme conditions of 20-m-high waves and wind gusts reaching 139 km/h. The storm's wind speeds peaked at 38.8 m per second, surpassing the project's previous records. During the storm, the operations and maintenance teams ensured the infrastructure's safety and continuous energy production (WindFloat Atlantic, 2023a, 2023b). This event highlighted the project's exceptional engineering and its capacity to endure severe weather, reinforcing WindFloat Atlantic's role as a pioneering model in floating offshore wind technology and environmental stewardship. (EDP, 2022; OceanWinds, 2021; WindFloat Atlantic, 2022, 2023a, 2023b).

In the Nordic region, WTs must withstand extreme weather conditions and work with minimal maintenance. The EU-funded Njord project provides durable WES for telecom, surveillance, and residential sectors, capable of operating at high altitudes for up to 25 years (European Commission, 2020). Icewind and the Njord team offer two models, Freya and Njord, of durable vertical-axis WTs for remote locations (Icewind, 2022a). The Freya model provides sustainable energy solutions with reduced operational costs and can survive wind speeds up to 60 m s^{-1} with a rated power of 100W and a max power of 600W (Icewind, 2022b). The Njord model (Njord 100 and Njord 500) serves industries in harsh climates and provides a maintenance-free solution for users, with startup and survival speeds of 2 m s^{-1} and 60 m s^{-1}, respectively. The Njord 100 has a rated power of 100W and a max power of 600W, while the Njord 500 has a rated power of 500W and a max power of 3000W (Icewind, 2022c).

Extreme cold and ice accumulation on wind energy systems is a major concern and an assessment of the climate where a wind farm is to be located includes not just cold, but humidity and wind speed. Strategies to minimize ice impact include adjusting turbine location and arrangement. De-icing or anti-icing products, such as the panels installed directly in the turbine rotors warm up the rotors, keeping them ice-free. Nacelles are equipped with fan heaters to maintain warmth and minimize extreme weather effects on wind farms. Components like gearboxes, wind sensors, and electrical systems have heating elements to prevent freezing. Turbines detect ice on blades and shut down until it melts for safe operation. However, only under very rare circumstances does the cold weather force a turbine to shut down, and when it happens, the turbines are keeping warm to continue protecting their systems and ensure they are ready to go once the blades are safe to spin again. Algorithms are adjusted for winter conditions, considering air density, pressure, and other factors affecting turbine performance (Kollar et al., 2019; MidAmerican Energy Company, 2021; Stoyanov & Nixon, 2020). As it said, an ice sensor integrated with an ice mitigation system is needed to prevent ice formation on wind turbine blades. Madi et al. (2019) review ice sensing and mitigation techniques for wind turbine blades. Integrated ice sensor and mitigation systems have drawbacks and require significant improvement as current technologies are inefficient when combined in integrated systems.

Thus, within the field of wind energy, predictive abilities are crucial to curtail production costs and mitigate the impact of unforeseeable ramp events, which can undermine the reliability of power networks. Additionally, improvements in planning tools are essential to optimize the economic and technical aspects of wind energy. This requires consideration of practical limitations and incorporation of available adaptable solutions. Consequently, the distinct attributes of WES, encompassing intermittency, turbine technology, and protective measures, pose new challenges to the effective integration of wind energy into the economy (Ahmed et al., 2020; Roga et al., 2022). Therefore, the vulnerability of the wind energy systems to weather conditions, as EWEs, needs to be understood and it is crucial to assess the impacts of these events on WES (resource, turbines and infrastructures associated) that have important implications for energy security and power system resilience.

Throughout this analysis, it can be concluded that WES are heavily exposed to extreme weather conditions, characterized mainly by extreme winds and gusts of wind, storms, typhoons and lightning, snowstorms, and ice accumulation on turbine components and the indirect effect of high waves. However, there are already numerous solutions developed to mitigate the effects of these extreme weather conditions on systems, which include:

- Forecasting and defense mechanisms against extreme winds and lightning, through the installation of sensors and more automated control systems.
- Backup mechanisms in situations where the turbine is forced to shut down, to protect the essential components of the turbine.
- Turbines, built with more resistant materials and components adapted to the locations where they will be installed.

These measures reduce installation and maintenance costs and, in turn, wind energy production costs, while increasing energy security and power system resilience, as is summarized in Fig. 3.

Strategies and measures for impact mitigation and adaptation of energy systems

Throughout this work, a comprehensive review is performed on the impacts of extreme weather events (EWEs) on energy systems (ES) and wind energy systems (WES), making evidence of the continuous and constant need for systems to be improved, adapted, and checked, to withstand the effects of the occurrence of EWEs.

Strategies and measures to mitigate the impacts of EWEs on energy systems include a series of proactive approaches aimed at reducing vulnerabilities, increasing resilience, and ensuring the continued operation of energy infrastructure during adverse weather conditions (Bruckner et al., 2014; IPCC, 2014; Panteli & Macarella, 2015). The main objective is to improve adaptability and reinforce energy systems against EWEs impacts, minimizing disruptions and ensuring sustained functionality, reliability, and sustainability of energy infrastructure (Gosh & De, 2022; Jufri et al., 2019).

Thus, to complete this review, the next sections explore these strategies and measures to mitigate the impacts of EWEs on systems and new technological solutions to minimize the impacts associated with EWEs.

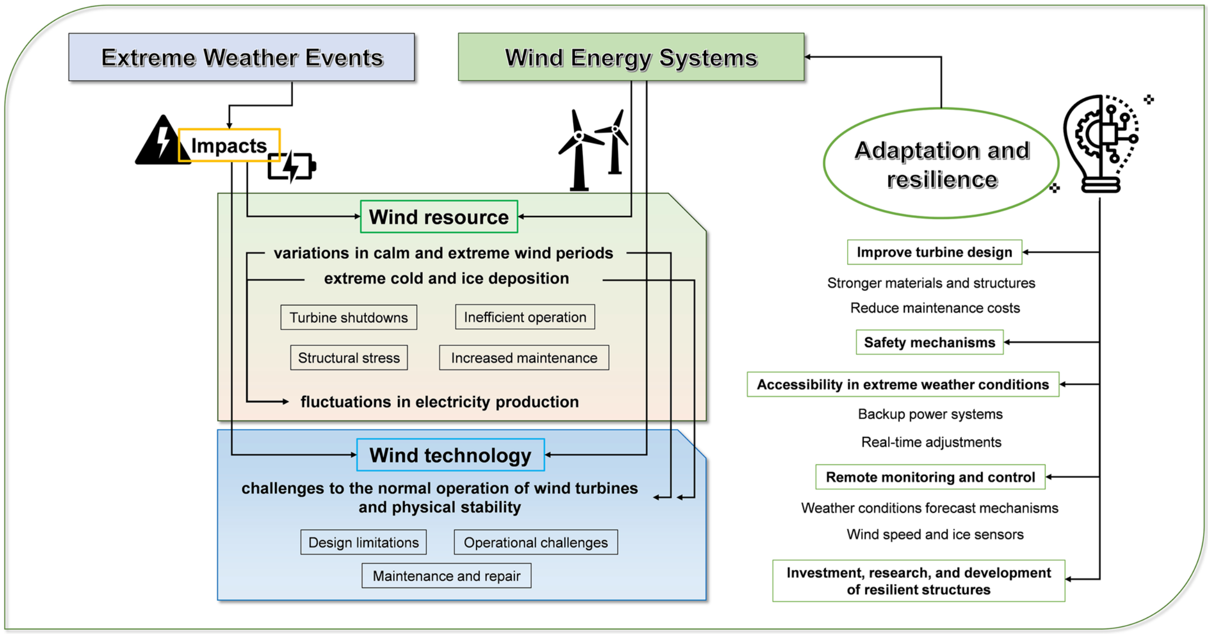

Fig. 3 Extreme weather events and their impacts on wind energy systems, and the adaptation and resilience solutions to minimize them

Mitigation of impacts on energy systems

Strategies and measures for mitigating the impacts of EWEs on ES are identified and some studies are analyzed in this work. The growing frequency and intensity of EWEs represent major risks to energy infrastructure and supply, so all stakeholders need to act to ensure that the systems can predict, adapt, and recover from adverse impacts (IEA, 2022). Table 2 synthetizes mitigation

Table 2 Mitigation strategies and measures (Adapted from: Afzal et al., 2020; Bhusal et al., 2020; Bie et al., 2017; Ghosh & De, 2022; Hossain et al., 2021; Ibrahim et al., 2022; Jufri et al., 2019; Mahzarnia et al., 2020; Panteli & Macarella, 2015; Webster & Jian, 2011)

Mitigation strategies	
Short-term	• Before, during, and after the weather emergency • Corrective actions help effectively manage the disaster as it unfolds
Long-term	• To provide robustness and adaptability to future weather conditions • Preventive control actions and proper operational procedures help to prepare for the forthcoming weather event
Mitigation measures	
Engineering	• To design more robust structures to withstand extreme conditions and weather • To relocate or refit extremely vulnerable existing infrastructure • To improve the reliability of control systems to be more resilient to higher temperatures and humidity
Non-engineering	• To revise operational procedures, policies, and regulations • To improve localized models used to predict storms and/or flood hazards
Systems and power grid	• Vegetation management • Physical revitalization and upgrade • Substation relocation, and line rerouting • Enhance visualization and awareness of situations with sophisticated surveillance and prediction capabilities • To improve planning for emergencies and prevention and precise forecast of the weather event location and intensity • The operation of the system linked to emergency generators and mobile substations • The management of repair parts and restoration teams • The network monitoring system • Updating of standards of regulated projects
Others	• To assess risks • To incorporate climate resilience in energy and climate plans • To identify cost-effective measures and incentivize utilities to act • To implement resilience measures, evaluate and adjust them to continuously improve system resilience

strategies and measures based on several works such as Panteli and Macarella, (2015); Jufri et al. (2019); Webster and Jian (2011); Ibrahim et al., (2022); Hossain et al., (2021); Ghosh and De, (2022); Bie et al., (2017); Afzal et al., (2020); Bhusal et al., (2020); Mahzarnia et al., (2020), which represent a wide range of fundamental aspects.

Moreover, supporting electrical safety in the ES requires new tools and approaches [Adapted from (IEA, 2022)]:

- Improved responsiveness and agility in power generators
- Greater connectivity and adaptability among consumers
- Reinforcement of network infrastructure
- Implementation of digitalization to facilitate dynamic electricity and information flows
- Adjustments to address climate change, weather patterns, and changes in consumer behavior.

It is worth noting that an enhancement strategy that works well in a particular event may have adverse effects on another event. For instance, underground power lines may improve infrastructure resilience against windstorms but may prolong the restoration time during a flood or earthquake due to the challenges in finding faults. Therefore, system planners need to make informed decisions when implementing enhancement measures. Specific characteristics of the systems and the utility grid must be prioritized, to find a balance between diverse types of measures and thus ensure the overall resilience of the system (Afzal et al., 2020).

Energy storage systems (ESS), distributed energy systems (DES), smart grids, and microgrids have been ranked as new technology solutions that enhance grid reliability (Hossain et al., 2021). In the following points, these topics are addressed including the definitions and means of operation of these systems.

Energy storage systems

The storage of energy and the incorporation of storage systems in the energy production systems can be one of the solutions to minimize the impacts of EWEs. ESS include various systems and components used to store diverse forms of energy. Among these, batteries, a key component of ESS, find wide application in providing emergency backup power and black-start services, thereby increasing grid resilience. ESS serve as an energy repository, mitigating the intermittent nature of distributed energy resources (DER) like renewable energy sources (RES), which depend on resource availability and require storage solutions (Hossain et al., 2020, 2021; Huggins, 2016).

Jasiunas et al. (2021) analyzed the impacts of EWEs on the energy sector, considering supply-side factors, demand-side, and energy storage. As RES grow, long-term electrical storage demand rises, and so, ESS balance supply–demand disruptions since batteries can provide emergency power to communication infrastructure (Jasiunas et al., 2021; Widera, 2020). On the other hand, Jing et al. (2021) propose a two-layer modeling framework for urban energy systems (UES) considering the impact of EWEs (such as heatwaves, floods, and typhoons). Applying the framework to Xiamen, China shows that energy storage (pumped hydro and battery) ensures critical demand during typhoons and avoids excessive supply investments. This adds a 2.8% cost over 20 years. Proper EWEs impact consideration in energy planning ensures reliable UES despite fluctuating renewables, offering a flexible and efficient paradigm for UES planning (Jing et al., 2021).

Despite the high initial costs, the use of ESS has multiple benefits (Hossain et al., 2020, 2021; Huggins, 2016), such as:

- The backup power, such as load leveling, frequency and voltage regulation, and power quality improvement
- The supply of backup power during emergencies and black-start services
- The effective planning of battery storage can reduce grid vulnerability
- The use of RES with associated ESS helps the transition to a decentralized and therefore, more reliable electricity grid
- ESS and renewable grids provide superior economic efficiency and increased operational productivity
- To present a vital role in the resilience of the system and grid reliability enhancement.

Distributed energy systems

Distributed energy systems (DES) comprehend small-scale energy generation units located at or near the site of consumption. In these systems, the end-users serve as producers, including individuals, small companies, or local communities. These energy-producing units might operate independently or connect to neighboring units via a network to exchange surplus energy. When interconnected, these form localized distributed energy networks that could further connect with similar networks nearby (Vezzoli et al., 2018 and references therein).

Moreover, ES can be also classified into centralized energy systems—defined as large-scale energy generation units that deliver energy via a vast distribution network, usually far from the point of use; and decentralized energy systems—characterized by small-scale energy generation units that deliver energy to local customers. These units can operate independently or be interconnected to share surplus energy, forming locally decentralized energy networks. These networks might further connect with neighboring similar networks to create a broader energy-sharing system.

Therefore, DES provide energy close to consumers using small-scale technologies. These systems integrate energy production, transmission, conversion, storage, and consumption, linking the different resources. In addition, DES allow the integration of renewable resources, recovery of waste heat, and matching between supply and demand levels. Therefore, these systems lead to economic and environmental advantages in distributed production plants (Soderman & Petterson, 2006; Somma et al., 2015), and improve grid quality, reduce congestion, and enhance flexibility without requiring new transmission lines (Liu et al., 2021; Mancarella, 2014; Mar et al., 2019).

On the other hand, using DES and Distributed Renewable Energy (DRE) are effective ways to enhance the distribution system's resilience. This is because DRE) generation refers to small-scale generation units that use RES like sun, wind, water, biomass, and geothermal energy at or near the point of consumption, where users are also producers. Thus, DRE systems bring about environmental advantages by using renewable resources, low greenhouse gas emissions, and low environmental impact compared to non-renewable centralized energy generation units. From a socioeconomic perspective, these systems offer benefits due to their small-scale nature, requiring modest economic investment, easy installation, and maintenance. This accessibility empowers individuals and local communities to set up and manage these systems, thereby democratizing resource access, enhancing the quality of life, reinforcing local employment, and promoting the dissemination of skills (Vezzoli et al., 2018). In addition, integrating DRE systems with ESS during isolated operations presents utilities with another solution to mitigate the adverse impacts of severe events (Gosh & De, 2022; Li et al., 2017) combined with other key features to improve the network resiliency which includes adaptability, redundancy, flexibility, fast recovery, and automation of the systems.

Smart grids and microgrids

Smart grids are a sophisticated version of electrical grid systems, integrating digital technology to improve the reliability, efficiency, and sustainability of electricity services. Overall, smart grids mark a substantial shift from conventional electrical grids, using advanced technology to create an electricity system that is more efficient, reliable, and environmentally sustainable (Escobar et al., 2021; Hossain et al., 2021).

Microgrids represent an alternative approach to mitigate the effects of EWEs. These microgrids can take the form of smart grids that offer greater stability and effectiveness in device management and security through sophisticated computing technologies and smart meters. This innovation emerged as a flexible structure capable of meeting the diverse requirements of different groups seeking to integrate distributed energy resources (DER) (Hirsch et al., 2018; Hossain et al., 2021).

Therefore, a microgrid offers essential power support in two distinct manners during substantial power outages: (1) operating independently of the main grid, using DER to sustain vital loads. This operation, known as islanding, is crucial for maintaining network reliability; (2) restoring power to critical loads in sections of the distribution system experiencing insufficient power. The microgrid reconnects to the network after isolating faulty areas and assists these sections as an immediate source of essential power supplies (Gosh & De, 2022; Li et al., 2014). So, integrating microgrids to assist in the restoration of critical loads during severe incidents presents an effective solution to increase the resilience of the distribution system (Gosh & De, 2022).

The use of microgrids offers several benefits as it improves available power generation, supplying greater energy to a wider region. Being situated in proximity to loads produces two effects: reduced losses and the potential to act as an alternative to network resources by minimizing power flows in transmission and distribution circuits. Under standard operating conditions, microgrids operate autonomously, without exchanging power with the primary grid or other microgrids. During emergencies, a failed microgrid receives power from other microgrids, preventing its failure and ensuring continued supply to customers during the repair period, on which they depend (Li et al., 2017; Mar et al., 2019). Smart grids and microgrids have reduced susceptibility to the effects of extreme weather events (EWEs) and can respond quickly and effectively to their impact. Specifically, defensively isolated microgrids have the potential to facilitate optimal grid restoration while allowing for the maximization of grid capacity. Additionally, DER and microgrid systems play a key role in minimizing the repercussions of failures in power transmission and distribution infrastructure by generating, storing, and regulating electricity locally (Hossain et al., 2021; Panteli et al., 2016; Xu et al., 2016).

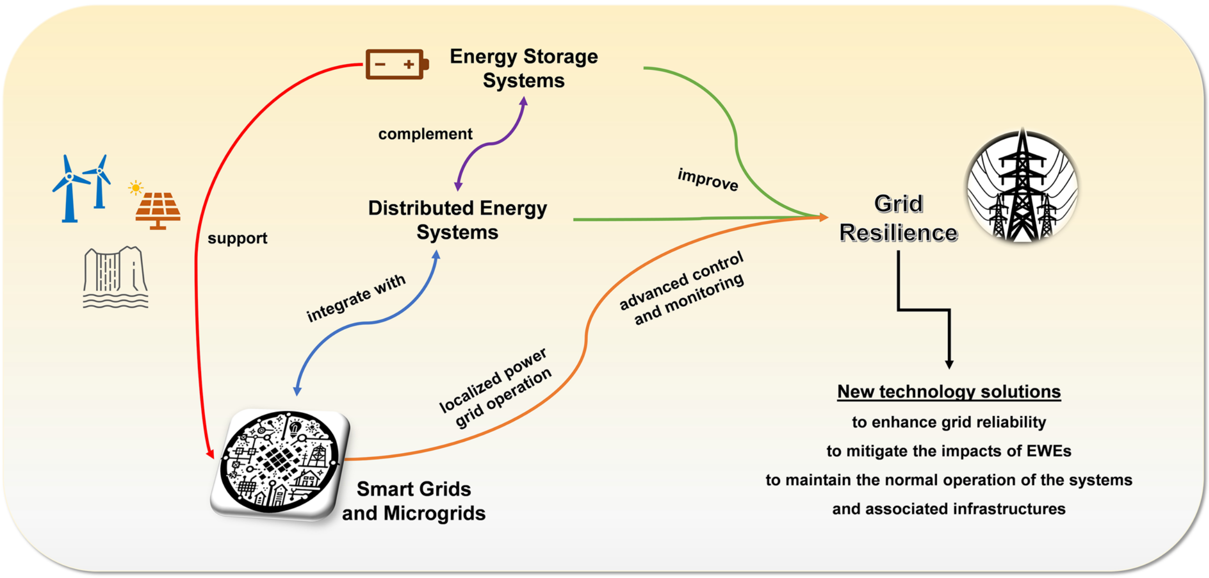

Fig. 4 Solutions to improve grid resilience based on energy storage systems, distributed energy systems, and smart grids and microgrids

These new technology solutions—energy storage systems (ESS), distributed energy systems (DES), smart grids, and microgrids—and the relationship between the concepts are represented in Fig. 4.

Therefore, microgrids and their several activities are emphasized as being one of the most efficient strategies to improve power distribution system resilience (Gao et al., 2015; Gosh & De, 2022; Mahzarnia et al., 2020). However, existing regulations around the world for power exchange between multiple microgrids are insufficient, necessitating immediate review and adjustment to meet the growing needs of interconnected microgrids, such as integrating more DER, implementing islanding, and enhancing energy storage within each microgrid (Afzal et al., 2020).

Forecast studies on extreme weather conditions and impacts on WES

In recent years, the relationship between forecasting an extreme weather event and its impact on energy systems has become a key area of study. For the power grid to become more resilient to these types of events, power utilities need to prepare and stage repair crews, which is only possible if they can accurately anticipate the impacts that extreme weather can have on their systems (Perera et al., 2020; Watson et al., 2022).

With the rise in renewable energy, such as wind power, the need to accurately predict EWEs has intensified, and so, numerous forecasting and prediction studies have investigated the impact of EWEs on resource availability and energy systems, aiming to improve planning, efficiency, and resilience (Mohamed et al., 2019; Panteli & Macarella, 2015; Perera et al., 2020; Watson et al., 2022). Furthermore, the ability to predict EWEs, particularly wind speed patterns—wind speed prediction and the prediction of operation probability for wind turbines—is essential for the efficient operation of wind turbines, as it directly impacts their performance (Arora et al., 2018; Bazionis & Georgilakis, 2021; Ghorbani et al., 2016; Jiang et al., 2021; Karaman, 2023; Liu et al., 2022; Xinxin et al., 2023).

Lei et al. (2009) divided the forecasting methods into four categories: *physical models* which use a lot of physical considerations to reach the best prediction precision; *conventional statistical models*, such ARMA model, which aim at finding the relationship of the online measured power data; *spatial correlation models* which consider the spatial relationship of the wind speed in different wind speed measurement stations. The wind speed time series of the predicted points and its neighboring observation points are employed to predict the wind speed*; new methods based on artificial intelligence*, such as artificial neural networks (ANN), fuzzy logic models, support vector regression machines (SVR), and hybrid models are advanced ones and have less error than others (Lei et al., 2009; Shi et al., 2012; Hu et al., 2016 and references therein; Arora et al., 2018; Jiang et al., 2021; Gupta et al., 2022; Farahbod et al., 2022 and references therein; Karaman, 2023).

Physical methods have advantages in long-term prediction while the statistical method does well in short-term prediction. Both physical and statistical models are utilized simultaneously in typical forecasting methods. To train the system on the local conditions, numerical weather prediction (NWP) results are regarded as input variables together with historical data and statistical theories. Statistical models are the autoregressive model (AR), moving average model (MA), autoregressive moving average model (ARMA), and autoregressive integrated moving average model (ARIMA) (Lei et al., 2009; Shi et al., 2012; Hu et al., 2016 and references therein; Jiang et al., 2021; Daniel et al., 2020; Bazionis & Georgilakis, 2021; Liu et al., 2022).

Several studies explored various modeling approaches, including GARCH (Generalized Autoregressive Conditional Heteroskedasticity) and machine learning models, to forecast wind speeds for better understanding and optimizing wind turbine operations (Chen et al., 2013; Liu et al., 2011, 2013; Zhou et al., 2010). In the study of Zhou et al. (2010), GARCH was used to model wind speed, effectively capturing variations in time series. By correlating the power curve and wind speed, the wind power estimate was easily derived from the predicted speeds. Validating its prediction model with an example, GARCH demonstrated its advantage in improving prediction accuracy over ARIMA. Numerical calculations using sequences with diverse volatility clusters highlighted GARCH as having better forecasting performance, particularly with sequences that highly fluctuate. Liu et al. (2011) evaluate ARMA–GARCH methodologies for wind speed modeling, employing 10 different model structures with various GARCH approaches on seven years of hourly wind speed data from Colorado, USA. Various evaluation methods confirm the effectiveness in capturing the changing trend of the mean and volatility of wind speed. These models display time-varying nonlinear and asymmetric characteristics in wind speed volatility, consistently improving sufficiency. However, as height increases, the explanatory power of the ARMA–GARCH(-M) model decreases slightly. No single model structure universally outperforms others at all heights, emphasizing the need to evaluate potential models for optimal sufficiency in wind speed datasets. In the study of Liu et al. (2013), the real wind speed and power data were used to apply a methodology that employs ARMA-GARCH-M to predict wind speed and calculate the operation probability and the expected power output of the wind turbine. The results affirm its effectiveness, and reliability in wind speed estimation, and accuracy in forecasting turbine operations and power output. Chen et al. (2013) introduce GARCH in mean-type models for wind power forecasting, incorporating volatility and intermittency impacts into the forecasting equation. The GARCH in the mean effect curve highlights volatility's negative influence on wind power. The parameters are estimated using Conditional Maximum Likelihood Estimation, applied to historical coastal wind power data from East China. Comparatively, the proposed GARCH in mean type model proves effective, outperforming classical wind power forecasting models like ARMA and GARCH, showcasing their superiority in accuracy. Chen et al. (2019) showcase GARCH-type models' effectiveness in capturing the time-varying volatility of wind power series, highlighting asymmetry through parameter estimation. Enhanced News Impact Curve analysis emphasizes volatility responses to shock magnitude and sign. Consistent results across multiple model specifications validate the effectiveness of the asymmetric effect of volatility models in improving wind power forecasting.

The integration of GARCH models and machine learning techniques provides a robust framework for predicting wind speeds, subsequently improving the operational assessment and management of wind turbines in renewable energy systems (Chen et al., 2019; Liu et al., 2022). So, this holistic approach allows energy systems to adapt and optimize their operations in response to changing weather dynamics, thereby maximizing energy generation while ensuring reliability and profitability (Xinxin et al., 2023). These models have been utilized due to their ability to capture time-varying characteristics and volatility in wind speed data, and to increase the accuracy of weather predictions, directly influencing the operational probability of wind turbines (Karaman, 2023; Xinxin et al., 2023).

Machine learning methods such as neural networks, random forests, and support vector machines have effectively predicted wind speed using diverse data to improve accuracy over varying time frames (Bazionis & Georgilakis, 2021; Farahbod et al., 2022). These models predict various EWEs (such as storms, extreme temperature fluctuations, and extreme windstorms), assisting in energy planning for proactive risk management and resource optimization (Liu et al., 2022; Xinxin et al., 2023).

Therefore, the interaction between GARCH models and machine learning algorithms offers a powerful solution for predicting extreme weather and its impact on energy systems, particularly wind speeds predicting for efficient operation of wind turbines (Chen et al., 2019; Liu et al., 2022).

Figure 5 synthesizes the main categories of wind speed forecast models covered in this section.

Continued advancement in predictive analytics has immense potential to optimize renewable energy integration, improve network management, and reinforce the reliability of energy systems in the face of increasingly

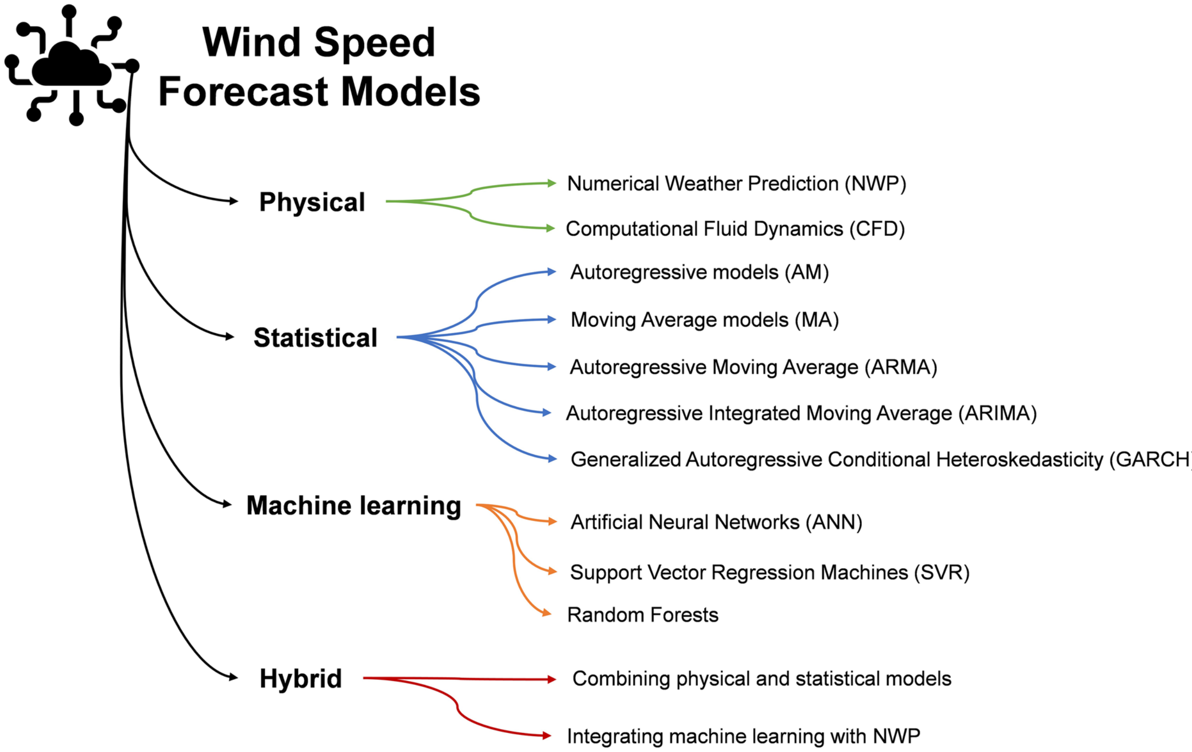

Fig. 5 Wind speed forecast models main categories

unpredictable and extreme weather patterns (Karaman, 2023; Liu et al., 2022).

Therefore, governments and energy companies must act to enhance the resilience of energy systems to EWEs. Since, the implementation of mitigation strategies and measures to improve the energy systems seeks to answer three questions—the reduction in the magnitude of the immediate impact caused by EWEs, maintenance, and the re-establishing of the operation of the systems and network as quickly as possible after the occurrence of such events (Gonçalves et al., 2023; Jufri et al., 2019; Watson et al., 2022). Figure 6 summarizes the points covered throughout this work. The interconnection between EWEs and energy systems, in particular wind energy systems, and the mitigation of the impacts of EWEs caused on ES. Mitigation of impacts therefore includes strategies and measures (as detailed in Table 2) that involve the implementation of technologies such as energy storage systems, distributed energy systems, smart grids, and microgrids. Concerning wind energy systems, implementing advanced forecasting systems and prediction models using artificial intelligence is crucial to accurately predict wind speed, and energy produced by wind turbines, and prevent extreme wind or low-speed events.

Concluding remarks

Extreme weather events (EWEs) are associated with numerous socioeconomic impacts on the energy sector, namely on energy systems (ES) and all associated infrastructures, and more specifically on wind energy systems (WES), which are comprehensively reviewed in this paper.

Concerning WES, there is a constant challenge wherein scientists and engineers must implement systems capable of initiating power generation at lower wind speeds while withstanding extreme wind conditions. In this way, wind farms may help mitigate some of the harmful effects of EWEs, when new technologies with resistant components allow them to take advantage of the full potential of wind systems, with a lot of energy available or very low wind speeds, during snowstorms or extreme winds. Moreover, the funding of wind energy projects heavily depends on the accurate projection of future wind resources at specific locations. Therefore, wind technology must remain adaptable to innovative solutions and be flexible to accommodate changes in physical and climatic parameters that continually affect it (Caltech, 2022; Gonçalves et al., 2022; Rajabzadeh & Kalantar, 2022).

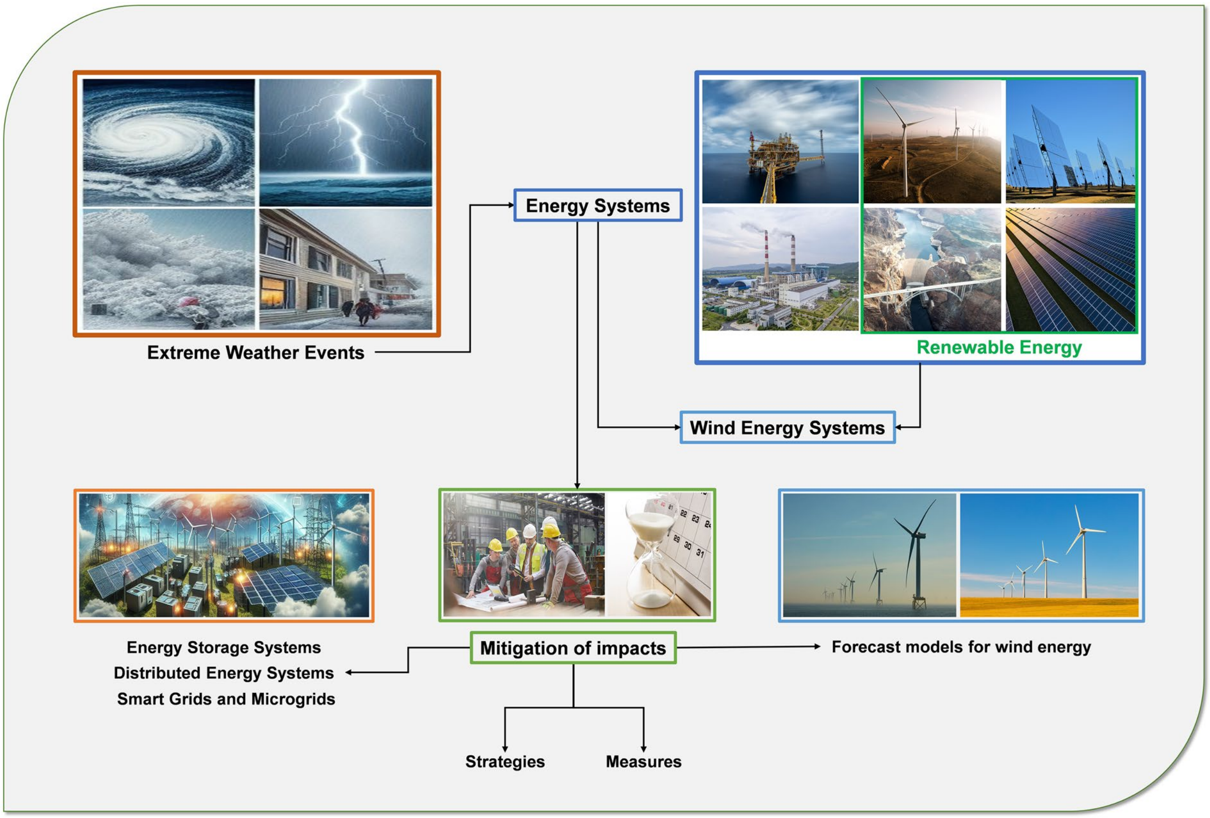

Fig. 6 The interrelations between extreme weather events, energy systems, and the mitigation of the impacts of EWEs on ES, technology, and tools

Therefore, the main highlights and conclusions of this review study may be summarized in the following points:

- Providing climate and weather data can help energy planners and suppliers better understand the potential risks and impacts of the EWEs. This knowledge aids in more effective risk assessment and the development of mitigation and adaptation strategies and measures.
- Evidence of the need to modify and upgrade engineering standards, operations, and maintenance standards due to increased EWEs severity.
- Need for significant investments in resilience strategies for improved system and grid capability.
- Implementing measures such as flood protection, relocation of substations, and stronger wind power plants.
- Upgrade electrical grids with underground lines and robust infrastructure to reduce damage.
- Integration of microgrid components (RES, DER, ESS) to improve energy management and grid resilience.
- Use smart technologies to monitor and control the grid, making the transition to a smarter grid.
- Accurate prediction of EWEs, especially wind speed patterns, is vital for optimizing wind turbine performance. The use of machine learning methods, such as neural networks and random forests, improves wind speed predictions on different time scales, aiding operation efficiency.
- Energy management plays a significant role in system operation and control, improving system efficiency.
- Resilient energy systems present high redundancy, functional diversity, adaptability, and modularity.
- Risks associated with inadequate maintenance and supervision lead to potential economic losses, so it is important to select strategies based on cost/benefit analysis.

Therefore, this interdisciplinary study contributes as a call of attention and action to the need to perform new interdisciplinary studies on the impacts of EWEs in the energy sector. Furthermore, it highlights the need to adapt systems to make them more resilient and prepared to face EWEs with minimal impacts.

With this review paper, it is possible to conclude that there is much published scientific work on this theme and that there are already good solutions and innovative strategies proposed to face the EWEs. However, this review also highlights that it is necessary to intensify the implementation and adaptation of the systems and, of course, to further foster research to develop new solutions that follow the evolution of technology and society, to mitigate the EWEs' impacts in the energy sector.

Abbreviations

ES	Energy systems
EWEs	Extreme weather events
WES	Wind energy systems
ESS	Energy storage systems
DES	Distributed energy systems
PV	Photovoltaic
RES	Renewable energy sources
OPL	Overhead power lines
DPSN	Distribution power system network
WTs	Wind turbines
DER	Distributed energy resources
UES	Urban energy systems
DRE	Distributed renewable energy

Acknowledgements
Some of the photographs used were obtained from free image databases such as Pexels (https://www.pexels.com/).

Author contributions
ACRG: conceptualization, methodology, investigation, writing-original draft; XC: writing—review and editing; RN: writing—review and editing, validation, supervision, project administration; MLRL: writing—review and editing, validation, supervision, project administration. All authors have read and agreed to the published version of the manuscript.

Funding
This work was funded by the Portuguese Fundação para a Ciência e a Tecnologia (FCT) I.P./MCTES through national funds (PIDDAC)—UIDB/50019/2020 (https://doi.org/10.54499/UIDB/50019/2020), UIDP/50019/2020 (https://doi.org/10.54499/UIDP/50019/2020) and LA/P/0068/2020 (https://doi.org/10.54499/LA/P/0068/2020), and project WEx-Atlantic (PTDC/CTAMET/29233/2017, LISBOA-01-0145-FEDER-029233, NORTE-01-0145-FEDER-029233). FCT is also providing for Ana Gonçalves doctoral grant (2021.04927.BD). The EPhysLab group was also funded by Xunta de Galicia, Consellería de Cultura, Educación e Universidade, under project ED431C 2021/44 "Programa de Consolidación e Estructuración de Unidades de Investigación Competitivas. X. Costoya is funded by Grant IJC2020-043745-I (Juan de la Cierva Postdoctoral Fellowship) funded by MCIN/AEI/https://doi.org/10.13039/501100011033 and by the "European Union NextGenerationEU/PRTR". This work was partially supported by Project TED2021-129479A-100 (SAFE project) funded by MCIN/AEI/https://doi.org/10.13039/501100011033 and the "European Union NextGenerationEU/PRTR".

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author details
[1]Centro de Investigación Mariña, Environmental Physics Laboratory (EPhysLab), Universidade de Vigo, Campus As Lagoas s/n, 32004 Ourense, Spain. [2]Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisbon, Portugal. [3]Universidade de Trás-os-Montes e Alto Douro, UTAD, 5000-801 Vila Real, Portugal.

Received: 28 July 2023 Accepted: 23 December 2023
Published online: 16 January 2024

References

Abdin, I. F., Fang, Y. P., & Zio, E. (2019). A modeling and optimization framework for power systems design with operational flexibility and resilience against extreme heat waves and drought events. *Renewable and Sustainable Energy Reviews, 112*(Jan), 706–719. https://doi.org/10.1016/j.rser.2019.06.006

Abedi, A., Gaudard, L., & Romerio, F. (2019). Review of major approaches to analyze vulnerability in power system. *Reliability Engineering and System Safety, 183*(Nov 2018), 153–172. https://doi.org/10.1016/j.ress.2018.11.019

Afzal, S., Mokhlis, H., Lllias, H. A., Mansor, N. N., & Shareef, H. (2020). State-of-the-art review on power system resilience and assessment techniques. *IET Generation, Transmission and Distribution, 14*(25), 6107–6121. https://doi.org/10.1049/iet-gtd.2020.0531

Ahmed, S. D., Al-Ismail, F. S. M., Shafiullah, Md., Al-Sulaiman, F. A., & El-Amin, I. M. (2020). Grid integration challenges of wind energy: A review. *IEEE Access, 8*(Type 1), 10857–10878. https://doi.org/10.1109/ACCESS.2020.2964896

Arora, P., Kumar, H., & Panigrahi, B.K. 2018. "A comparative study for short term wind speed forecasting using statistical and machine learning approaches." *2018 2nd IEEE International Conference on Power Electronics, Intelligent Control and Energy Systems, ICPEICES 2018*, 200–205. https://doi.org/10.1109/ICPEICES.2018.8897457.

Auffhammer, M., & Mansur, E. T. (2014). Measuring climatic impacts on energy consumption: A review of the empirical literature. *EnergyEcon, 46*, 522–530.

Bazionis, I. K., & Georgilakis, P. S. (2021). Review of deterministic and probabilistic wind power forecasting: models, methods, and future research. *Electricity, 2*(1), 13–47. https://doi.org/10.3390/electricity2010002

Behrens, P., van Vliet, M. T. H., Nanninga, T., Walsh, B., & Rodrigues, J. F. D. (2017). Climate change and the vulnerability of electricity generation to water stress in the European Union. *Nature Energy, 2*(8), 1–7. https://doi.org/10.1038/NENERGY.2017.114

Beven, J.L., Hagen, A., & Berg, R. (2022). HURRICANE IDA (AL092021). National Hurricane Center. NOAA. 4 April 2022. Retrieved January 28, 2023, from https://www.nhc.noaa.gov/data/tcr/AL092021_Ida.pdf

Bhusal, N., Abdelmalak, M., Kamruzzaman, Md., & Benidris, M. (2020). Power system resilience: Current practices, challenges, and future directions. *IEEE Access, 8*, 18064–18086. https://doi.org/10.1109/ACCESS.2020.2968586

Bie, Z., Lin, Y., Li, G., & Li, F. (2017). Battling the extreme: a study on the power system resilience. *Proceedings of the IEEE, 105*(7), 1253–1266. https://doi.org/10.1109/JPROC.2017.2679040

Bie, Z., Lin, Y., & Qiu, A. (2015). Concept and research prospects of power system resilience. *Automation of Electric Power Systems, 39*(22), 1–9.

Bloomfield, H. C., Brayshaw, D. J., Shaffrey, L. C., Coker, P. J., & Thornton, H. E. (2016). Quantifying the increasing sensitivity of power systems to climate variability. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/11/12/124025

Bompard, E., Huang, T., Wu, Y., & Cremenescu, M. (2013). Classification and trend analysis of threats origins to the security of power systems. *International Journal of Electrical Power and Energy Systems, 50*(1), 50–64. https://doi.org/10.1016/j.ijepes.2013.02.008

Brás, T. A., Simoes, S. G., Amorim, F., & Fortes, P. (2023). How much extreme weather events Have affected European power generation in the past three decades? *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2023.113494

Bruckner, T., Bashmakov, I. A., Mulugetta, Y., Chum, H., de la Vega Navarro, A., Edmonds, J., Faaij, A., Fungtammasan, B., Garg, A., Hertwich, E., Honnery, D., Infield, D., Kainuma, M., Khennas, S., Kim, S., Nimir, H. B., Riahi, K., Strachan, N., Wiser, R., & Zhang, X. (2014). Energy systems. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, & J. C. Minx (Eds.), *Climate change 2014: Mitigation of climate change. Contribution of Working Group III to the Fifth*

Assessment Report of the Intergovernmental Panel on Climate Change 2014. Cambridge University Press.
Caltech—California Institute of Technology. (2022). What is the future of wind energy?. Retrieved January 10, 2022, from https://scienceexchange.caltech.edu/topics/sustainability/wind-energy-advantages-disadvantages
Carvalho, D., Rocha, A., Costoya, X., DeCastro, M., & Gómez-Gesteira, M. (2021). Wind energy resource over Europe under CMIP6 future climate projections: what changes from CMIP5 to CMIP6. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2021.111594
Catto, J. L., Ackerley, D., Booth, J. F., Champion, A. J., Colle, B. A., Pfahl, S., Pinto, J. G., Quinting, J. F., & Seiler, C. (2019). The future of midlatitude cyclones. *Current Climate Change Report, 5*(4), 407–420. https://doi.org/10.1007/s40641-019-00149-4
Che, L., Khodayar, M., & Shahidehpour, M. (2014). Only connect: Microgrids for distribution system restoration. *IEEE Power and Energy Magazine, 12*(1), 70–81. https://doi.org/10.1109/MPE.2013.2286317
Chen, H., Wan, Q., Li, F., & Wang, Y. (2013). GARCH in mean type models for wind power forecasting. *IEEE Power and Energy Society General Meeting*. https://doi.org/10.1109/PESMG.2013.6672237
Chen, H., Zhang, J., Tao, Y., & Tan, F. (2019). Asymmetric GARCH type models for asymmetric volatility characteristics analysis and wind power forecasting. *Protection and Control of Modern Power Systems*. https://doi.org/10.1186/s41601-019-0146-0
Chen, L., Li, C., Xin, Z., & Nie, S. (2022). Simulation and risk assessment of power system with cascading faults caused by strong wind weather. *International Journal of Electrical Power and Energy Systems, 143*(52007109), 108462. https://doi.org/10.1016/j.ijepes.2022.108462
Clarke, E. D., Sweeney, C., McDermott, F., Griffin, S., Correia, J. M., Nolan, P., & Cooke, L. (2021). Climate change impacts on wind energy generation in Ireland. *Wind Energy*. https://doi.org/10.1002/we.2673
Cole, W., Greer, D., & Lamb, K. (2020). The potential for using local PV to meet critical loads during hurricanes. *Solar Energy, 205*(Feb), 37–43. https://doi.org/10.1016/j.solener.2020.04.094
Costoya, X., deCastro, M., Carvalho, D., Arguilé-Pérez, B., & Gómez-Gesteira, M. (2022). Combining offshore wind and solar photovoltaic energy to stabilize energy supply under climate change scenarios: A case study on the Western Iberian Peninsula. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2021.112037
Couto, A., Costa, P., & Simões, T. (2021). Identification of extreme wind events using a weather type classification. *Energies*. https://doi.org/10.3390/en14133944
Cronin, J., Anandarajah, G., & Dessens, O. (2018). Climate change impacts on the energy system: A review of trends and gaps. *Climatic Change, 151*(2), 79–93. https://doi.org/10.1007/s10584-018-2265-4
Cronin, P., Ryan, F., & Coughlan, M. (2008). A step-by-step approach. *British Journal of Nursing, 17*(1), 38–43.
Damm, A., Köberl, J., Prettenthaler, F., Rogler, N., & Töglhofer, C. (2017). Impacts of + 2 °C global warming on electricity demand in Europe. *Climate Services, 7*, 12–30. https://doi.org/10.1016/j.cliser.2016.07.001
Daniel, L. O., Sigauke, C., Chibaya, C., & Mbuvha, R. (2020). Short-term wind speed forecasting using statistical and machine learning methods. *Algorithms, 13*(6), 1–30. https://doi.org/10.3390/A13060132
Davy, R., Gnatiuk, N., Pettersson, L., & Bobylev, L. (2018). Climate change impacts on wind energy potential in the European domain with a focus on the Black Sea. *Renewable and Sustainable Energy Reviews, 81*(Jan 2017), 1652–1659. https://doi.org/10.1016/j.rser.2017.05.253
De Caro, F., Carlini, E. M., & Villacci, D. (2019). Flexibility sources for enhancing the resilience of a power grid in the presence of severe weather conditions. *AEIT International Annual Conference AEIT*. https://doi.org/10.23919/AEIT.2019.8893389
Devis, A., Van Lipzig, N. P. M., & Demuzere, M. (2018). Should future wind speed changes be taken into account in wind farm development? *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aabff7
Doe US. (2013). U.S. energy sector vulnerabilities to climate change and extreme weather
Doorman, G. L., Uhlen, K., Kjølle, G. H., & Huse, E. S. (2006). Vulnerability analysis of the Nordic power system. *IEEE Transactions on Power Systems, 21*, 402–410. https://doi.org/10.1109/TPWRS.2005.857849
Dowling, P. (2013). The impact of climate change on the European energy system. *Energy Pol, 60*, 406–417. https://doi.org/10.1016/j.enpol.2013.05.093
Dumas, M., Kc, B., & Cunliff, C.I. (2019). Extreme weather and climate vulnerabilities of the electric grid: A summary of environmental sensitivity quantification methods. *OAK Ridge National Laboratory,* no. ORNL/TM-2019/1252: 27. http://www.osti.gov/scitech/. Accessed 5 Nov 2022.
EDP. 2022. *WindFloat Atalntic.* Retrieved December 14, 2023, from https://www.edp.com/en/innovation/windfloat
Enercon. (2022) WEC features—configuration specific to the site. Retrieved January 10, 2022, from https://www.enercon.de/en/technology/wec-features/
Eriksson, S., Bernhoff, H., & Leijon, M. (2008). Evaluation of different turbine concepts for wind power. *Renewable and Sustainable Energy Reviews, 12*(5), 1419–1434. https://doi.org/10.1016/j.rser.2006.05.017
Escobar, J. J. M., Matamoros, O. M., Padilla, R. T., Reyes, I. L., & Espinosa, H. Q. (2021). A comprehensive review on smart grids: challenges and opportunities. *Sensors, 21*(21), 1–41. https://doi.org/10.3390/s21216978
European Commission. (2020). CORDIS EU research results. Novel wind turbines to withstand exposure to very bad weather. Retrieved October 28, 2022, from https://cordis.europa.eu/article/id/428500-novel-wind-turbines-to-withstand-exposure-to-very-bad-weather
Farahbod, S., Niknam, T., Mohammadi, M., Aghaei, J., & Shojaeiyan, S. (2022). Probabilistic and deterministic wind speed prediction: ensemble statistical deep regression network. *IEEE Access, 10*, 47063–47075. https://doi.org/10.1109/ACCESS.2022.3171610
Fernández-Alvarez, J. C., Costoya, X., Pérez-Alarcón, A., Rahimi, S., Nieto, R., & Gimeno, L. (2023). Dynamic downscaling of wind speed over the North Atlantic Ocean using CMIP6 projections: implications for offshore wind power density. *Energy Reports, 9*, 873–885. https://doi.org/10.1016/j.egyr.2022.12.036
Feron, S., Cordero, R. R., Damiani, A., & Jackson, R. B. (2021). Climate change extremes and photovoltaic power output. *Nature Sustainability, 4*(3), 270–276. https://doi.org/10.1038/s41893-020-00643-w
Fortune. (2021). Turbines are being adapted for extreme weather—but can they handle 'Black Swan' events?. Retrieved October 28, 2022, from https://fortune.com/2021/02/20/wind-turbines-texas-winter-storms-ice-extreme-weather/
Gao, D. W. (2015). Applications of ESS in renewable energy microgrids. *Energy Storage for Sustainable Microgrid*. https://doi.org/10.1016/b978-0-12-803374-6.00002-0
Ghorbani, M. A., Khatibi, R., FazeliFard, M. H., Naghipour, L., & Makarynskyy, O. (2016). Short-term wind speed predictions with machine learning techniques. *Meteorology and Atmospheric Physics, 128*(1), 57–72. https://doi.org/10.1007/s00703-015-0398-9
Ghosh, P., & Mala, De. (2022). A Comprehensive survey of distribution system resilience to extreme weather events: Concept, assessment, and enhancement strategies. *International Journal of Ambient Energy*. https://doi.org/10.1080/01430750.2022.2037460
Gonçalves, A., Liberato, M.L.R., & Nieto, R. (2022). Impacts of extreme weather events on wind energy systems. In *5th International Conference on Energy and Environment: bringing together Engineering and Economics Porto, Portugal 2–3 June 2022. Book of Proceedings*. https://www.webofscience.com/wos/woscc/full-record/WOS:000850447400017. Accessed 10 Nov 2022.
Gonçalves, A., Liberato, M. L. R., & Nieto, R. (2021). Wind energy assessment during high-impact winter storms in Southwestern Europe". *Atmosphere, 12*(4), 1–20. https://doi.org/10.3390/atmos12040509
Gonçalves, A., Marques, M. C., Loureiro, S., Nieto, R., & Liberato, M. L. R. (2023). Disruption risk analysis of the overhead power lines in Portugal. *Energy, 263*(PC), 125583. https://doi.org/10.1016/j.energy.2022.125583
Google Scholar. (2022). Retrieved June 14, 2022, from https://scholar.google.com/
Grant, M. J., & Booth, A. (2009). A typology of reviews: an analysis of 14 review types and associated methodologies. *Health Information and Libraries Journal, 26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Green, B. N., Johnson, C. D., Adams, A. (2006). Writing narrative literature reviews for peer-reviewed journals: secrets of the trade. *Journal of Chiropractic Medicine*, *5*(3), 101–117.
Gündüz, N., Küfeoğlu, S., & Lehtonen, M. (2017). Impacts of natural disasters on swedish electric power policy: A case study. *Sustainability*. https://doi.org/10.3390/su9020230
Guo, J., Feng, T., Cai, Z., Lian, X., & Tang, W. (2020). Vulnerability assessment for power transmission lines under typhoon weather based on a cascading failure state transition diagram. *Energies*. https://doi.org/10.3390/en13143681
Gupta, D., Natarajan, N., & Berlin, M. (2022). Short-term wind speed prediction using hybrid machine learning techniques. *Environmental Science and Pollution Research, 29*(34), 50909–50927. https://doi.org/10.1007/s11356-021-15221-6
Han, T., McCann, G., Mücke, T. A., & Freudenreich, K. (2014). How can wind turbines survive a tropical cyclone? Renew. *Energy, 70*, 3–10. https://doi.org/10.1016/j.renene.2014.02.014
Hewitt, K. (1983). The idea of calamity in a technocratic age. In K. Hewitt (Ed.), *Interpretation of calamity: from the viewpoint of human ecology* (pp. 3–32). Boston: Allen & Unwinn.
Hirsch, A., Yael, P., & Josep, G. (2018). Microgrids: A review of technologies, key drivers, and outstanding issues. *Renewable and Sustainable Energy Reviews, 90*, 402–411.
Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics, 4*(1), 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245
Höltinger, S., Mikovits, C., Schmidt, J., Baumgartner, J., Arheimer, B., Lindström, G., & Wetterlund, E. (2019). The impact of climatic extreme events on the feasibility of fully renewable power systems: a case study for Sweden. *Energy, 178*, 695–713. https://doi.org/10.1016/j.energy.2019.04.128
Hossain, E., Faruque, H. M. R., Sunny, M. S. H., Mohammad, N., & Nawar, N. (2020). A Comprehensive review on energy storage systems: types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects. *Energies, 13*(14), 3651. https://doi.org/10.3390/en13143651
Hossain, E., Roy, S., Mohammad, N., Nawar, N., & Dipta, D. R. (2021). Metrics and enhancement strategies for grid resilience and reliability during natural disasters. *Applied Energy, 290*(Feb), 116709. https://doi.org/10.1016/j.apenergy.2021.116709
Hu, Q., Zhang, R., & Zhou, Y. (2016). Transfer learning for short-term wind speed prediction with deep neural networks. *Renewable Energy, 85*, 83–95. https://doi.org/10.1016/j.renene.2015.06.034
Hueging, H., Haas, R., Born, K., Jacob, D., & Pinto, J. G. (2013). Regional changes in wind energy potential over Europe using regional climate model ensemble projections. *Journal of Applied Meteorology and Climatology, 52*(4), 903–917. https://doi.org/10.1175/JAMC-D-12-086.1
Huggins, R. A. (2016). *Energy storage fundamentals, materials and applications*. Springer. https://doi.org/10.1007/978-3-319-21239-5
Ibrahim, N. A., Alwi, S. R. W. A., Manan, Z. A., Mustaffa, A. A., & Kidam, K. (2022). Risk matrix approach of extreme temperature and precipitation for renewable energy systems in Malaysia. *Energy*. https://doi.org/10.1016/j.energy.2022.124471
ICEWIND. (2022a). Extreme energy solutions. Retrieved October 28, 2022, from https://icewind.is/
ICEWIND. (2022b). THE FREYA CW100. Retrieved October 28, 2022, from https://www.icewindusa.com/freya/
ICEWIND. (2022c). THE FREYA CW100. Retrieved October 28, 2022, from https://www.icewindusa.com/njord/.
IEA. (2021). *Severe power cuts in Texas highlight energy security risks related to extreme weather events*. Retrieved October 10, 2021, from https://www.iea.org/commentaries/severe-power-cuts-in-texas-highlight-energy-security-risks-related-to-extreme-weather-events
IEA. (2022). World Energy Outlook. License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A). IEA, Paris. https://www.iea.org/reports/world-energy-outlook-2022. Accessed 15 May 2023.
IPCC. (2014). Summary for policymakers. In C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, M. Chatterjee, K. L. Ebi, Y. O. Estrada, R. C. Genova, B. Girma, E. S. Kissel, A. N. Levy, S. MacCracken, P. R. Mastrandrea, & L. L. White (Eds.), *Climate Change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 1–32). Cambridge: Cambridge University Press.
IPCC. (2018). Global Warming of 1.5 ℃: An IPCC Special Report on the impacts of global warming of 1.5 ℃ above pre-industrial levels and related global greenhouse gas emission pathways. In P. V. Zhai, H.-O.D. Pörtner Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, & T. Waterfield (Eds.), *The context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty.* Cambridge University Press.
IPCC (Intergovernmental Panel on Climate Change). (2021). Climate Change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FullReport.pdf. Accessed 8 Jan 2023.
IPCC (2022a) The Intergovernmental Panel on Climate Change. Glossary. Retrieved July 11, 2022, from https://www.ipcc-data.org/guidelines/pages/glossary/glossary_e.html
IPCC. (2022b) Climate change—impacts, adaptation, and vulnerability. Summary for policymakers. Retrieved July 16, 2021, from https://report.ipcc.ch/ar6wg2/pdf/IPCC_AR6_WGII_SummaryForPolicymakers.pdf
IRENA. (2019). Future of wind: Deployment, investment, technology, grid integration, and socio-economic aspects (A Global Energy Transformation paper), International Renewable Energy Agency, Abu Dhabi 2019
Jasiūnas, J., Lund, P. D., & Mikkola, J. (2021). Energy system resilience—a review. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2021.111476
Jerez, S., Tobin, I., Vautard, R., Montávez, J. P., López-Romero, J. M., Thais, F., Bartok, B., Christensen, O. B., Colette, A., Déqué, M., & Nikulin, G. (2015). The impact of climate change on photovoltaic power generation in Europe. *Nature Communications*. https://doi.org/10.1038/ncomms10014
Jerez, S., & Trigo, R. M. (2013). Time-scale and extent at which large-scale circulation modes determine the wind and solar potential in the Iberian Peninsula. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/8/4/044035
Jiang, P., Liu, Z., Niu, X., & Zhang, L. (2021). A combined forecasting system based on statistical method, artificial neural networks, and deep learning methods for short-term wind speed forecasting. *Energy, 217*, 119361. https://doi.org/10.1016/j.energy.2020.119361
Jing, R., Wang, X., Zhao, Y., Zhou, Y., Wu, J., & Lin, J. (2021). Planning urban energy systems adapting to extreme weather. *Advances in Applied Energy, 3*(May), 100053. https://doi.org/10.1016/j.adapen.2021.100053
Jufri, F. H., Widiputra, V., & Jung, J. (2019). State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. *Applied Energy, 239*, 1049–1065. https://doi.org/10.1016/j.apenergy.2019.02.017
Karaman, Ö. A. (2023). Prediction of wind power with machine learning models. *Applied Sciences, 13*(20), 11455. https://doi.org/10.3390/app132011455
Karremann, M. K., Liberato, M. L. R., Ordóñez, P., & Pinto, J. G. (2016). Characterization of synoptic conditions and cyclones associated with top ranking potential wind loss events over Iberia. *Atmospheric Science Letters, 17*(6), 354–361. https://doi.org/10.1002/asl.665
Ke, X., Wu, D., Rice, J., Kintner-Meyer, M., & Lu, N. (2016). Quantifying impacts of heat waves on power grid operation. *Applied Energy, 183*, 504–512. https://doi.org/10.1016/j.apenergy.2016.08.188
Khchine, Y. E. L., Sriti, M., & Elyamani, N. E. E. K. (2019). Evaluation of wind energy potential and trends in morocco. *Heliyon, 5*(6), e01830. https://doi.org/10.1016/j.heliyon.2019.e01830
Kim, E., Manuel, L., Curcic, M., Chen, S.S., Phillips, C., & Veers, P. (2016). On the use of coupled wind, wave, and current fields in the simulation of loads on bottom-supported offshore wind turbines during hurricanes. National Renewable Energy Laboratory (NREL). Technical Report NREL/TP-5000-65283. https://www.nrel.gov/docs/fy16osti/65283.pdf. Accessed 30 Oct 2022.
Kiwi Energy. (2019). "Differences Between Onshore & Offshore Wind Energy". Retrieved October 12, 2022, from https://kiwienergy.us/differences-between-onshore-offshore-wind-energy/
Kollar, L., Laszlo, E., & Mishra, R. (2019). Inverse design of wind turbine blade sections for operation under icing conditions. *Energy Conversion and*

Management, 180(Nov 2018), 844–858. https://doi.org/10.1016/j.enconman.2018.11.015

Kyriakides, E., & Polycarpou, M. (2015). *Intelligent monitoring, control, and security of critical infrastructure systems*. Springer.

Lei, M., Shiyan, L., Chuanwen, J., Hongling, L., & Yan, Z. (2009). A review on the forecasting of wind speed and generated power. *Renewable and Sustainable Energy Reviews, 13*(4), 915–920. https://doi.org/10.1016/j.rser.2008.02.002

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., Mcinnes, K., et al. (2014). A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change, 5*, 113–128. https://doi.org/10.1002/wcc.252

Li, J., Ma, X., Liu, C., & Schneider, K. P. (2014). Distribution system restoration with microgrids using spanning tree search. *IEEE Transactions on Power Systems, 29*(6), 3021–3029.

Li, Z., Shahidehpour, M., Aminifar, F., Alabdulwa-hab, A., & Al-Turki, Y. (2017). Networked microgrids for enhancing the power system resilience. *Proceedings of the IEEE, 105*(7), 1289–1310.

Liberato, M.L.R., Santos, J.A., Fernandes, C., & Pinto, J.G. (2015). Future Projections of Offshore Wind Energy Potentials in Portugal Simulated by the Cosmo-Clm Regional Model. *2nd International Conference on Energy and Environment-Bringing Together Engineering and Economics (ICEE)*, (2000), 207–14. http://gateway.webofknowledge.com/gateway/Gateway.cgi?GWVersion=2&SrcAuth=ORCID&SrcApp=OrcidOrg&DestLinkType=FullRecord&DestApp=WOS_CPL&KeyUT=WOS:000379409300028&KeyUID=WOS:000379409300028. Accessed 7 Apr 2023.

Liberato, M. L. R. (2014). The 19 January 2013 windstorm over the North Atlantic: large-scale dynamics and impacts on Iberia. *Weather and Climate Extremes*. https://doi.org/10.1016/j.wace.2014.06.002

Liberato, M. L. R., Montero, I., Gouveia, C., Russo, A., Ramos, A. M., & Trigo, R. M. (2021). Rankings of extreme and widespread dry and wet events in the Iberian Peninsula between 1901 and 2016. *Earth System Dynamics, 12*(1), 197–210. https://doi.org/10.5194/esd-12-197-2021

Liberato, M. L. R., Pinto, J. G., Trigo, I. F., & Trigo, R. M. (2011). Klaus—an exceptional winter storm over northern Iberia and Southern France. *Weather, 66*(12), 330–334. https://doi.org/10.1002/wea.755

Liberato, M. L. R., Pinto, J. G., Trigo, R. M., Ludwig, P., Ordóñez, P., Yuen, D., & Trigo, I. F. (2013). Explosive development of winter storm Xynthia over the subtropical North Atlantic Ocean. *Natural Hazards and Earth System Sciences, 13*(9), 2239–2251. https://doi.org/10.5194/nhess-13-2239-2013

Lin, X., Wang, Z., Ding, S., Zhang, Z., & Li, Z. (2019). A power output and mechanical model of a wind turbine and its control strategy under severe wind conditions. *Journal of Renewable and Sustainable Energy*. https://doi.org/10.1063/1.5088666

Liu, G., Wang, C., Qin, H., Fu, J., & Shen, Q. (2022). A novel hybrid machine learning model for wind speed probabilistic forecasting. *Energies*. https://doi.org/10.3390/en15196942

Liu, H., Erdem, E., & Shi, J. (2011). Comprehensive evaluation of ARMA-GARCH(-M) approaches for modeling the mean and volatility of wind speed. *Applied Energy, 88*(3), 724–732. https://doi.org/10.1016/j.apenergy.2010.09.028

Liu, H., Shi, J., & Qu, X. (2013). Empirical investigation on using wind speed volatility to estimate the operation probability and power output of wind turbines. *Energy Conversion and Management, 67*, 8–17. https://doi.org/10.1016/j.enconman.2012.10.016

Liu, H., Zhao, Y., Gu, C., Ge, S., & Yang, Z. (2021). Adjustable capability of the distributed energy system: definition, framework, and evaluation model. *Energy, 222*, 119674. https://doi.org/10.1016/j.energy.2020.119674

Lledó, L. L., Torralba, V., Soret, A., Ramon, J., & Doblas-Reyes, F. J. (2019). Seasonal forecasts of wind power generation. *Renewable Energy, 143*, 91–100. https://doi.org/10.1016/j.renene.2019.04.135

Machi, L. A., & McEvoy, B. T. (2016). *The literature review: six steps to success* (3rd ed.). Corwin, a SAGE Company.

Madi, E., Pope, K., Huang, W., & Iqbal, T. (2019). A review of integrating ice detection and mitigation for wind turbine blades. *Renewable and Sustainable Energy Reviews, 103*(Nov 2018), 269–281. https://doi.org/10.1016/j.rser.2018.12.019

Mahzarnia, M., Moghaddam, M. P., Baboli, P. T., & Siano, P. (2020). A review of the measures to enhance power systems resilience. *IEEE Systems Journal, 14*(3), 4059–4070. https://doi.org/10.1109/JSYST.2020.2965993

Mancarella, P. (2014). MES (multi-energy systems): An overview of concepts and evaluation models. *Energy, 65*, 1–17. https://doi.org/10.1016/j.energy.2013.10.041

Mann, W.N., Biegel, K., Stauff, N.E., & Dixon, B. (2021). *Electricity Blackouts and Natural Gas Shortages in Texas*. Preliminary Analysis of Texas 2021 Power Outages. United States. https://doi.org/10.2172/1822217

Mar, A., Pereira, P., & Martins, J. F. (2019). A survey on power grid faults and their origins: A contribution to improving power grid resilience. *Energies*. https://doi.org/10.3390/en12244667

Martin, S., Jung, S., & Vanli, A. (2020). Impact of near-future turbine technology on the wind power potential of low wind regions. *Applied Energy, 272*(May), 115251. https://doi.org/10.1016/j.apenergy.2020.115251

Martinez, A., Murphy, L., & Iglesias, G. (2023). Evolution of offshore wind resources in northern Europe under climate change. *Energy, 269*(January), 126655. https://doi.org/10.1016/j.energy.2023.126655

Martínez, D. M., Ebenhack, B. W., & Wagner, T. P. (2019). Electric power sector energy efficiency. *Energy Efficiency*. https://doi.org/10.1016/b978-0-12-812111-5.00005-6

Matko, M., Golobic, M., & Kontic, B. (2017). Reducing risks to electric power infrastructure due to extreme weather events using spatial planning: Case studies from Slovenia. *Util Pol, 44*, 12–24. https://doi.org/10.1016/j.jup.2016.10.007

McMahan, B., & Gerlak, A. K. (2020). Climate risk assessment and cascading impacts: risks and opportunities for an electrical utility in the U.S. Southwest. *Climate Risk Management*. https://doi.org/10.1016/j.crm.2020.100240

McPhillips, L. E., Chang, H., Chester, M. V., Depietri, Y., Friedman, E., Grimm, N. B., et al. (2018). Defining extreme events: A cross-disciplinary review. *Earth's Future, 6*, 441–455. https://doi.org/10.1002/2017EF000686

MidAmerican Energy Company. (2021). *Do wind turbines freeze*?. Retrieved October 28, 2022, from https://www.midamericanenergy.com/articles/turbines-cold-weather-protection

Mikellidou, C. V., Shakou, L. M., Boustras, G., & Dimopoulos, C. (2018). Energy critical infrastructures at risk from climate change: A state-of-the-art review. *Safety Science, 110*(Dec 2017), 110–120. https://doi.org/10.1016/j.ssci.2017.12.022

Modaberi, S. A., Tohidi, S., Zadeh, S. G., & Bolandi, T. G. (2023). A review of power system resilience assessment and enhancement approaches by focusing on wind farms and wind turbines. *IET Renewable Power Generation*. https://doi.org/10.1049/rpg2.12722

Moemken, J., Reyers, M., Feldmann, H., & Pinto, J. G. (2018). Future changes of wind speed and wind energy potentials in EURO-CORDEX ensemble simulations. *Journal of Geophysical Research Atmospheres*. https://doi.org/10.1029/2018JD028473

Mohamed, M. A., Chen, T., Su, W., & Jin, T. (2019). Proactive resilience of power systems against natural disasters: A literature review. *IEEE Access, 7*, 163778–163795. https://doi.org/10.1109/ACCESS.2019.2952362

Najafi, M. R., Zhang, Y., & Martyn, N. (2021). A flood risk assessment framework for interdependent infrastructure systems in coastal environments. *Sustainable Cities and Society, 64*(Mar 2020), 102516. https://doi.org/10.1016/j.scs.2020.102516

National Grid. (2022). *Energy explained. "Onshore vs offshore wind energy: what's the difference?"*. Retrieved October 12, 2022, from https://www.nationalgrid.com/stories/energy-explained/onshore-vs-offshore-wind-energy

Nik, V. M., Perera, A. T. D., & Chen, D. (2021). Towards climate resilient urban energy systems: A review. *National Science Review*. https://doi.org/10.1093/nsr/nwaa134

Nogueira, M., Soares, P. M. M., Tomé, R., & Cardoso, R. M. (2019). High-resolution multi-model projections of onshore wind resources over Portugal under a changing climate. *Theoretical and Applied Climatology, 136*(1–2), 347–362. https://doi.org/10.1007/s00704-018-2495-4

Ocean Winds. (2021). *WindFloat Atlantic Project*. Retrieved December 14, 2023, from https://www.oceanwinds.com/projects/windfloat-atlantic-project/

Omogoye, O. S., Folly, K. A., & Awodele, K. O. (2021). A review of power system predictive failure model for resilience enhancement against hurricane events". *The Journal of Engineering, 11*, 644–652. https://doi.org/10.1049/tje2.12092

Onwuegbuzie, A. J., & Frels, R. (2016). *7 steps to a comprehensive literature review: A multimodal & cultural approach*. SAGE Publications.
Otto, C., Piontek, F., Kalkuhl, M., & Frieler, K. (2020). Event-based models to understand the scale of the impact of extremes. *Nature Energy, 5*(2), 111–114. https://doi.org/10.1038/s41560-020-0562-4
Panteli, M., & Mancarella, P. (2015). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. *Electric Power Systems Research, 127*, 259–270. https://doi.org/10.1016/j.epsr.2015.06.012
Panteli, M., Pickering, C., Wilkinson, S., Dawson, R., & Mancarella, P. (2017). Power system resilience to extreme weather: Fragility modeling, probabilistic impact assessment, and adaptation measures. *IEEE Transactions on Power Systems, 32*, 3747–3757. https://doi.org/10.1109/TPWRS.2016.2641463
Panteli, M., Trakas, D. N., Mancarella, P., & Hatziargyriou, N. D. (2016). Boosting the power grid resilience to extreme weather events using defensive islanding. *IEEE Trans Smart Grid, 7*(6), 2913–2922.
Pautasso, M. (2019). The structure and conduct of a narrative literature review. In M. Shoja, A. Arynchyna, M. Loukas, A. V. D'Antoni, S. M. Buerger, M. Karl, & R. S. Tubbs (Eds.), *A guide to the scientific career* (pp. 299–310). Wiley. https://doi.org/10.1002/9781118907283.ch31
Peduzzi, P. (2019). The disaster risk, global change, and sustainability nexus. *Sustainability, 11*(4), 1–21. https://doi.org/10.3390/su11040957
Perera, A. T. D., Nik, V. M., Chen, D., Scartezzini, J. L., & Hong, T. (2020). Quantifying the impacts of climate change and extreme climate events on energy systems. *Nature Energy, 5*, 150–159. https://doi.org/10.1038/s41560-020-0558-0
Pinto, J. G., Neuhaus, C. P., Leckebusch, G. C., Reyers, M., & Kerschgens, M. (2010). Estimation of wind storm impacts over Western Germany under future climate conditions using a statistical-dynamical downscaling approach. *Tellus A Dynamic Meteorology and Oceanography, 62*, 188–201.
Popular Science. (2021). *Here's how wind turbines stay afloat during storms—The secret to wind turbines' storm hardiness? Oil rig tech—for now*. Retrieved October 28, 2022, from https://www.popsci.com/environment/wind-turbines-during-hurricanes/
Priestley, M. D. K., Dacre, H. F., Shaffrey, L. C., Hodges, K. I., & Pinto, J. G. (2018). The role of serial European windstorm clustering for extreme seasonal losses as determined from multi-centennial simulations of high-resolution global climate model data. *Natural Hazards and Earth Systems Sciences, 18*, 2991–3006.
Pryor, S. C., & Barthelmie, R. J. (2013). Assessing the vulnerability of wind energy to climate change and extreme events. *Climatic Change, 121*(1), 79–91. https://doi.org/10.1007/s10584-013-0889-y
Pryor, S. C., & Barthelmie, R. J. (2010). Climate change impacts on wind energy: A review. *Renewable and Sustainable Energy Reviews, 14*, 430–437. https://doi.org/10.1016/j.rser.2009.07.028
Qazi, S. (2017). Photovoltaics for disaster relief and remote areas. *Standalone photovoltaic (PV) systems for disaster relief and remote areas* (pp. 1–30). https://doi.org/10.1016/b978-0-12-803022-6.00001-0
Rajabzadeh, M., & Kalantar, M. (2022). Enhance the resilience of distribution system against direct and indirect effects of extreme winds using battery energy storage systems. *Sustainable Cities and Society, 76*(Aug 2021), 103486. https://doi.org/10.1016/j.scs.2021.103486
Ravestein, P., van der Schrier, G., Haarsma, R., Scheele, R., & van den Broek, M. (2018). Vulnerability of European intermittent renewable energy supply to climate change and climate variability. *Renewable and Sustainable Energy Reviews, 97*(Oct 2017), 497–508. https://doi.org/10.1016/j.rser.2018.08.057
Reinoso, E., Niño, M., Berny, E., & Inzunza, I. (2020). Wind risk assessment of electric power lines due to hurricane hazard. *Natural Hazards Review, 21*(2), 1–14. https://doi.org/10.1061/(asce)nh.1527-6996.0000363
Reyers, M., Moemken, J., & Pinto, J. G. (2016). Future changes of wind energy potentials over Europe in a large CMIP5 multi-model ensemble. *International Journal of Climatology, 36*, 783–796. https://doi.org/10.1002/joc.4382
Rezaei, S. N., Chouinard, L., Langlois, S., & Legeron, F. (2016). Analysis of the effect of climate change on the reliability of overhead transmission lines. *Sustainable Cities and Society, 27*, 137–144. https://doi.org/10.1016/j.scs.2016.01.007
Roberts, J. F., Champion, A. J., Dawkins, L. C., Hodges, K. I., Shaffrey, L. C., Stephenson, D. B., Stringer, M. A., Thornton, H. E., & Youngman, B. D. (2014). The XWS open access catalogue of extreme European windstorms from 1979 to 2012. *Natural Hazards and Earth System Sciences, 14*(9), 2487–2501. https://doi.org/10.5194/nhess-14-2487-2014
Rocchetta, R., Li, Y. F., & Zio, E. (2015). Risk assessment and risk-cost optimization of distributed power generation systems considering extreme weather conditions. *Reliability Engineering and System Safety, 136*, 47–61. https://doi.org/10.1016/j.ress.2014.11.013
Roga, S., Bardhan, S., Kumar, Y., & Dubey, S. K. (2022). Recent technology and challenges of wind energy generation: A review. *Sustainable Energy Technologies and Assessments, 52*(PC), 102239. https://doi.org/10.1016/j.seta.2022.102239
Rübbelke, D., & Vögele, S. (2011). Impacts of climate change on European critical infrastructures: The case of the power sector. *Environmental Science and Policy, 14*(1), 53–63. https://doi.org/10.1016/j.envsci.2010.10.007
Santos, J. A., Rochinha, C., Liberato, M. L. R., Reyers, M., & Pinto, J. G. (2015). Projected changes in wind energy potentials over Iberia. *Renewable Energy, 75*(2015), 68–80. https://doi.org/10.1016/j.renene.2014.09.026
Schaeffer, R., Szklo, A. S., de Lucena, A. F. P., Borba, B. S. M. C., Nogueira, L. P. P., Fleming, F. P., Troccoli, A., Harrison, M., & Boulahya, M. S. (2012). Energy sector vulnerability to climate change: A review. *Energy, 38*(1), 1–12. https://doi.org/10.1016/j.energy.2011.11.056
Scherb, A., Garrè, L., & Straub, D. (2019). Evaluating component importance and reliability of power transmission networks subject to windstorms: methodology and application to the Nordic Grid. *Reliability Engineering and System Safety, 191*(May 2018), 106517. https://doi.org/10.1016/j.ress.2019.106517
Schweikert, A. E., & Deinert, M. R. (2021). Vulnerability and resilience of power systems infrastructure to natural hazards and climate change. *Wiley Interdisciplinary Reviews: Climate Change, 12*(5), 1–14. https://doi.org/10.1002/wcc.724
Scopus. (2022). Retrieved June 14, 2022, from https://www.scopus.com/home.uri
Shao, C., Shahidehpour, M., Wang, X., Wang, X., & Wang, B. (2017). Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience. *IEEE Transactions on Power Systems, 32*(6), 4418–4429. https://doi.org/10.1109/TPWRS.2017.2672728
Shi, J., Guo, J., & Zheng, S. (2012). Evaluation of hybrid forecasting approaches for wind speed and power generation time series. *Renewable and Sustainable Energy Reviews*, *16*(5): 3471–80. https://doi.org/10.1016/j.rser.2012.02.044.
Shrestha, S., Panchalogaranjan, V., & Moses, P. (2023). The February 2021 U.S. Southwest power crisis. *Electric Power Systems Research*. https://doi.org/10.1016/j.epsr.2023.109124
Siemens Gamesa. (2022). *Tremendous technology: second Siemens Gamesa offshore turbine awarded typhoon-resistant type certificate*. Retrieved January 1, 2022, from https://www.siemensgamesa.com/en-int/newsroom/2021/07/210706-siemens-gamesa-press-release-typhoon-proof
Sims, R., Mercado, P., Krewitt, W., Bhuyan, G., Flynn, D., Holttinen, H., Jannuzzi, G., Khennas, S., Liu, Y., O'Malley, M., Nilsson, L. J., Ogden, J., Ogimoto, K., Outhred, H., Ulleberg, O., & van Hulle, F. (2011). Integration of renewable energy into present and future energy systems. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlomer, & C. von Stechow (Eds.), *IPCC special report on renewable energy sources and climate change mitigation.* Cambridge University Press.
Söderman, J., & Pettersson, F. (2006). Structural and operational optimisation of distributed energy systems. *Applied Thermal Engineering, 26*(13), 1400–1408. https://doi.org/10.1016/j.applthermaleng.2005.05.034
Solaun, K., & Cerda, E. (2019). Climate change impacts on renewable energy generation: A review of quantitative projections. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2019.109415
Somma, M. D., Yan, B., Bianco, N., Graditi, G., Luh, P. B., Mongibello, L., & Naso, V. (2015). Operation optimization of a distributed energy system considering energy costs and exergy efficiency. *Energy Conversion and Management, 103*, 739–751. https://doi.org/10.1016/j.enconman.2015.07.009
Spectra. (2020). *The turbines harness the power of typhoons*. Retrieved October 28, 2022, from https://spectra.mhi.com/the-turbines-that-harness-the-power-of-typhoons

Sperstad, I. B., Kjølle, G. H., & Gjerde, O. (2020). A Comprehensive framework for vulnerability analysis of extraordinary events in power systems. *Reliability Engineering and System Safety, 196*(June 2019), 106788. https://doi.org/10.1016/j.ress.2019.106788

Staffell, I., & Pfenninger, S. (2018). The increasing impact of weather on electricity supply and demand. *Energy, 145*, 65–78. https://doi.org/10.1016/j.energy.2017.12.051

Stojanovic, M., Gonçalves, A., Sorí, R., Vázquez, M., Ramos, A. M., & Nieto, R. (2021). Consecutive extratropical cyclones Daniel, Elsa and Fabien, and their impact on the hydrological cycle of Mainland Portugal. *Water*. https://doi.org/10.3390/w13111476

Stoyanov, D. B., & Nixon, J. D. (2020). Alternative operational strategies for wind turbines in cold climates. *Renewable Energy, 145*, 2694–2706. https://doi.org/10.1016/j.renene.2019.08.023

Tari, N., Sepasian, A. M. S., & Kenari, M. T. (2021). Resilience assessment and improvement of distribution networks against extreme weather events. *International Journal of Electrical Power and Energy Systems*. https://doi.org/10.1016/j.ijepes.2020.106414

Tobin, I., Greuell, W., Jerez, S., Ludwig, F., Vautard, R., van Vliet, M. T. H., & Breón, F. M. (2018). Vulnerabilities and resilience of European power generation to 1.5 °c, 2 °c and 3 °c warming. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/aab211

Tobin, I., Jerez, S., Vautard, R., Thais, F., Van Meijgaard, E., Prein, A., Déqué, M., Kotlarski, S., Maule, C. F., Nikulin, G., & Noël, T. (2016). Climate change impacts on the power generation potential of a European mid-century wind farms scenario. *Environmental Research Letters, 11*(3), 34013. https://doi.org/10.1088/1748-9326/11/3/034013

Tomaszewski, M., & Ruszczak, B. (2013). Analysis of the frequency of occurrence of weather conditions favoring wet snow adhesion and accretion on overhead power lines in Poland. *Cold Regions Science and Technology, 85*, 102–108. https://doi.org/10.1016/j.coldregions.2012.08.007

Trigo, R. M., Pozo-Vázquez, D., Osborn, T. J., Castro-Díez, Y., Gámiz-Fortis, S., & Esteban-Parra, M. J. (2004). North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula. *International Journal of Climatology, 24*(8), 925–944. https://doi.org/10.1002/joc.1048

U.S. Department of Energy. (2018). Office of energy efficiency & renewable energy. Wind turbines in extreme weather: solutions for hurricane resiliency. Retrieved October 28, 2022, from https://www.energy.gov/eere/articles/wind-turbines-extreme-weather-solutions-hurricane-resiliency

U.S. Energy Information Administration (EIA). (2021). *Hurricane Ida caused at least 1.2 million electricity customers to lose power*. https://www.eia.gov/todayinenergy/detail.php?id=49556#:~:text=Hurricane%20Ida%20resulted%20in%20service,and%20Emergency%20Response%20(CESER). Accessed 28 Jan 2023.

van der Wiel, K., Stoop, L. P., van Zuijlen, B. R. H., Blackport, R., van den Broek, M. A., & Selten, F. M. (2019). Meteorological conditions leading to extreme low variable renewable energy production and extreme high energy shortfall. *Renewable and Sustainable Energy Reviews, 111*(May), 261–275. https://doi.org/10.1016/j.rser.2019.04.065

Vestas. (2019). V*estas expands the 4 MW platform to unlock sites with extreme weather conditions*. Retrieved October 28, 2022, from https://www.vestas.com/en/media/company-news/2019/vestas-expands-4-mw-platform-to-unlock-sites-with-extre-c2963231#!NewsView

Vestas. (2020). *MHI Vestas Secures First Firm Order in Japan for Akita Noshiro Offshore Wind Farm Project*. Retrieved October 28, 2022, from https://www.vestas.com/en/media/mwow-press-releases/2020/Akita-Noshiro-Offshore-Wind-Farm-Project

Vestas. (2022). "V136-4.2 MW™". Retrieved January 10, 2022, from https://www.vestas.com/en/products/4-mw-platform/V136-4-2-MW

Vezzoli, C., Ceschin, F., Osanjo, L., M'rithaa, M. K., Moalosi, R., Nakazibwe, V., & Diehl, J. C. (2018). *Green energy and technology—designing sustainable energy for all 2018*. Springer.

Wang, Q., Yu, Z., Ye, R., Lin, Z., & Tang, Y. (2019). An ordered curtailment strategy for offshore wind power under extreme weather conditions considering the resilience of the grid. *IEEE Access, 7*(3), 54824–54833. https://doi.org/10.1109/ACCESS.2019.2911702

Ward, D. M. (2013). The effect of weather on grid systems and the reliability of electricity supply. *Climate Change, 121*, 103–113. https://doi.org/10.1007/s10584-013-0916-z

Waseem, M., & Manshadi, S. D. (2020). Electricity grid resilience amid various natural disasters: challenges and solutions. *Electricity Journal, 33*(10), 106864. https://doi.org/10.1016/j.tej.2020.106864

Watson, P. L., Spaulding, A., Koukoula, M., & Anagnostou, E. (2022). Improved quantitative prediction of power outages caused by extreme weather events. *Weather and Climate Extremes, 37*(June), 100487. https://doi.org/10.1016/j.wace.2022.100487

Watson, S., Moro, A., Reis, V., Baniotopoulos, C., Barth, S., Bartoli, G., Bauer, F., Boelman, E., Bosse, D., Cherubini, A., & Croce, A. (2019). Future emerging technologies in the wind power sector: A European perspective. *Renewable and Sustainable Energy Reviews, 113*(Sept 2018), 109270. https://doi.org/10.1016/j.rser.2019.109270

Webster, P. J., & Jian, J. (2011). Environmental prediction, risk assessment and extreme events: adaptation strategies for the developing world. *Philosophical Transactions of the Royal Society a: Mathematical, Physical and Engineering Sciences, 369*(1956), 4768–4797. https://doi.org/10.1098/rsta.2011.0160

Wenz, L., Levermann, A., & Auffhammer, M. (2017). North-South polarization of european electricity consumption under future warming. *Proceedings of the National Academy of Sciences of the United States of America, 114*(38), E7910–E7918. https://doi.org/10.1073/pnas.1704339114

Whittlesey, R. (2017). Vertical axis wind turbines: Farm and turbine design. In T. M. Letcher (Ed.), *Wind energy engineering: A handbook for onshore and offshore wind turbines*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-809451-8.00010-2

Widera, B. (2020). Renewable hydrogen implementations for combined energy storage, transportation, and stationary applications. *Thermal Science and Engineering Progress, 16*(Sept 2019), 100460. https://doi.org/10.1016/j.tsep.2019.100460

WindEurope. (2023). *Wind energy in Europe 2022 Statistics and the outlook for 2023–2027*. https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcmFpbHMiOnsibWVzc2FnZSI6IkJBaDdDRG9JYTJWNVNTSWhkbVF3TkhBelozQm5NakI3TjJnMWVHbDNhbVZqWmpKb2VEWTNiZ1k2QmtWVU9oQmthWE53YjNOcGRHbHZia2tpQVk1cGJteHBibVU3SUdacGJHVnVZVzFsUFNKWGFXNWtSWFZ5YjNCbElDMGdWMmx1WkNCbGJtVnlaM2tnYVc0Z1JYVnliM0JsSUMwZ01qQXlNaTV3WkdZaU95Qm1hV3hsYm1GdFpTbzlWVlJHTFRnbkoxZHBibVJGZFhKdmNHVWxNakF0SlRJd1YybHVaQ1V5TUdWdVpYSm5lU1V5TUdsdUpUSXdSWFZ5YjNCbEpUSXdMVEl3TWpJdWNHUm1JanQmpzR1ZEb1JZMjl1ZEdWdWRGOTBlWEJsSUU1NJVVlYQndiR2xqWVhScGIyNHZjR1JtQmpzR1ZBPT0iLCJleHAiOiIyMDIzLTA1LTIzVDEwOjIyOjIxLjIzNFoiLCJwdXIiOiJibG9iX2tleSJ9fQ==--c4b098e7d9d0787eae8b7af7e454f26bcfd27a10/WindEurope%20-%20Wind%20energy%20in%20Europe%20-%202022.pdf?content_type=application%2Fpdf&disposition=inline%3B+filename%3D%22WindEurope+-+Wind+energy+in+Europe+-+2022.pdf%22%3B+filename%2A%3DUTF-8%27%27WindEurope%2520-%2520Wind%2520energy%2520in%2520Europe%2520-%25202022.pdf. Accessed 10 Apr 2023.

WindFloat Atlantic. (2022). *The wind farm*. Retrieved December 14, 2023, from https://www.windfloat-atlantic.com/the-wind-farm/#project

WindFloat Atlantic. (2023a). *WindFloat Atlantic Project*. Retrieved December 14, 2023, from https://www.windfloat-atlantic.com/

WindFloat Atlantic. (2023b). *WindFloat Atlantic thrives in the face of a record storm*. Retrieved December 14, 2023, from https://www.windfloat-atlantic.com/windfloat-atlantic-thrives-in-the-face-of-a-record-storm/

Worsnop, R. P., Lundquist, J. K., Bryan, G. H., Damiani, R., & Musial, W. (2017). Gusts and shear within hurricane eyewalls can exceed offshore wind turbine design standards. *Geophysical Research Letters, 44*(12), 6413–6420. https://doi.org/10.1002/2017GL073537

Xinxin, W., Xiaopan, S., Xueyi, A., & Shijia, L. (2023). Short-term wind speed forecasting based on a hybrid model of ICEEMDAN, MFE, LSTM and informer. *PLoS ONE, 18*(9 Sept), 1–27. https://doi.org/10.1371/journal.pone.0289161

Xu, J., Wang, Z., Shen, F., Ouyang, C., & Tu, Y. (2016). Natural disasters and social conflict: A systematic literature review. *International Journal of Disaster Risk Reduction, 17*, 38–48. https://doi.org/10.1016/j.ijdrr.2016.04.001

Yalew, S. G., van Vliet, M. T., Gernaat, D. E., Ludwig, F., Miara, A., Park, C., Byers, E., De Cian, E., Piontek, F., Iyer, G., & Mouratiadou, I. (2020). Impacts of climate change on energy systems in global and regional

scenarios. *Nature Energy, 5*(10), 794–802. https://doi.org/10.1038/s41560-020-0664-z
Zhang, D., Xu, Z., Li, C., Yang, R., Shahidehpour, M., & Wu, Q. (2019). Economic and sustainability promises of wind energy considering the impacts of climate change and vulnerabilities to extreme conditions. *The Electricity Journal, 32*(6), 7–12. https://doi.org/10.1016/j.tej.2019.05.013
Zhou, H., Fang, J., & Huang, M. (2010). "Numerical analysis of application GARCH to short-term wind power forecasting". *IEEE*, 1–6
Zhou, S., Li, Y., Jiang, C., Xiong, Z., Zhang, J., & Wang, L. (2023). Enhancing the resilience of the power system to accommodate the construction of the new power system: Key technologies and challenges. *Frontiers in Energy Research, 11*(Mar 2021), 1–12. https://doi.org/10.3389/fenrg.2023.1256850
Zhou, S., & Yang, P. (2020). Risk management in distributed wind energy implementing analytic hierarchy process. *Renewable Energy, 150*, 616–623. https://doi.org/10.1016/j.renene.2019.12.125
Zimba, S.K., Houane, M.J., & Chikova, A.M. (2020). Impact of tropical cyclone Idai on the Southern African electric power grid. *IEEE PES/IAS PowerAfrica, Power Africa,* no. Idm. https://doi.org/10.1109/PowerAfrica49420.2020.9219944
Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R. M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M. D., & Maraun, D. (2020). A Typology of compound weather and climate events. *Nature Reviews Earth & Environment, 1*(7), 333–347. https://doi.org/10.1038/s43017-020-0060-z

Publisher's Note
Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.