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Power System Resiliency: A Comprehensive Overview from Implementation Aspects and Innovative Concepts

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ABSTRACT

The bulk electrical system, a critical infrastructure for societal functionality, must meet the electricity demands of end-users sustainably, economically, and in compliance with standards. The concept of power system resiliency has gained significant attention as vulnerabilities and potential attacks could lead to substantial losses. This paper distinguishes power system resiliency from reliability through a detailed literature review. It discusses the development of quantitative metrics from operational and infrastructural perspectives to better understand this emerging concept. We categorize the threats into natural disasters and cyber threats, evaluating their impacts on power system components. The integration of smart grid technologies—including demand response, electric vehicles, distributed generation, energy storage systems, and microgrids—is explored to demonstrate how they enhance resilience against external shocks. This review not only offers a comprehensive analysis of load restoration techniques through smart grid practices but also identifies future challenges, such as adapting to increasingly severe climate conditions, advancing cybersecurity measures to match evolving threats, and ensuring the scalability of resilient systems to meet growing energy demands. These challenges highlight the necessity for innovative research and strategic planning to strengthen power systems against a broad spectrum of emerging threats. This work serves as a critical reference for researchers and planners dedicated to enhancing resiliency strategies.

1. Introduction

1.1. Motivation and Background

The bulk power system is one of the most sophisticated architectures, including clusters of substations, transmission and distribution lines, and transformers to serve electrical energy to the end-users. The fundamental aims of this critical infrastructure (CI) are supplying energy efficiently to consumers as economically as possible in an environmental-friendly way [1]. Furthermore, the sustainable operation of the power system is significant to the proper operation of local and public missions [2]. From the banking and finance systems to transportation, CIs such as natural gas, water supply, health care, and emergency services are directly dependent on electrical energy. There are also interlinkages between them, and any outage may rapidly cause wide-ranging disruptions to the other system components [3]. In the modern world, end-users expect that energy demands will be supplied by the providers sustainably with reasonable continuity and high power quality. However, the potential failures in hardware and software systems can cause the loss of services and dysfunction of assets during an extended period. The international design criteria, namely "N-1" and "N-2", have been determined by utility decision-makers for satisfying the power system reliability requirements to tackle the challenges regarding operationalizing the electrical grid [4]. Namely, the power grid has been built and operated to withstand any failure of a single component or simultaneous failures of two components for ensure the continued supply of electricity. From the power system operator's perspective, these types of failures are categorized as low-impact and highly probable events. A wide range of international indices has already been defined by notable organizations for assessing the reliability of engineering systems, which present a generic framework [5]. On the other hand, it is not wrong to say that given the prevalence of high-impact and low-probability (HILP) events in an aging network, the problems experienced by the system operators have evolved into riskier ones. The neglected impacts of weather-related issues have started to be taken

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Nomenclature

CI	Critical Infrastructure
HILP	High-impact Low-probable
DS	Distribution System
TPS	Transmission Power System
DR	Demand Response
MG	Microgrid
ESS	Energy Storage System
DG	Distributed Generation
EV	Electric Vehicles
DSM	Demand Side Management

under study in recent years and have triggered a vast amount of discussions. For example, in the history of the US, Hurricane Sandy was an "N-90" contingency [6]. As a result, stakeholders have agreed that the metrics employed in reliability analyses are no longer adequate. And they can be upgraded as soon as feasible in many ways.

In this sense, the concept of power grid resiliency has recently become a burgeoning area for active research, and the issue of resiliency has been receiving considerable attention. The extraordinary events can increase the number of electrical outages on CIs and affect the millions of end-users in hazard-prone areas [7]. The highly uncertain and infrequent events bring about not only a substantial amount of load losses but also significant direct and indirect economic losses. The striking financial loss estimation comes from the Electric Power Research Institute, Lawrence Berkeley National Laboratory, and the U.S. Department of Energy as nearly $30–$400 billion per annum because of instantaneous interruptions and blackouts [8-10]. The rare but risky blackouts have originated in cascading failures, according to the reported results in [11-13]. Therefore, a growing body of literature has begun to study the concept of power system resiliency, particularly in light of the extraordinary frequency of natural disasters in recent years.

The wide-area electrical outages happened on March 11, 2011, aftermath of the Great East Japan Earthquake, which left approximately 4.4 million households without energy for nine days [14]. Also, over 5 million end-users suffered from electricity disruption during the Hokkaido Eastern Earthquake in 2018 when the power plant shut down after the high-magnitude event [15-17]. Hurricane Sandy [18] and Hurricane Irene [19] were among the most destructive events causing extreme disruptions, i.e., over 8 million and 6.5 million end-users were left without power in 2012 and 2011 in the US, respectively. The recent weather-oriented events leading to partial/localized or whole system collapse and power supply interruption to loads are summarized with related dates and locations in Fig. 1 [20-21].

According to the reports based on historical data, the intensity and duration of electrical disturbances due to HILP events are expected to increase as a direct impact of climate change [22]. One of the researches conducted by North American Electric Reliability Corporation [23] revealed that there was a quickening rate in the weather-related electrical disturbances since 1992, as also shown in Fig. 2.

In this respect, many regulators and research institutions have rigorous endeavors to strengthen the power system, especially in critical conditions. They perform such an activity considering the vulnerabilities of system assets and the negative impact of global warming. Among them, the U.S. Department of Energy has put forward that resilience should be a characteristic of the smart grid and also emphasized the five requirements of a resilient distribution system as follows [24]:

- develop resilience metrics
- enhance system design for resiliency
- improve preparedness and mitigation measures
- improve system response and recovery
- analyze and manage interdependencies."

Moreover, Electric Power Research Institute has undertaken the concept of resiliency from different points of view, i.e., promising technological innovations, tools, and strategies were all explained in detail. Also, it was noted that a comprehensive roadmap should be set

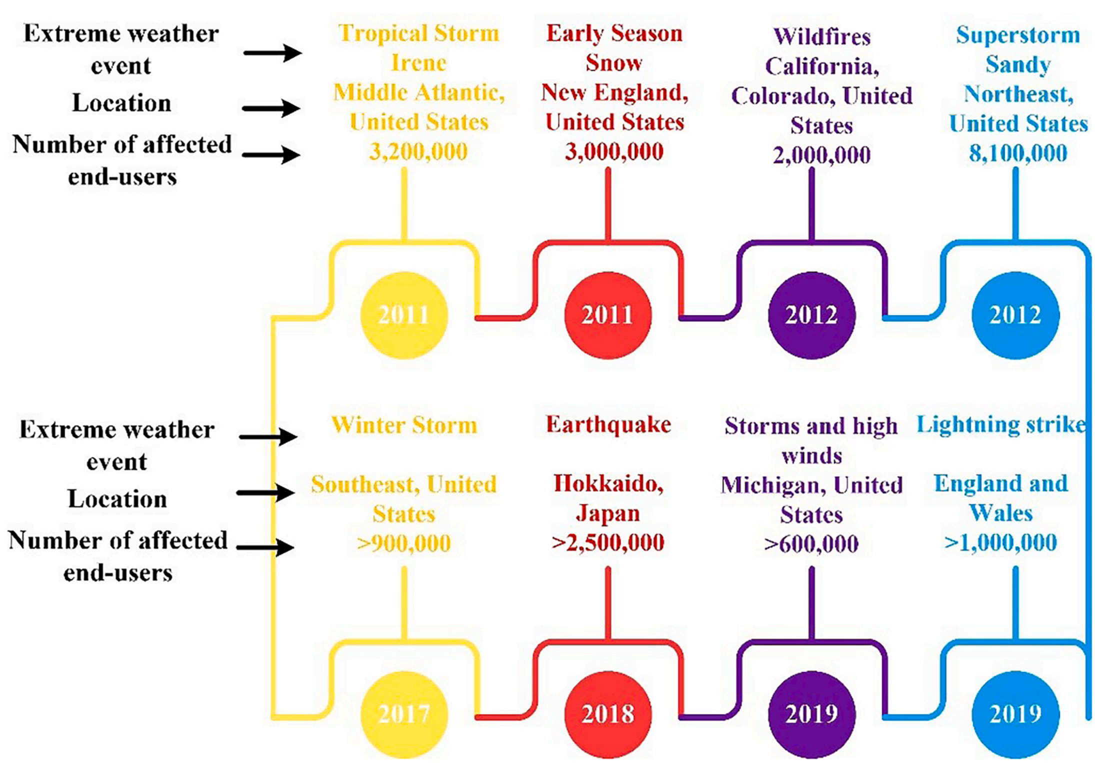

Fig. 1. Major extreme weather events with the relevant data regarding date, location, and affected end-users [20-21].

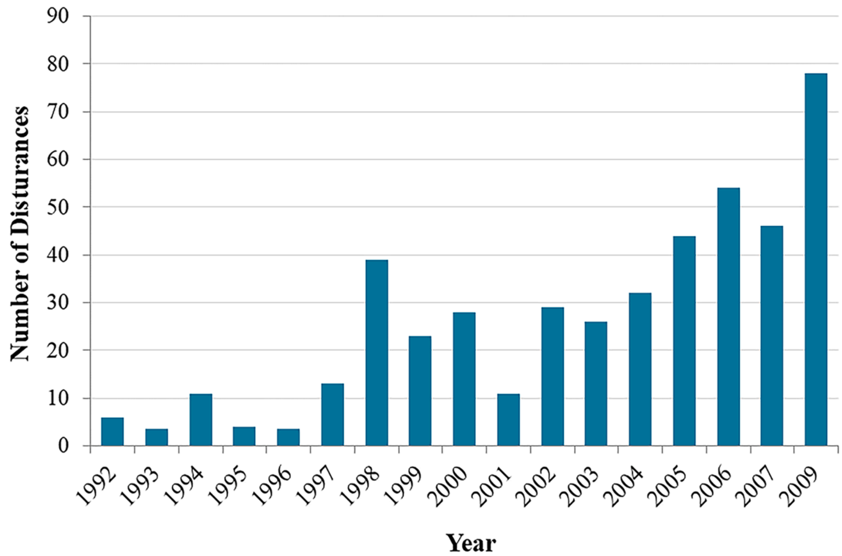

Fig. 2. Weather-related electrical disturbances in North America [23].

out for bridging the gaps in collaborating with other stakeholders on the governmental and non-governmental scale [23]. The reliability analyses, metrics, restoration, and operational tools are insufficient and should be improved while considering the increasing rate of weather-related wide-area electrical disturbances. Therefore, the main aim of this study is to shine new light on the concept of power system resiliency from different perspectives.

1.2. Literature Review

In recent years, there has been an increasing amount of literature on power system resiliency. Among them, the comprehensive review paper in [25] outlined the concept of resiliency by investigating the definitions and methodologies associated with the disciplines and provided a unique framework to define resiliency. The differences between "risk assessment objectives" and resiliency were clarified by categorizing the threats. Lastly, it was intended to pave the way for future studies to incorporate power system resilience measurements. A methodological basis for vulnerability analysis of power transmission and distribution system (DS) was presented in [26] that is complementary to classical reliability and risk analysis. A conceptual framework, a general methodology, and vulnerability indicators were evaluated as the main components of vulnerability analyses in the context of power system resiliency. In [27], the assessment of resilience in power distribution networks against natural disasters was explored through the development of a conceptual model and framework. The impacts of natural disasters on the infrastructure of power networks across several provinces of Iran were examined, illustrating how each damage influenced the network load. Jufri et al. [28] conducted a holistic review study for technically investigating the concept of resiliency from a power system engineering perspective. Also, improving resiliency metrics for comparative studies and strategies for hedging against the HILP events were all compiled. Xu et al. [29] provided a review of the current strategies and technologies aimed at enhancing the resilience of power systems integrated with renewable energy sources. The definitions of resiliency for different disciplines and resiliency assessment techniques were summarized in [30] to assist infrastructure system engineers in increasing the situational awareness of risk analysis. The introduced metric was implemented on the electric power network of a fictional city called Micropolis to quantify its operational performance against hurricanes. The presented paper in [31] leveraged a data-driven two-stage hybrid risk estimation model to predict the intensities of power disruptions and describe the underlying risk factors on electricity supply interruptions from the end-users point of view. Risk model was trained by integrating publicly available data, including historical major power outages from 2000 to 2015, electricity consumption profiles, socio-economic data and climatological observations. Wang et al. [32] reviewed 30 energy infrastructure models associated with the modelling and simulation of gas and power networks under the concept of resiliency. They also proposed five indicators for evaluating a resilience model. The brief research study presented in [33] intended to compile weather-based outages and their impacts on the power system with investigating mitigation strategies. Guo et al. [34] aimed to conduct an in-depth analysis comprising cascading failures in the power system with examining the relevant literature, mitigation strategies, estimation, prevention, and restoration of related failures in a comparable manner. In [35], data from the Web of Science database on the concept of resiliency was reviewed, with definitions, qualitative and quantitative methodologies presented from essentially four discipline viewpoints, namely, economic, organizational, engineering, and social. Ahmadi et al. [36] provided an overview of energy system resilience by addressing technical, mathematical, and analytical issues from the perspective of energy systems subjected to disruptive events. The concept was discussed into five phases, which covered the characterization of resilience, quantitative methods and indicators, and characteristics of energy system modeling. Umunnakwe et al. [37] aimed to classify the presented power system quantitative metrics as distribution-level, transmission-level, and generic system metrics. Axiomatic Design Process was employed to define major specifications of a resilient system and improve criteria for evaluating the discussed metrics using the design parameters. Also, the detailed report presented in [38] classifies the emerging threats to the power system by indicating the definitions of resiliency and reliability. On the other hand, quantitive metrics were reviewed from broader view. From a different perspective, Zamudaa et al. [39] intended to provide a framework to assist utility decision-makers in advancing their planning and preparation strategies based on the best management practices of utilities. These practices included experiences against extraordinary weather-related hazards and long-term chronic risk pertaining to climate change. On the other hand, investment costs and monetizing benefits of resiliency enhancement strategies were compared in [40]. The peer-review study surveyed the literature studies and currently used methods at a high level in this particular time (the increasing density or frequency of weather-related issues). Also, the paper in [41] focused on reviewing various methods and approaches which were proposed for identifying the vulnerabilities of the power system. The adopted models were reviewed considering the random failures, natural disasters, and intentional attacks. The study presented in [42] provided a review of advanced research in transmission network reconfiguration optimization models aimed at enhancing grid resilience. Complex network theory-based indices for identifying critical nodes and lines, along with various optimization approaches for modeling and simulation, were discussed. Additionally, practical challenges and technical issues, such as transient phenomena during network reconfiguration, were addressed in detail.

1.3. Contributions and Paper Organization

The articles reviewed in this study are searched in Google Scholar, Elsevier, and IEEE databases along with the published reports from the U.S. Department of Energy and associated Laboratories. “resilien*”, “vulnerability”, “cyber-threats” and “smart grid” are used as keywords while finding related papers in Google Scholar and Elsevier databases. The scanned articles are classified based on published years, the subject of the methodology, and the journals. Irrelevant studies conducted in the context of resiliency and the studies that did not present original contributions to the literature are disregarded. The examined studies, along with others, revealed that power system resiliency is becoming increasingly important. The main motivation behind this study is to present a comprehensive overview concentrating primarily on the quantitative metrics and incorporating concepts to enhance electrical grid performance concerning several types of both malicious and non-malicious threats. More categorically, the contributions of this study are as follows:

- The research encompasses an assessment of the distinguishing differences between two mutually related but adequately dissimilar concepts, i.e., resiliency and reliability. Accordingly, the technical background of the power system resiliency is detailed comparatively to better understand the philosophy behind this concept.
- The proposed quantitative metrics in the literature are discussed in the assessment methodology in detail to reveal the requirements of the power system from both operational and infrastructural aspects.
- The potential threats and their impacts on special types of power grid equipment by classifying them as natural disasters (earthquake, tropical cyclone and storm, and flood) and cyber-threats are all investigated comprehensively.
- The grid resiliency enhancement strategies that should be improved to mitigate the risks associated with identified threats are presented which include smart and innovative solutions.

The remainder of the paper is organized as follows: Section 2 discusses the concept of power system resiliency in detail by presenting definitions, introduced metrics and assessment techniques in the literature as well as the major differences between resiliency and reliability. A generic framework for the classification of the threats and risk sources and their impact on system performance is presented in Section 3. Section 4 reviews the promising resources for boosting power grid resiliency, existing methodologies, and mixture contextual platforms based on a large number of literature studies. The concluding remarks, discussions, and possible future extensions of the study are presented in Section 5.

2. The Conceptual Framework of Power System Resiliency

2.1. Grid Resiliency vs. Grid Reliability

Designing and operating the electrical power grid encompasses two mutually related and otherwise adequately different concepts: resiliency and reliability. Power system reliability is widely-used concept for quantifying how efficiently a system meets load demand under all potential circumstances. A conceptual definition of grid reliability by IEC’s viewpoint is performing an adequate operation of a system or a device for achieving specified purposes under planned conditions for the intended period [43]. The frequency and duration of the outages due primarily to typical failures are examined within the reliability concept, which is essential to emphasize that related power outages are abnormal but predictable or controllable contingencies. Therefore, it would not be wrong to indicate that reliability protects the system and its components against foreseeable, low-impact high-probability events. They only affect the limited areas during a short time interval, and even the network can stay intact. However, combating extraordinary and less frequent severe situations remains a challenge from the power system operators point of view. Therefore, the concept of resiliency is considered as an effective solution for years in this respect. In response to the distinctions between power system reliability and resiliency, it is evident that while reliability focuses on ensuring consistent electricity delivery under normal conditions, resiliency is concerned with the system’s capacity to anticipate, respond to, and recover swiftly from significant disruptions. Therefore, operational and planning measures for resiliency emphasize investing in adaptive technologies such as grid automation and advanced metering infrastructure, incorporating robust and redundant infrastructures like microgrids, and employing dynamic operational strategies that utilize real-time data analytics for enhanced situational awareness. The main differences between the two concepts are shown in Fig. 3 [44]. The concept of resiliency has important areas in various disciplines, from financial systems, communication infrastructures, transportation systems to community engineering and bulk electrical system. Resilience within a system refers to its capacity to manage disruptions that interfere with its normal functioning [45]. As demonstrated in Fig. 4 [46], the metrics have been improved for increasing situational awareness and withstanding any external perturbations while staying restorable. A broad spectrum of actors involved in power system operation has carried out numerous studies and has presented the definition of power grid resiliency from their perspective to pave the way for implementing the concept appropriately. In practical terms, operators are actively incorporating resiliency measures into system planning and operation, as evidenced by the efforts of TERNA, the Italian transmission system operator. In collaboration with Ricerca sul Sistema Energetico, TERNA has developed a new methodology to assess the resilience of the Italian Transmission Grid, which is structured around three key pillars which are prospective climatological models, vulnerability assessment and contingency analysis approach [47]. Additionally, in the UK, Ofgem (The Office of Gas and Electricity Markets) has mandated that electricity distribution network operators integrate various resilience aspects into their business plans [48]. Moreover, The Australian Energy Regulator has released a brief note addressing the key issues related to the resilience expenditures of distribution system operators [49].

Fig. 5 presents the taxonomy of the resiliency definitions together with the particular properties provided by the abovementioned organizations. While organizations, government, and non-governmental entities have proposed a range of definitions for the term power

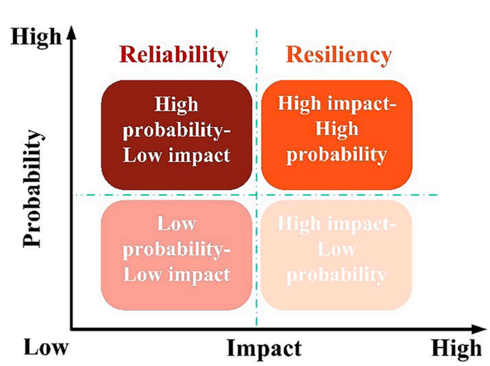

Fig. 3. Threats classification of reliability and resiliency concepts [44].

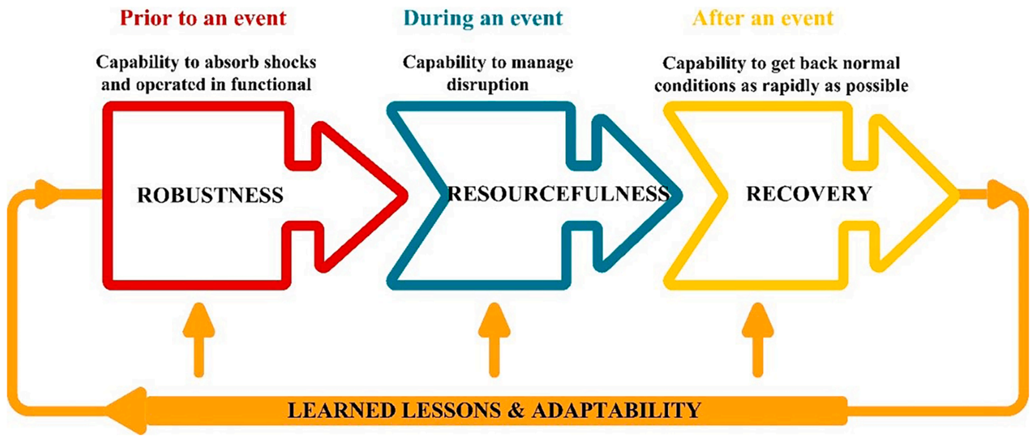

Fig. 4. Boosting power system resiliency when exposed to shocks [46].

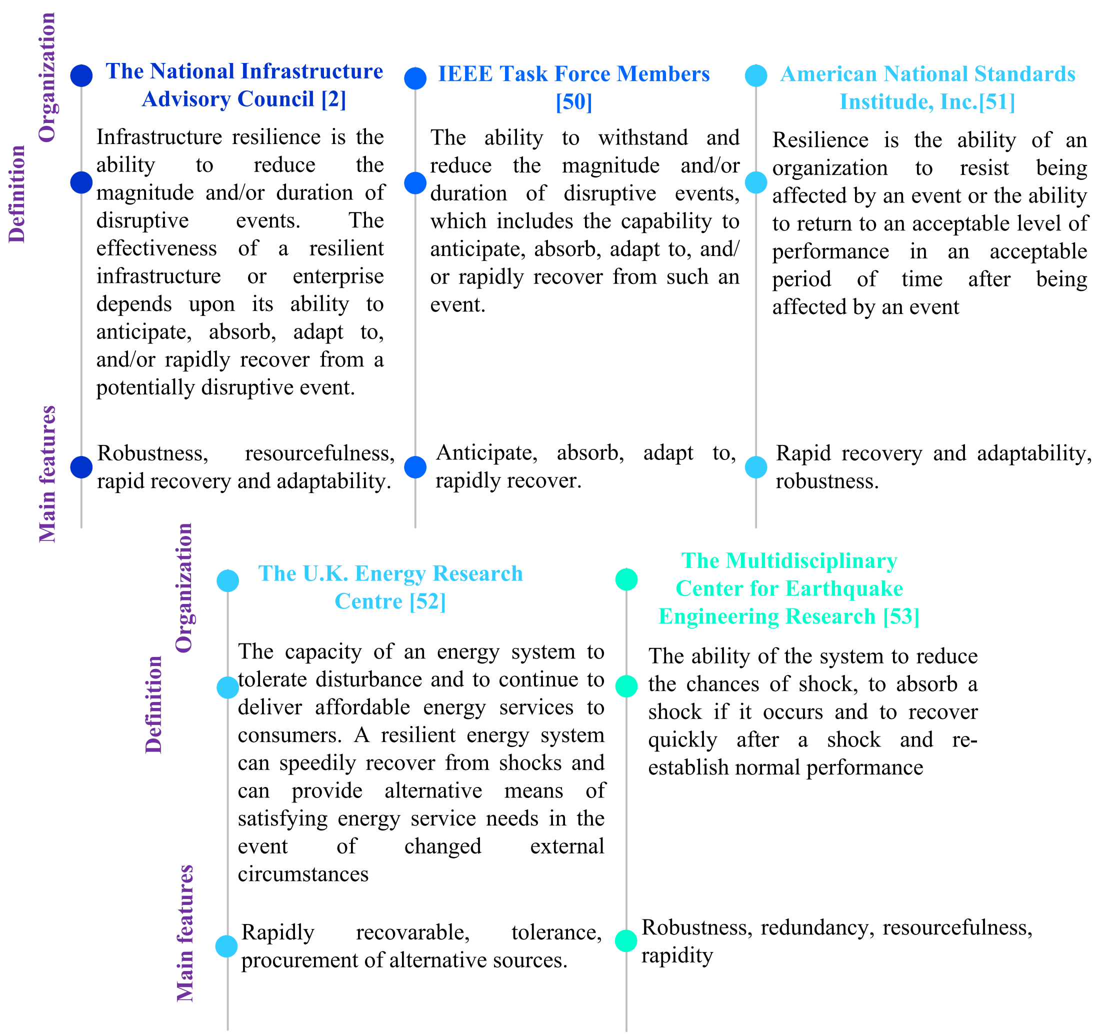

Fig. 5. Taxonomy of the definitions and main features of power system resiliency from different organizations [2,50–53].

system resiliency, this study provides the following definition based on core characteristics of resiliency. "The ability to hedge against initial shocks, potential deliberate attacks, and/or weather-related events as well as adapting to changing conditions to avoid service interruptions; to reduce the time for load restoration as well as drawing a roadmap based on learned lessons and experiences for similar events."

2.2. *Assessment of Power System Resiliency*

This sub-section put the power system resiliency assessment under the microscope to elucidate how the system responds to disruptions.

The commonly-used typical resiliency evaluation curve is illustrated in Fig. 6 following Ref. [54] in which the strategies are divided into five categories from a broader perspective: Pre-event resilient state,

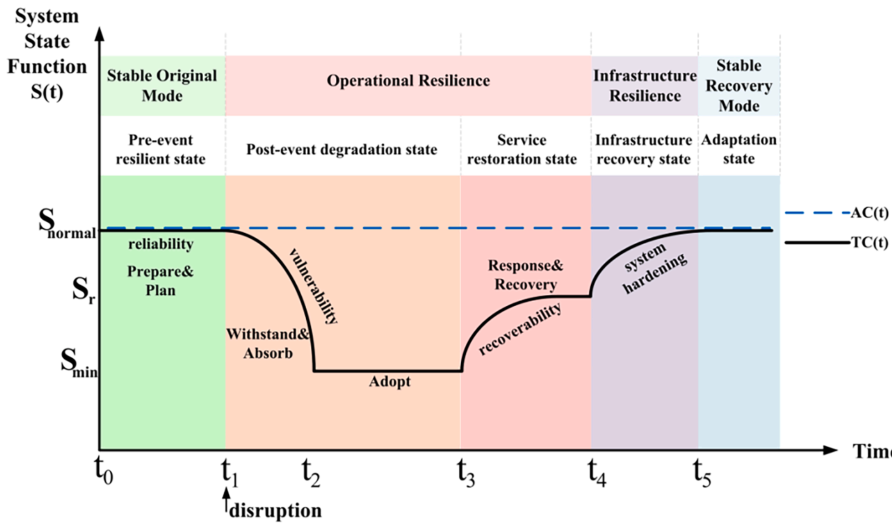

Fig. 6. Typical resiliency evaluation curve in face of event [54].

post-event degradation state, service restoration state, infrastructure recovery state, and adaptation state indicate the time-dependent conditions of the power system.

Pre-event resilient state: Before the occurrence of disruption, the utility grid is deemed to be operated under normal conditions (S_{normal}) from t_0 to t_1, and the characteristics of this phase are preparing and planning to initial shocks. To improve preparedness and minimize the probability of potential damages, system vulnerabilities are to be determined by monitoring the grid performances and status in this planning phase [55].

Post-event degradation state: Following a disruption, the system enters the post-event degradation state and the state function decreases significantly until reaching its lowest level (S_{min}) at time t_2. The system operation experiences a rapid decline based on the severity of the event, and a great number of losses in services occur due to disruptive effects.

Service restoration state: The controls of the grid aim to spring it back to the pre-event resilient state by responding to the changing conditions and deploying numerous restoration strategies. Service restoration state starts and ends at t_3 and t_4, respectively. It is clearly shown that the system state increases S_r the level which is below the normal condition depending strongly on the performance of operational resiliency strategies.

Infrastructure recovery state and adaptation state: With implementing several system hardening strategies, the system state is increased from S_r to S_{normal} between t_4 and t_5. The functionality of the power system can be enhanced with infrastructure recovery actions. In the last state, the transition from abnormal conditions to stable recovery mode is achieved.

There have been introduced fundamental and modified resiliency metrics to quantify the power system resiliency and to investigate which requirements have been provided or not. There have been attempts to provide additional insights about the fundamentals of resiliency, its quantification methods, and assessment metrics in [56]. Also, it is aimed to develop new network performance indices to quantify the resiliency level of power systems for operational and infrastructure integrity against extreme weather-related events in [57]. A comprehensive review has been conducted including quantitative power system resilience metrics in different categories to determine the requirements for resilience quantification [37]. An extended version of the widely-used triangle scheme is introduced as a resiliency trapezoid for defining the different phases of the power system during an event. The new metrics are considered as a benchmark which is called as $\phi\Lambda E\Pi$. The related resiliency indices with their equations are shown in Table 1.

ϕ can be used in order to calculate the number of tripped lines per hours during an event. Λ represents to total amount of power system resilience level reduction when the infrastructure is under stressed or attack. E indicates the time duration that it takes to start service restoration with integrating several sources after the major disaster. The number of retrieved lines per hour between service restoration state and infrastructure recovery state is indicated as Π. Power system resilience is quantified with R_t based on the areas between two curves within the starting and ending periods of an event. Performance loss as well as the degradation level of power system resilience are measured by the expression *Loss* and *VI*. When *VI* equals to 1, it shows complete degraded condition while it becomes 0, it is perfect condition for resiliency.

When system enters the service restoration state at time t_3, the several restoration actions (back-up generation, traditional and smart solutions) are deployed to enhance grid resiliency. To quantify the capability, the normalized restoration efficiency index is presented. In

Table 1
Resiliency indices with their mathematical formulations.

Reference	Power system resiliency index	Equation
[57]	ϕ : The number of tripped lines per hour during an event	$\phi = \frac{S_{min} - S_{normal}}{t_2 - t_1}$
	Λ : The total amount of power system resiliency level reduction	$\Lambda = S_{min} - S_{normal}$
	E : The time duration that it takes to start service restoration	$E = t_3 - t_2$
	Π : The number of retrieved lines per hour	$\Pi = \frac{S_{normal} - S_{min}}{t_5 - t_3}$
[58]	R_t : Power system resiliency	$R_t = \int_{t_1}^{t_5} [TC(t) - AC(t)]dt$
[59]	*Loss* : Performance loss	$Loss = \frac{S_{normal} - S_{min}}{S_{min}}$
[60]	*VI* : Vulnerability index	$VI = \frac{S_{normal} - S_{min}}{S_{normal}}$
	DI : Normalized degradation index	$DI = \frac{\int_{t_1}^{t_2} (S_{normal} - S(t))dt}{S_{normal}(t_2 - t_1)}$
	REI : The normalized restoration efficiency index	$REI = \frac{\int_{t_3}^{t_4} (S(t) - S_{min})dt}{(S_{normal} - S_{min})(t_4 - t_3)}$
[30]	R_{Gc} : The grid capacity resiliency index	$R_{Gc} = \frac{S(t_2)}{S(t_1)} \times \frac{S(t_5)}{S(t_1)} \times S_p$
	S_p : The recovery speed index	$S_p = (t_2 - t_1)/(t_5 - t_1),\ t_5 \geq t_2$
[61]	*LRI* : Lost Revenue Impact	$LRI = \sum_t \sum_j Q_j\ (PLN_j - PLR_{j,t}) \times D_t$

order to obtaine the normalized the damaged and restored states of the system to its stable original mode, R_{Gc} is presented in [30]. The proposed grid capacity resilience index shows the absorptive, restorative and adaptive capabilities of power system. $S(t_1)$, $S(t_2)$, $S(t_5)$ denote the system states which are normal, damaged and restored conditions, respectively. The recovery speed index and the economic index of utility's lost revenue can be calculated by S_p and LRI.

3. Threats to Power System Stability

The bulk grid, which is spread over wide areas, is threatened by various events. It is of utmost importance to perform a comprehensive threat categorization for utility decision-makers to improve resiliency-driven strategies against the greatest challenge of modern network. Threats depend strongly on the location of the power system, i.e., the geographic and political region that causes unplanned outages in more than one instrument which is contingency [62]. Threats to the power system can be divided into two main categories: malicious and non-malicious. In general, natural disasters, accidental threats, and other threats are catalogued as non-malicious threats; while cyber-attack, terrorism, vandalism are evaluated in the malicious threats category [63].

3.1. Impacts of Natural Disasters and Extreme Weather Events

Earthquakes, floods, hurricanes, tropical cyclones, windstorms, and ice storms are one of the most hazardous events that can be classified into two main categories as shown in Fig. 7 [64].

3.1.1. Earthquakes: Risks and Responses

An earthquake is a natural phenomenon that can cause a series of vibrations and a sudden shake of the ground resulting from the waves moving on and below the Earth's surface [65]. There is a vast amount of vulnerable equipment in the power system that can be damaged following an earthquake. And it takes a long-time to be repaired after the breakdowns ranging from a few days to weeks [66]. Table 2 comprises the potential impacts of an earthquake on the power system components in detail.

Much of the current literature on resiliency pays particular attention to investigating earthquake-based destructions and improving mitigation strategies. The model intended to study the resiliency level of urban power DS by considering the interdependency between the buildings and electrical infrastructure system based on component fragility curves. Energy-not-supplied was used to evaluate the obtained results. Also, a new index was introduced for comparing resiliency performances of the networks [69]. The plausible hazards and cascading failures on power systems due to seismic events and intentional disturbances were investigated by Chang and Wub [70] by employing the MSR method. The stability and reliability level of 118-bus high voltage transmission power system (TPS) in Hainan, China were determined. Lagos et al. [71] developed a hierarchical approach-based resiliency enhancing framework for identifying investment needs during the occurrence of any natural disaster events and distinguishing between reliability needs. Also, it was aimed to evaluate the improvements of resiliency levels related to investment propositions using the OvS approach.

A new community resiliency index based on fragility curves, repair cost, and repair time functions for especially housing system after an earthquake was developed in [72]. This metric can quantify the resiliency level of communities. Based on the results, effective mitigation techniques can be improved and appropriate disaster management plans can be scheduled. It is important to highlight that the developed index was based on post-earthquake reconstruction data [72]. Similarly, the study presented in [73] introducing a new indicator methodology to evaluate the seismic resiliency particularly in urban areas against the hazards of an earthquake. From different points of view, a

Table 2
The potential impacts of earthquake event on bulk electrical system equipment and areas.

Ref.	Equipment or Place	Explanation
[66]	Switchyards	The instruments are made up of ceramic columns for insulation and they can break off in the event of a large earthquake.
	Transmission Towers	They can collapse and sustain significant damage depending on the magnitude of ground motion.
[67]	Overhead Lines	Poles shaking in opposite directions may cause partial or complete damage to overhead lines.
[68]	Underground Cables	Seismic events may cause ground liquefaction, which could damage underground cables.

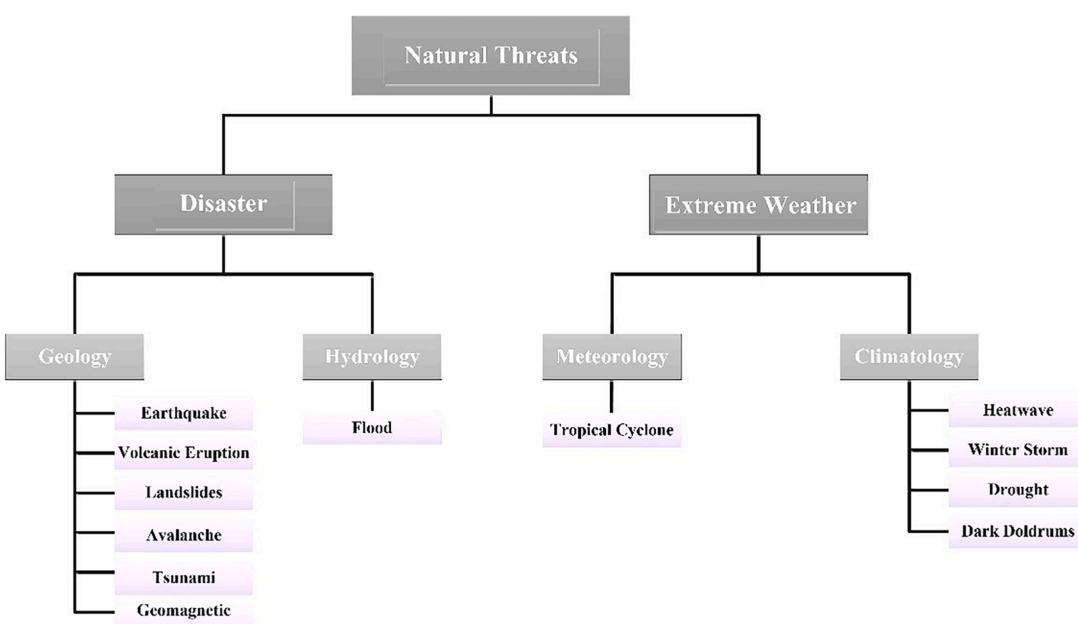

Fig. 7. Classification of natural disasters [64].

transdisciplinary project was carried out by the teams from China, the UK, and the US to create an earthquake scenario for Weinan and Shaanxi addressing the need for preparedness strategy in case of an extreme event and investigating the government-identified gaps between top-down policies [74]. On the other hand, the seismic vulnerabilities of the buildings were taken under study in [75] for urban areas that have important impacts on paths in terms of supplying first aid actions. The algorithm was tested on Italian historic centers and the methodology was based on processing satellite images and photographic documentation in this post-earthquake study [75]. Same as [75], there have been targeted to investigate the transportation system performance in [76] considering destructive impacts of extreme weather events such as earthquakes. A decision-making approach was improved as a solution by processing data related to the transportation system in post-disaster phase to achieve successful emergency management operation.

3.1.2. Tropical Cyclones and Storms: Challenges and Mitigations

Tropical cyclones are called by different names depending on where they occur. They are known as "hurricanes" in North America and the Caribbean while "cyclones" and "typhoons" are used for describing this event in the Indian Ocean and in Southeast Asia, respectively [77]. The bulk power grid is threatened by typical tropical cyclones and storms that can cause huge amounts of damage in several vulnerable parts of the network particularly transmission and local DSs [64]. It is well-known that hurricanes and storms are one of the main reasons for wide-area and prolonged electrical outages. The operation of countless infrastructure systems can be affected adversely ranging from financial transactions to heating, security systems, water distribution, and business operations, and other services [78]. Violently high-speed winds and/or airborne debris may cause transmission lines to be downed and physical damage in distribution poles may occur [79].

Ouyang and Dueñas-Osorio [3] provided a probabilistic modeling framework that included sub-models such as component fragility models, system restoration models, and hurricane hazard models to quantify the multi-dimensional hurricane resiliency of power systems. Economic losses can be estimated and the network's resiliency level can be evaluated thanks to the model. Ouyang et al. [53] presented a multi-stage resiliency assessment approach which was evaluated on TPS in the U.S. under random and hurricane threats, intending to quantify the effectiveness of resiliency enhancement strategies versus the original grid model. To emphasize the performance response process of a CI system, the stages were separated into three categories: reflecting system resistant, absorptive, and restorative capacities. The study in [80] intended to perform an empirical assessment on the resilience of the U.S. power grid through integrating reliability information of utility systems obtained from The U.S. Department of Energy. The capability of resisting first rare shocks was accepted as an indicator and trend tests were conducted based on the disruptions of eight North American Electric Reliability Corporation regions.

To withstand hurricane events in the distribution network, a pre-event repair team placement model based on the Monte Carlo simulation technique and component fragility curves was presented in [81] using the hurricane speed. The best location for the operational crews and vehicles was determined before the event considering distribution companies' assets subject to the objective function. Also, Arab et al. [82] proposed an architecture addressing the impact of hurricanes on power system operation. Pre-hurricane and post-hurricane models were developed to manage the crews and schedule the resources to restore the system before and after the event, respectively. Minimizing the restoration cost and maximizing social welfare were the main aims in MILP-based formulation. In the context of proactive preparedness to deal with emergency conditions, an AC security-constrained optimal power flow-based risk-averse generation dispatch methodology for boosting TPS resiliency was presented in [83] in face of a hurricane event. The power system operators have been aided in re-dispatching the generating units in a proactive manner when experiencing upcoming events, with the goal of reducing the likelihood of future failures, thanks to the developed model. Hughes et al. [84] proposed a damage modeling framework for overhead distribution lines considering the various uncertainties regarding several economic parameters based on Monte Carlo simulation. The cost-effectiveness of the grid hardening strategies imposed on a hurricane, namely the historical data of Hurricane Sandy, was analyzed in detail.

To characterize the potential impacts of hurricane events upon TPS, damage predictions and topological assessment models were integrated into the new proposed methodology in [85]. The failure probabilities of distribution and TPS assets were considered in the context of the component fragility curve. Panteli et al. [86] developed a novel risk-based defensive islanding algorithm to investigate the cascading effects on TPS, especially at HILP events. Also, it was aimed to evaluate the resiliency level of TPS components against windstorms by considering the fragility curves and minimizing load shedding. To determine the resiliency factors i.e. lost power generating capacity and restoration cost, fragility curve-based models were developed in [87] for each TPS component in case of hurricane wind damage event. Synthetic grid data were integrated into the Energy Reliability Council of Texas electrical grid and Hurricanes Rita, Ike, and Harvey were used. The goal of the research presented in [88] was to provide a risk-based approach for planning resilient DSs exposed to severe windstorms. Various resilient network plans were developed to minimize the financial risks of handling the uncertainties of input parameters. These parameters were storm duration and its annual occurrence rate, maximum wind speed, the fragility of network equipment, repairment duration as well as forecasted load, and production from renewable units.

There have been great interests in the literature to investigate the resiliency of interconnected CIs. For example, an innovative two-stage stochastic optimization model was developed in [89] to reduce the water DS dependency on power network failures after hurricane events with the objectives of maximizing social welfare and the accessibility period of load and water in the shortest possible time after a disruption. Ilbeigi [90] focused on developing a quantitive analysis for determining abnormal patterns via monitoring the closeness centrality of the transportation network statistically processing of taxi GPS data. The proposed scheme was implemented in the New York transportation system in case of Hurricane Sandy by calculating the required time to restoration. The work in [91] emphasized the need for resiliency enhancement of power-traffic networks. The Authors proposed a bi-level, stochastic, and simulation-based decision-making model for improving mitigating strategies by prioritizing the required repair resources. Maximizing the expected resiliency improvement of this coupled structure was determined as an objective function.

3.1.3. Floods and Climatic Issues

The flooding risks and violent consequences are projected to increase in forthcoming years stemming from atmospheric warming. Flooding, an overflowing of a vast amount of water far beyond its normal capacity on a land-covered scale, is leading to plausible problems in power systems and other interconnected structures [87]. Unlike tropical cyclones, heavy rainfalls and floods are deemed not to pose a danger for overhead transmission lines but equipment located in basements, and/or ground floor levels are threatened by flooding [92]. The most vulnerable critical components are substations, underground distribution lines, control centers, and service panels [93]. These elements could malfunction when exposed to water seepage even if for a short time. Furthermore, if critical components are submerged, permanent damage to the generating equipment is likely to occur [65].

Pant et al. [94] focused on developing an integrated framework including hazard estimation, network estimation, and infrastructure failure assessment steps for quantifying flood impact on CIs for further resiliency planning. The interdependent assets were modeled through spatial network models; power generation facilities and substations were represented by nodes while edges were used for overhead lines and underground cables in the electricity network. To boost the integrated water and electricity DS resiliency in case of hurricane and flood events, and an efficient interaction approach was presented in [95] for restoring/recovering damaged components by providing power supply between multiple-MGs and distributed power system operator. The impacts of floods and hurricanes with demand response (DR) and energy storage system (ESS) were all considered under different case studies. Sánchez-Muñoz et al. [96] attempted to develop a novel methodology to evaluate the hazards and potential consequences of the flood event in the electrical sector particularly in Barcelona and Bristol cities. A probabilistic approach-based analysis was performed in this impact assessment tool to determine the most critical locations after an adverse event which would assist to implement adaptation measures effectively. The formalization of the resiliency assessment and enhancement measures based on a multi-phase approach for electrical power systems in the case of the HILP was presented in [97] in detail. The first phase was identified as threat characterization and the magnitude, event occurrence probability, and spatiotemporal hazard profile were aimed to be modeled. The most vulnerable assets were identified and modeled based on the fragility curve concept in the second phase of this architecture. The performance analysis of the power system was performed in the third phase while the restoration process was considered in the fourth phase, respectively. From the other point of view, there has been an attempt to conduct a preliminary study for revealing whether social media data can be utilized in modelling and understanding the infrastructure resiliency in [98]. The techniques of geotagging and text mining have been utilized by extracting Tweets produced by the habitants of Chennai during the flood in 2015 for determining the location, defects, and failure intensities of infrastructure during an event. On the other hand, it is also possible to increase the resiliency of the power system by integrating several strategies that can be realized in pre-event phases. Although the electricity infrastructure of Seattle City Light was not designed to withstand high-intensity rainfall, flooding, or higher summer temperatures, it can adapt to resist any new threats [99].

Besides earthquakes, hurricanes, storms, and flooding events; heatwaves, droughts, wildfires and other climatic issues have great impacts on the power system that all threaten the components in the power sector, tremendously. Even though the extremely increasing temperature after exposure to heat waves and droughts cannot directly lead to destructive effects on the assets, these make it highly possible to reduce transmission line capacity and efficiency as well as increasing the power losses and line sagging. Due to rising temperatures, the operating ratings and limitations of the elements are likely to be derated, and they will serve lower power than their capacity. Moreover, the energy consumption of the cooling/air conditioning systems has become higher on the demand side [100]. To assess the power system resiliency degradation in face of extreme heatwaves and drought events, a modeling and optimization framework for power system planning was presented in [101]. Piece-wise linear models were used for modeling the changing conditions on power generation system outputs and system loads by linearizing the non-linear formulation. The algorithm was tested on the southern French geographical area with minimizing the total discounted costs over the planning horizon. Furthermore, there have been expectations that the frequency of wildfires will increase due to climate change and will contribute to catastrophic consequences in the power grid. In [102], a stochastic-programming-based approach was proposed to increase DS resiliency to wildfires and high temperatures to minimize the expected social cost. The dynamic line rating of overhead lines has been affected by wildfires and their current flowing capacity is changing. Also, Mohagheghi and Rebennack [103] focused on developing a two-stage, convex mixed-integer quadratically constrained programming formulation for proactive system dispatch of DS exposed particularly to wildfires. The transmission capacity of overhead lines was assumed to be reduced during an event and weather-related issues were modeled based on this. The critical loads were to be served in emergency conditions through distributed generation (DG) units, several DR strategies, MG integration and islanded mode of operation. From different points of view, Verdelho et al. [104] developed a risk assessment technique to prevent damages due to falling trees and forest fires. Thanks to the model, the resiliency level of the high voltage to medium voltage overhead lines operated by the Portuguese DS operator was increased. The data were processed which was obtained through Laser Imaging Detection and Ranging and High Definition camera. Table 3 encompasses the specialized literature in the proposed research area by comprehensively comparing them.

3.2. *Cyber Threats: Identifying Vulnerabilities and Strategies*

New devices have been highly integrated into the electrical grid ranging from phasor measurement units and smart meters to Internet of Things nodes to distributed control systems with programmable logic controllers and others [105]. Thanks to the modernized applications, the system operators can monitor the main equipments, sending and receiving signals from countless distributed end-user points, efficiently performing real-time control. Two-way communication between parties has also presented additional functionalities and opportunities in achieving different targets such as improving power system resiliency, operational efficiency, and decreasing costs [106]. However, there is a growing concern about security and privacy issues which creates critical challenges due primarily to the intrinsic weakness of communication technology. The smart grid is more vulnerable to sophisticated cyber-attacks due to the collection and processing of large volumes of data over the Internet, which may result in undesirable consequences in power systems such as blackouts and invasions of end-user privacy. Therefore, the rapidly evolving and expanding cybersecurity threats have been taken under study by the academic community, government, and industry stakeholders to protect the smart grid from prolonging disruptions to guarantee the resiliency needs of system operation. Cyber threats can be classified under three main headings based on smart grid security objectives which are confidentiality, integrity, and availability. Confidentiality attacks attempt to steal information such as power usage of customers by unauthorized users via violating personal privacy and security [107]. Integrity attacks target altering the content of original data deliberately as well as reordering and illegally delaying the bunch of messages [108]. The deliberate attacks are a set of actions that require long time planning, substantial resources, and an organized expert team for performing damaging actions, intentionally [109]. Besides, availability attacks, namely denial of service attacks, aim to block and delay the data transmission via destabilizing authorized access. As a consequence, the disruption in data transfer potentially emerges invading one of the most important cybersecurity necessities in the smart grid [110]. Breaking down the confidentiality, availability, and/or integrity of the communication system can lead to many serious results such as a great number of financial losses, national security deficits, and destruction of the infrastructure. Since smart grid contains complex architectures including critical devices, it is a very attractive target for attackers. For instance, after an attack on electrical devices, the supply and demand balance in real time could be disrupted by falsifying the data created by the appliances [111]. Therefore, effective countermeasures should be considered in detail against the known vulnerabilities. In this context, cryptography is evaluated as a solution that plays certainly a key role in terms of enhancing the integrity and confidentiality in smart grid [108]. Data encryption, namely primary cryptographic technique, decreases replay and eavesdropping attacks substantially [112]. Also, authentication, risk assessment, data privacy, anonymity, sandboxing, secure software updates, single-use passwords are cybersecurity precautions. On the other hand, electronic appliances that have lightweight cryptographic capabilities contribute to increasing secure and resilient smart grid applications. Fig. 8 encompasses several attacks on the power system in different regions since 2001 [113].

The survey paper presented in [114] aimed to address cyber security issues in the operation of smart cities from the perspective of

Table 3
The taxonomy of the specialized literature in the proposed research area.

			Implementation Level			
Ref.	**Event**	**Method**	**Dist.**	**Trans.**	**Integrated**	**Test System**
[3]	Tropical Cyclone	Probabilistic model		✔		Harris County, Texas, US
[53]	Tropical Cyclone	Multi-stage resiliency assessment approach		✔		TPS in Harris Country, Texas, US.
[69]	Earthquake	Monte Carlo simulation-based similarities design method and the density design method	✔			Large-scale virtual city in Ideal City.
[70]	Earthquake	MSR method		✔		118-bus high voltage TPS in Hainan, China.
[81]	Tropical Cyclone	Monte Carlo simulation technique, component fragility curves, heuristic algorithm	✔			Real distribution network in Iran including 81-buses.
[82]	Tropical Cyclone	Mixed integer linear programing model	✔	✔		
[83]	Tropical Cyclone	AC security-constrained optimal power flow based risk-averse generation dispatch methodology		✔		IEEE 118-bus test system.
[85]	Tropical Cyclone	Damage predictions and topological assessment models and monte Carlo simulation		✔		Bexar, Cameron, and Harris in the US.
[86]	Windstorm	Sequential Monte Carlo simulation		✔		Great Britain TPS
[89]	Tropical Cyclone	Two-stage stochastic optimization model			✔	Integrated water-electrical grid with modifying IEEE 33-bus radial DS.
[91]	Tropical Cyclone	Bi-level, stochastic model			✔	Traffic-electric power system in Galveston, Texas.
[96]	Flood	A probabilistic approach-based analysis				Barcelona and Bristol cities
[97]	Windstorms and Floods	Fragility curve concept, sequential Monte Carlo-based simulation		✔		Great Britain's power network to
[101]	Extreme Heat Waves and Drought	Non-linear formulation was linearized by a piece-wise linear approximation	✔			Southern French geographical area
[102]	Wildfires	Mixed integer problem with quadratic constraints model	✔			IEEE 33-bus DS
[103]	Wildfires	Convex mixed-integer quadratically constrained programming model	✔			IEEE 123-bus test DS
[104]	Falling Tress and Forest Fires	Risk assessment technique	✔	✔		The area operated by Portuguese DS operator

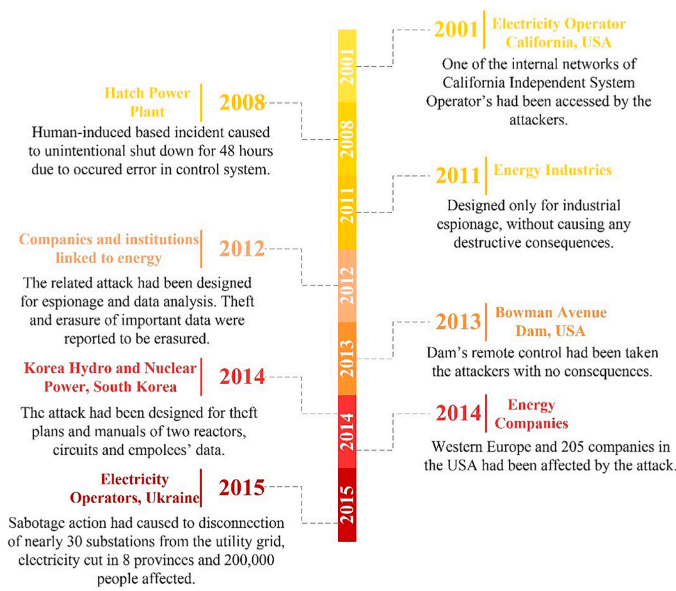

Fig. 8. Cyber-attacks on energy systems from 2001 to 2015 [113].

policymakers and technical aspects while identifying the mitigation methods for certain vulnerabilities. Venkataramanan et al. [115] improved a tool for investigating the impacts of cyber-attacks on the MG's resiliency called CyPhyR which is useful for operators and planning engineers. The formulation was created based on the graph theory indices and cyber-power system characteristics. To increase the situational awareness of power system operators against cyber-attacks with understanding vulnerabilities in a device level, the study presented in [116] was conducted with developing a new cyber-physical resiliency metric.

To address the need for withstanding coordinated cyber-physical attacks particularly on intruding the communication network of protection relays, a tri-level optimization-based algorithm was formulated in [117] to improve optimal defending strategy against certain attack scenarios. In the lower level, the system operator aimed to minimize unserved energy. The behavior of the attacker was formulated in the middle level for maximizing unserved energy. And, the optimal defending strategy improved by the planner was taken under study in the upper level. To hedge against cyber-physical attacks of the smart power systems, a game-theoretic framework based on static and dynamic attacker-defender model was proposed in [118]. From the attacker's perspective, maximizing the load losses was the main objective while the defender resists these activities and protects the critical substations developing resiliency-enhancing strategies. Similarly, Lin and Bie [119] evaluated the resiliency of smart DS from the aspects of combined hardening and operational restoration measures and proposed a tri-level defender-attacker-defender model. It was intended to develop the best hardening strategy in the face of any malicious attacks. An effective strategy was presented in [120] that intentional islanding of a TPS was considered from two aspects. Time and scheme for preventing catastrophic blackouts ensure secure operation of the electrical grid and boost its resiliency. The main idea of the strategy was to split the power system into controlled islands. The authors in [121] analyzed the resilience of power networks to false data injection attacks by simulating a false data injection attack with varying intensities and quantities of false data. A steady-state AC power flow model aligned with an outage model was utilized to simulate and evaluate the power system's response following a false data injection attack. The simulation investigated potential outcomes such as blackouts and the shutdown of transmission networks. Xiang et al. [122] extended the conventional security-constrained optimal power flow analysis by incorporating potential risks caused by attacks and presented a holistic robustness framework to reduce the consequences of attacks. N-1 contingency risks, as well as human-induced attacks, have been considered for the first time in the literature in the security-constrained optimal power flow.

The study presented in [123] introduced a concept called "cyber restoration" to rapidly restore the cyber layer of power systems and maintain observability following significant cyber disruptions. The restoration challenge was formulated as a MILP problem, focusing on the optimal sequence of actions to regain system observability. By optimizing the placement and utilization of phasor measurement units, the method addressed vulnerabilities to cyber threats, enhancing the security and resilience of power systems.

4. Strategies and Advancements in Smart Grids for Enhancing Power System Resiliency

In recent years, high-impact threats are diversifying and transforming from conventional to near-future characteristics while considering the evolving structure of the power system. The risks of extreme load peak due mainly to high and low temperatures are expected to increase in the future when considering global warming. For example, the extra cooling demand as imposing an additional pressure [124] has been experienced by the Europe [124] in August 2003, in July 2010, and June-August 2015 heatwaves [125]. On the other hand, abnormally cold weather spell brought about a rise in electricity demand in most of Europe supplemented by low wind speed and low solar generation at that time. Afterward, the unforeseeable extreme event created an unexpected high wholesale electricity price for the countries France and Germany [126]. The fact that the output power of renewable energy systems, whose deployment in the power system is increasing [127], is highly affected by meteorological conditions can be evaluated as a near-future threat from the utility decision-makers' point of view. For a specific example, the highly renewable European power system has meteorological sensitivity in which posing new challenges and risks associated with energy safety and security. Temporal meteorological variability results in temporal variability on both supply and demand sides [128]. The variability in the high sea surface temperature, through the low surface wind speeds, caused wind drought in the U.S. in 2015 which shows the change in the characteristics of high impact risks [129]. In the smart grid era, there is a broad number of advanced technological innovations and various smart solutions that can easily be utilized in coping with the abovementioned risks in planning and operation phases that are vitally important to boost grid resiliency. DG, ESSs, electric vehicles (EVs), DR strategies and MG architectures have been evaluated as key components of the smart grid and may contribute to improving the hardening strategies in such situations. Also, novel methods for urban resilient grid operation due to extreme consumption or power scarcity have been presented in the literature providing the presence of smart meter and advanced metering infrastructures [130].

4.1. Role of Distributed Generation and Energy Storage Systems

One of the top priority solutions is pointing out the DGs and ESSs to be employed as emergency resources in grid-support strategies thanks to the capability of self-supply in islanded mode. To enhance the resilience of power systems and minimize economic losses, it is essential to develop an advanced, reliable tool for rapid self-healing within power systems [131]. Exploiting these advanced technologies ensures sustainable energy to the end-users and assists communities in meeting the goals in the resiliency level of the power system. There have been plans to incorporate different types of DG resources with increasing numbers in various locations within New York and California to achieve fast restoration of services [132]. Diesel generation to match the demand of critical lifeline services such as hospital and sewer systems were utilized for nearly two and half months as an emergency responder after Hurricane Iniki [99]. In pursuit of practical evidence, there is an interesting example that Verizon's Garden City Central Office building has never lost power after Superstorm Sandy which is a striking natural disaster thanks to integrated diesel engine generators and fuel cells [133]. Also, the project, namely ESKIES, focuses on enhancing the resilience of communities in New South Wales that are vulnerable to disruptions in power supply due to devastating bushfires and other extreme weather events. As these incidents often result in widespread loss of access to the electricity grid and the essential services it powers, there is a crucial need to explore alternative energy solutions. This project is dedicated to enhancing energy resilience within vulnerable communities by exploring how solar panels, batteries, and other renewable energy sources, alongside energy management strategies, can sustain electricity supply to regional and rural areas during bushfires and other disruptions to the electricity grid [134]. Moreover, in the Dominican Republic, two 10 MW ESSs played a crucial role in sustaining grid operations during the severe winds and heavy rainfall brought by Hurricanes Irma and Maria. Specifically, a 30-minute duration storage system located in a protected building enclosure in Santo Domingo—was instrumental in stabilizing sudden fluctuations in grid frequency throughout the storm [135]. Therefore, a considerable amount of successful studies have systematically examined the implementation of DGs, ESSs, and their combined architecture to overcome the above-mentioned challenges of the power system. Xu et al. [136] proposed a resiliency-oriented method for formulating and solving the problem of using DGs in supplying the loads in secondary network DS after a major outage or disaster. A load restoration approach was implemented to maximize resiliency, taking into account both technical and operational difficulties such as inrush currents when activating transformers and circulating currents among DGs and others. Khazraj et al. [137] presented a multi-objective optimization problem for increasing the resiliency of DS by managing DERs, ESSs, and various dynamic reconfiguration strategies after significant line outages occurrence when exposed to HILP event. Minimizing the penalty costs for energy not supplied and maximizing the benefits of DER-ESS owners by using flexible reconfiguration and dynamic operational planning were the objective functions of the hybrid optimization algorithm. A resiliency-driven methodology was introduced in [138] to improve a dynamic response to sudden disturbances in renewable-based standalone hybrid energy systems, focusing on ESS failures and associated impacts on resiliency indices. The magnitude, duration, and instant of battery failure were considered while measuring the resiliency level of standalone architecture. A simulation-based optimization model was developed in [139] to withstand severe grid outages and serve notably hospital demands, and it was also aimed at designing photovoltaic and battery systems optimally from a cost and resiliency perspective. Various case studies were performed to optimize total system cost while taking reliability criteria and/or constraints into account. Panwar et al. [140] presented a real-time resiliency assessment framework based on hierarchical analytical processes capable of adapting changing configurations, DERs, different grid conditions, and switching operations. In [141], a resiliency-oriented planning model for smart city energy infrastructure, interconnected Energy Hubs, was proposed. This model aimed to minimize customer interruption costs and energy not supplied, focusing on the prioritization of critical load restoration. The model's effectiveness was evaluated under scenarios where connections between the electricity distribution grid and the upstream grid were disrupted, using a MILP model applied to a 33-bus distribution system.

In the MG scale, numerous literature studies have been conducted for utilizing DGs and ESSs capability in resiliency enhancement strategies again. Among them, Sedzro et al. [142] proposed a heuristic approach for the post-disturbance model and pre-disturbance model for the MG formation problem for obtaining the time-efficient solution even in large-scale designs. The placement of DG units was a decision variable, and it was planned to maximize the expected critically weighted load that could be served. With integrating the physical and economic constraints, Chen and Zhu [143] conducted a study for performing renewable energy generation planning of MGs based on a non-cooperative game-theoretic scheme to enhance the resiliency of the smart grid. A power-sharing framework was proposed in [144] for resiliency enhancement within interconnected MG architectures to solve a higher rate of battery degradation especially at non-ideal situations. Discharging batteries at depth-of-discharge levels for preventing unplanned load shedding was aimed to be avoided. The effectiveness of the developed linearized energy management system was evaluated by comparing experimental and simulation-based results, and the key discrepancies were studied in depth. The optimal management strategy for managing islanded MG equipped with ESS and photovoltaic-based commercial building was proposed in [145] when extreme contingencies occur on the utility grid side. The key goal was to operate MG at the lowest possible cost while simultaneously increasing resiliency by ensuring a continuous supply of electricity for an extended period. Dong et al. [146] presented an optimal sizing problem of battery and backup generator in grid-connected MG by taking the stochastic event occurrence time and duration into consideration. The required reliability index in the occurrence of any extreme events was aimed to be satisfied to supply critical loads. The objective function was determined based on the operational mode. Minimizing the total cost was indicated for grid-connected mode of operation while maintaining the reliability of critical end-users and minimizing the investment cost were determined for islanded mode. Khodaei [147] aimed to present a resiliency-oriented MG optimal scheduling model by considering the uncertainties in power supply, demand, and disconnecting time from the main grid. To minimize the MG load curtailment in islanded mode, DG and ESS-based available resources were scheduled optimally via linear programming (LP)-based formulation. A two-stage adaptive robust formulation for optimally managing the MG resources and minimizing the potential risks in case of adverse events was taken under study [148]. Damaging consequences of islanded mode of operation were aimed to be minimized in the day-ahead scheduling algorithm as well as minimizing the cost of load shedding. In [149], a novel energy hub model was introduced, incorporating both thermal and electrical storage units to enhance the resilience and economic efficiency of power systems transitioning from centralized networks to localized grids and MGs. Utilizing a cutting-edge metaheuristic solver, the Slime Mould Algorithm, the impacts of these storage facilities on reducing operational costs and improving reliability under both normal and fault conditions were assessed.

4.2. Microgrid Contributions to Resilience

For more resilient network operation, MG formation can be considered an effective solution [150,151]. Thanks to this ability, the survivability of prioritized critical loads can be enhanced even in extreme events and the adaptation ability is substantially increased. As a practical implementation, Sendai MG is one of the most popular frameworks which presented great performance in terms of providing electrical and heat energy to customers during the extreme devastation due to the Great East Japan Earthquake [152]. Additionally, in central Tokyo, Roppongi Hills, a distinct area within the city, serves residential users and offices. The energy system at Roppongi Hills provided electricity during broader grid outages, allowing local residents and businesses to continue their activities uninterrupted. Also, this system was utilized to export power to the larger utility grid, supplying up to 4,000 kW to the surrounding area during blackouts following the Great East Japan Earthquake. In the context of smart MG effectiveness on resilience, a residential "smart energy system" MG in Saitama, Japan, demonstrated significant benefits following the Great East Japan Earthquake. When the external power supply was lost, the house's electrical system seamlessly switched to the MG, drawing power from batteries and PV systems. Consequently, the residents maintained a normal lifestyle despite widespread grid outages [153]. Combined Heat and Power (CHP) systems can be a valuable investment for critical infrastructure facilities due to their ability to enhance resilience, reduce the effects of disasters, and offer energy cost savings. In real-world applications, such as during Superstorm Sandy, the energy needs of many places, including Greenwich Hospital, Princeton University, New York University, and South Oaks Hospital, were met by CHP units. These units were quickly activated shortly after the power outage, significantly contributing to the rapid supply of power to critical loads [154]. For more precise representation, Fig. 9 [155] can be investigated.

Hussain et al. [156] targeted to elaborate on the contributions and roles of the MG architecture on the resiliency enhancement strategies, and three-step detailed analyses were conducted. The generic background of the concept and the implementations of power systems were reported in the first step, while different topological structures of MG and its effectiveness in utilizing as a resiliency source were discussed in the second step. In the third step, outage management and feasible islanding strategies were evaluated in terms of increasing power system performance by utilizing MG. Similarly, the research paper presented in [157] focused on the deployment of MGs concerning resiliency enhancement of critical loads as well as their performances for adequately hardening the physical and cyber-attacks. Using a path-based mechanism for boosting DS resiliency, a new approach was developed in [158] to use the modularity capabilities of MG and DG

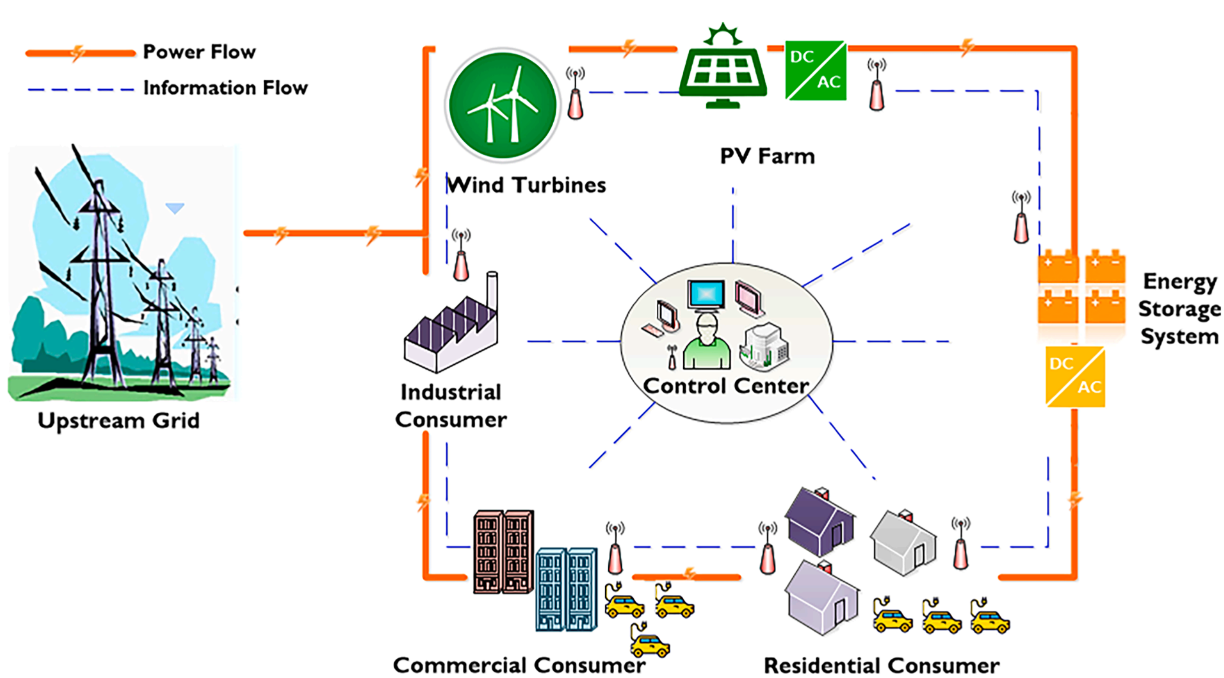

Fig. 9. The demonstration of an example microgrid [155].

units. Zhu et al. [159] considered an iteration-based linear approximation of the mixed-integer non-linear programming (MINLP)-based MG formation method for ensuring a resilient solution for DS operation with achieving an islanding mode of operation for MG when major disruptions occur. It was assumed that a short circuit fault occurred in the feeder line and it was aimed to maximize the restored load in MGs. On the other side, Hussain et al. [160] discussed the impacts of optimal sizing and siting of DGs on smart DS resiliency enhancement that conventional network was divided into autonomous MGs by applying heuristic optimization techniques. The service reliability was targeted to enhance thanks to the proposed framework to minimize load shedding, total power losses, and voltage deviations in the conventional network during DG outages. Similarly, a MILP-based methodology was developed in [161] for increasing the resiliency level of integrated large office buildings in case of blackout with considering the increasing rate of the resiliency of power customer supply in improving optimal sizing strategy in MG. A mixed-integer quadratic programming-based recovery framework for supplying critical loads in different priority scales was developed in [162] by deploying multi-MG schemes including different types of DG units capable of performing DR strategies. Khederzadeh and Zandi [163] proposed a framework based on graph theory and a spanning tree search algorithm for restoring critical loads of DS after single and multiple faults by adopting MG architecture as an emergency resource in the restoration process with the target of minimizing the number of switching operations, total system losses and out-of-service loads. Similarly, Xu et al. [164] focused on utilizing MGs as an emergency resource for coping with multiple faults and proposed a resiliency-based service restoration methodology to maximize the number of critical loads to be restored considering their priorities and minimize the number of non-critical loads. To serve hospitals in an emergency, the study [165] was presented with quantifying the potential benefits of deploying MG, including photovoltaic-based generation unit, ESS, and diesel generator in the power supply side with also considering economic issues. The study presented in [166], primarily focuses on the integration and optimization of DERs and ESSs within smart microgrids to enhance their resilience and reliability. The authors present a comprehensive model based on an IEEE test network that includes various DERs, demonstrating how these can be strategically utilized to improve the resilience of the grid against storm events. The model assessed the resilience of the network by simulating scenarios like storms and evaluating metrics such as the Energy Not Supplied (ENS) index.

Another important widely-known implementation of MG is networked architecture. This concept is presented with more considerable efforts enhance resiliency and to reduce total investment and operational costs while improving efficiency. In this regard, Li et al. [59] intended to elaborate on the role of networked-MG architecture in boosting the power system resiliency when exposed to an extreme weather event. The general definitions using MG as resiliency sources were discussed in detail with also introducing an index for contributing resiliency assessment methodologies. A two-stage stochastic programming-based mathematical formulation was presented in [167] to design resilient distribution grids by providing system resiliency targets against the destructive impacts of HILP events. The 1200 node DS was upgraded constantly to achieve the required resiliency needs, which reduce disruption periods of load demands. From different points of view, Bedoya et al. [168] investigated the incorporation of asynchronous and uncertain pieces of information into optimal restoration plans of DS in the decision-making process which was the novel point of the study. The networked-MG concept was considered in the proposed two-module architecture to serve critical loads with maximizing the resiliency function via modeled binary LP. A stochastic LP-based comprehensive planning methodology forming the main problem with two sub-problems was proposed in [169] for boosting the coupled power distribution and water DS resiliency by withstanding unexpected hurricane events. The deployment of multi-MGs was accepted as a promising solution and upgrading the sizing of ESS as well as water tanks was also considered from different perspectives. On the other hand, Kwasinski [170] considered planning a process-based risk assessment approach to improve power supply resiliency of the critical loads in case of a hurricane in which all phases were encompassed.

4.3. Combining Smart Solutions for Resiliency Enhancement

The use of EVs has significantly increased recently, thanks to their ability to reduce fossil fuel consumption, lower greenhouse gas emissions, and improve energy efficiency. These benefits position EVs as a central element of future transportation systems [171]. Through their ability to perform vehicle-to-grid and grid-to-vehicle modes, EVs, as one of the most promising storage technologies, can play a vital role in power system resiliency enhancement strategies, as evidenced by 25 years of research. EVs are fast-responding emergency resources that can leverage the load pickup by neutralizing the imbalances between supply and demand. As a consequence, the adoption of one of the most widely-used flexible energy options in the restoration and recovery processes of the power system has been growing to ensure the survivability of critical loads. It is expected that these potential power sources will become increasingly popular in the future based on the idea of grid-support services or emergency resources in major outages in the smart grid context. To address the issue, EVs were aimed to be utilized in an emergency power supply strategy via transferring the energy from ships that survived the tsunami after the earthquake happened in Fukushima Japan in 2011 to the land for hospitals and shelters [172]. Following the earthquake and tsunami in Japan in March 2011, the New York Times documented the deployment of EVs in response to a gasoline shortage caused by oil refineries going out of service [173]. Brown and Soni [174] aimed to investigate the potential benefits, opportunities, and challenges of incorporating EVs into the power system with different modes of operation, grid-to-vehicle, vehicle-to-building, and vehicle-to-grid for enhancement of grid resiliency as well as examining a considerable number of literature studies, current policies and the stakeholders in this area. A MILP-based multi-period critical load restoration problem was developed in [175] for dispatching mobile power sources and repair crews in the transportation system after major outages. The dynamic traffic state and even traffic congestion after the disaster was considered in the mobile emergency resource dispatch problem for ensuring efficient critical load restoration. Similarly, a MILP-based bottom-up system restoration plan was developed by Sun et al. [176] to maximize restored energy and return to normal operating conditions by applying restoration plans for transmission and DS.

As a practical implementation, it is known that mobile generators were dispatched to the damaged zones in telecommunication facilities after the Great East Japan Earthquake in 2011 according to the pre-prepared disaster plans by Japanese authorities for increasing system restoration capability. Also, they were incorporated into the deicing and rush repairs tasks during Chinese winter storms in 2008 to provide electrical supply continuity [133]. In the latest event in Turkey in 2021, mobile generators and electric poles were transported to the region by helicopter to supply electricity to rural areas whose accessibility was restricted due to floods [177]. For example, during the 2020 and 2021 wildfire seasons, Pacific Gas and Electric deployed mobile power sources to provide essential backup power to medical baseline customers and food banks during Public Safety Power Shutoffs caused by wildfires [178].

Besides the mentioned solutions, the concept of demand-side management (DSM) has drawn significant attention and is evaluated as the other promising solution [179] thanks to its capabilities such as increasing power grid resiliency, deferring system cost, and stability issues. DR strategies are one of the most popular techniques of DSM, enabling to adjustment of the power profile of end-users in response to operator requests or dynamic market pricing. TPS operational performance was determined based on the obtained fragility curves of transmission lines and towers and the incorporation of sequential wind data of six cities of the U.S. under windstorm events in the presented study [180]. While using DSM axioms to improve system resiliency, a weather-condition-based pricing mechanism was proposed for altering end-user demand patterns based on local weather conditions. Also in [181], a direct-load control-based DR program along with changing the network topology to maximize power supply during contingent events.

In the literature, there is a growing body of literature combining different smart solutions for increasing TPS, DS, and MG resiliency. To mitigate the destructive consequences of natural disasters and other failures, incorporating the flexibility sources under an effective framework was extensively studied. To utilize DG units and EVs as emergency resources to tolerate risky events during emergency conditions, the IEC 61850-based communication model for the optimal formation of MG was developed in [182]. The interoperability and information exchanges were aimed to be transferred properly in the context of Cognitive Radio. The current paper in [183] proposed a home energy management framework that is capable of managing EV power transfers from vehicle-to-home mode, producing electrical energy from a wind turbine, and activating the DR program with the goal of increasing system resiliency.

Hafiz et al. [184] proposed a three-step method, including three optimization formulations modelled via LP, MILP, and T-stage stochastic programming approach for leveraging the flexibility of DS by integrating DR strategies. Household-level flexible appliances were managed optimally in an effective distribution service restoration plan to enhance the network's performance. A two-stage stochastic programming-based framework was presented in [185] to evaluate DS resiliency level by taking optimum MG formation, DSM strategies, ESS, and DG units into consideration from different points of view. Several case studies were performed for investigating the impacts of mentioned promising solutions on the resiliency enhancement and recovery indices in the face of HILP events with maximizing restored loads considering the priorities. Wang et al. [186] presented a two-stage decision-making framework to determine an optimal restoration strategy with maximizing the number of restored critical loads by utilizing the sources of DGs, ESSs, and MGs. Similarly, Kahnamouei and Lotfifard [187] proposed a two-stage method for increasing load restoration via reconfiguration strategies, DSM axioms as well as MG and DG integration. Thanks to the distribution system reconfiguration, the system restoration can be optimized [188-190].

To operate critical infrastructures against severe weather and environmental conditions affecting primarily electricity consumption in a resilient fashion, the methods and models have been developed in the literature within the smart resilient distribution management concept. A novel risk-based method to avoid large-scale blackouts that might occur as a result of exceeding the DS' capacity due primarily to power shortages or extreme power demands was presented in [130]. Thanks to the integration of smart scheduling and control concepts, the DS operation could be kept in stable mode, and also urban critical functions could be provided sufficiently enough. Same as [130], the authors in [191] aimed to take advantage of demand-responsive loads flexibility in the proposed models to enhance grid resiliency. A unified scheme for ensuring the power balance between generation and demand-responsive resources was addressed in [191] when the power system was exposed to extreme temperatures during a heatwave. To reduce the total load on the network, several strategies, such as demand shifting were applied to convenient appliances.

On the other hand, for analyzing the impact of thermal power plants on power system resilience in face of extremely high temperatures and water availability/unavailability, a system-level quantification framework was proposed in [192] with also introducing a resilience-oriented metric. Alipour et al. [193] presented a Bayesian ensemble-of-trees algorithm-based probabilistic predictive framework to perform an accurate estimation of the climate sensitivity of daily peak load by using statistical machine learning. The methodology was implemented in the Texas region for validating its performance and the results were discussed in the context of supply shortages and socio-economical impacts of extreme events. Table 4 shows the literature studies conducted in special research area comparing them in a detailed manner.

5. Conclusion and Path Forward

5.1. Concluding Remarks

The increasing incidence of weather-related events and coordinated cyber-attacks has elevated the study of power system resiliency among researchers, governmental, and non-governmental organizations, emphasizing the need to ensure continuous electricity supply under adverse conditions. This paper thoroughly examined the distinction between power system resiliency and reliability, elaborating on definitions from various notable organizations and detailing the primary features of resiliency. We presented a comprehensive framework for resiliency assessment, including quantitative metrics derived from operational and infrastructural viewpoints. Moreover, we classified threats into malicious and non-malicious categories, discussing the extensive impacts of natural disasters such as earthquakes, floods, tropical cyclones, heatwaves, droughts, wildfires, and cyber-threats on power system components. Our review also covered current smart and innovative solutions aimed at enhancing resiliency, highlighting numerous mitigation algorithms and frameworks from the literature that help reduce restoration times.

5.2. Path Forward

While some of the resiliency strategies discussed are beginning to be adopted by utilities worldwide, their application on a global scale remains nascent. Future directions include:

- Given the rising frequency and severity of extreme weather events, power system operators should increasingly factor these into their planning and operational strategies to ensure robust, sustainable power delivery in emergency situations.
- Future designs of power systems should incorporate international resiliency criteria alongside traditional reliability metrics, tailoring these standards to the specific threats and risks pertinent to the geographical locations of the networks. They are particularly crucial for giving responses to specific regional challenges like earthquakes or geopolitical instability, ensuring that power systems can quickly recover from disruptions and adapt to local conditions effectively. By establishing these global standards, these criteria aim to support the development of robust power systems capable of addressing a wide range of environmental and geopolitical risks.
- Much of the current infrastructure is not equipped to withstand emerging weather extremes, rendering it particularly susceptible to failures. It is crucial to upgrade this infrastructure to withstand harsher conditions. Moreover, extreme temperatures lead to significant increases in electricity demand, especially for heating and cooling. Power systems must evolve to manage these demand surges without compromising their stability.
- The integration of renewable energy sources adds another layer of complexity. As we accelerate the transition to renewable energy, maintaining grid resilience amidst the variability of solar and wind energy, especially during adverse weather conditions, becomes increasingly challenging.
- Relying solely on historical data is insufficient for accurately characterizing power system interruptions due to the dynamic nature of extreme weather, which is intensifying rapidly due to global warming. Recent advances in climate research are enhancing our ability to forecast shifts in extreme weather patterns. It is imperative that these improved forecasts be converted into proactive strategies. This would involve developing anticipatory measures for managing

Table 4
Taxonomy table including various smart solutions in the research paper.

Ref.	Smart Solutions					Implementation Level			Method
	DG	ESS	DR	EV	MG	Distribution	Transmission	MG	
[136]	✔					✔			MILP
[137]	✔	✔				✔			Genetic algorithm and ε-constraint method
[138]	✔	✔				✔			LP
[139]	✔	✔				✔			Simulation-based optimization model
[140]	✔	✔				✔			Analytical hierarchical processes
[142]	✔							✔	Heuristic approach
[143]	✔							✔	Non-cooperative game-theoretic scheme
[144]		✔						✔	MILP
[145]	✔	✔						✔	LP
[146]	✔	✔						✔	MILP
[147]	✔	✔						✔	LP
[148]	✔	✔						✔	MILP
[175]				✔		✔			MILP
[176]				✔		✔			MILP
[180]			✔				✔		Monte Carlo simulation method
[182]	✔			✔		✔			Communication-based architecture
[183]	✔		✔	✔		✔			Stochastic mixed integer binary model
[184]	✔		✔			✔			LP, MILP, and T-stage stochastic programming
[185]	✔	✔	✔		✔	✔			MILP
[186]	✔	✔			✔	✔			Mixed integer semidefinite program

power outages and mitigating other impacts on the energy system. Future efforts should focus on integrating real-time data and predictive analytics into power system operations. This integration will enable utilities to respond more effectively to the changing climate conditions, ensuring both the resilience and reliability of the energy infrastructure in the face of increasing climatic uncertainties
- Decision-makers in utilities should perform comprehensive cost-benefit analyses to determine optimal investments in resiliency for both hybrid autonomous systems and bulk power grids, avoiding under- or over-investment.
- The resiliency of power systems overlaps with various disciplines, including statistics, software engineering, meteorology, control systems, and optimization techniques. Future policies and regulations should be developed using interdisciplinary insights that combine the expertise of professionals from these diverse fields.
- The interdependence between the electrical power system and other critical infrastructures such as traffic, water distribution, and natural gas systems should be considered in all operational and planning stages to enhance overall resiliency. This involves developing a socio-technical systems design that accommodates the varying priorities of multiple stakeholders.
- The adoption of smart solutions should be evaluated comprehensively, considering both normal and emergency conditions. It is crucial to identify and address the challenges posed by operational constraints from various perspectives.

CRediT authorship contribution statement

Ayşe Kübra Erenoğlu: Writing – review & editing, Writing – original draft, Visualization, Resources, Project administration, Formal analysis, Conceptualization. **Ibrahim Sengor:** Writing – review & editing, Resources, Project administration, Supervision, Conceptualization. **Ozan Erdinç:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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