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A comprehensive review on resilience definitions, frameworks, metrics, and enhancement strategies in electrical distribution systems

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HIGHLIGHTS

- In-depth understanding of EDS resilience and the distinction between reliability and resilience.
- Assess a systematic approach for resilience based on various definitions and frameworks.
- Highlight the need for qualitative and quantitative measures to evaluate resilience.
- Explore strategies for enhancing resilience during the planning and operation of EDS.
- Identify existing gaps in the literature and provide directions for future research.

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ABSTRACT

The importance of resilience in electrical distribution systems (EDS) is emphasized by their susceptibility to natural calamities that cause widespread infrastructure damage and prolonged service interruptions. This review article provides a comprehensive examination of resilience in the area of EDS, with an emphasis on understanding the multifaceted nature of this concept, as evidenced by the breadth of definitions from different organizations and the variety of frameworks proposed for evaluation and enhancement. In recent years, extreme weather events have repeatedly challenged the robustness of electrical distribution systems, bringing to light the limitations of existing infrastructures and the need for enhanced resilience strategies. The devastating impacts of hurricanes, cyclones, and other natural disasters have not only caused immediate disruptions but have also had lingering effects on the affected populations and economies. These events have brought forth a need for a critical assessment of resilience within EDS, propelling the search for metrics and solutions that could withstand and swiftly recover from such adversities. Our exploration begins with a comparison of the concepts of resilience and reliability, highlighting their interconnected yet distinct roles in ensuring the efficacy of EDS. The definitions and frameworks of resilience proposed by various organizations are outlined. This review also discusses existing resilience metrics and their capacity to capture the electrical and topological aspects of EDS. We assess the readiness of these metrics to capture the elements of resilience across different operational and planning scenarios. Moreover, we present the introduction of complex network theory as a tool through which the resilience of EDS could be quantified, revealing critical points and vulnerabilities within network topology. Additionally, the paper examines recent methods for enhancing resilience, encompassing both planning and operational techniques. From the review, existing research gaps and challenges are identified, providing suggestions for future directions to enhance EDS resilience. This comprehensive overview aims to provide guidelines and tools to improve the resilience of distribution systems to endure and recover from extreme events and disruptions.

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1. Introduction

High impact low probability (HILP) extreme events pose a significant threat to electrical distribution systems (EDS), which are otherwise considered reliable under normal operating conditions [1]. Resilience, in addition to reliability, is an important aspect that should no longer be ignored in the modern EDS. A resilient system anticipates and detects catastrophic events, and exhibits the ability to quickly recover and restore power supply with first priority to essential loads such as healthcare systems, emergency services, and public infrastructure such as transport, communications, water, and national security [2]. Extreme events are (i) natural, such as floods, hurricanes, wildfires, tsunamis, and earthquakes, and (ii) man-made, such as human errors, cyber-physical attacks, and market-induced crashes.

Conventionally, reliability analysis is conducted in power systems, which focuses on preventing interruptions under normal operational conditions and is not adequately equipped to handle the extraordinary and complex challenges posed by extreme events. Reliability analysis typically does not account for the low probable and high-impact scenarios that could cause widespread and prolonged power outages. Thus, reliability could be seen as the day-to-day dependability of the EDS and a measure of how well the system performs under normal operating conditions [1].

As a result, the concept of resilience has emerged as a critical new paradigm in the face of such limitations, as shown in Fig. 1. Resilience goes beyond preventing disruptions; it is about making systems robust enough to withstand severe shocks. More importantly, resilience is characterized by the system's ability to prepare for, effectively deal with, and swiftly recover from these high-impact events. It includes the capacity to adapt to changing conditions and to maintain or quickly re-establish functionality, even during or after a severe disturbance. Building resilient power systems, therefore, means developing infrastructure that not only has the strength to endure the initial impact of a disaster but also has the agility and strategic planning in place to promptly go back to normal operations [5].

The significant contributions of the review article are as follows:

1. To provide an in-depth understanding of resilience in EDS and a clear distinction between reliability and resilience.
2. To assess a systematic approach for resilience assessment based on the various definitions and frameworks of resilience.
3. Reflect the growing consensus on the need for qualitative and quantitative measures to evaluate resilience, as they provide actionable insights for system operators and improve the robustness of power infrastructures against inevitable and unforeseen events.
4. To explore the various strategies for enhancing resilience during the planning and operation of EDS.
5. To identify existing gaps in the literature and provide directions for future work.

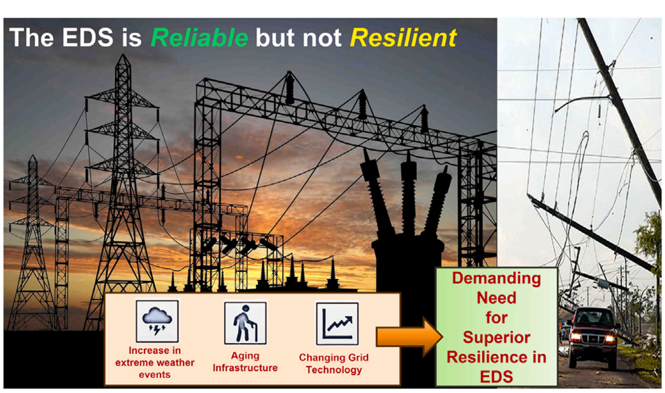

Fig. 1. Challenges faced by reliable EDS demanding the need for resilience [3,4].

The article is organized as follows: Section 1 begins with a discussion on extreme events affecting system resilience, distinguishing between reliability and resilience. Section 2 provides a thorough survey of various metrics put forth by different organizations. Section 3 delves into the frameworks necessary to gain insights into the objectives, methodologies, principles, performance analysis, outcomes, and government policies necessary for implementing strategies required for resilience evaluation and enhancement in EDS. Section 4 presents the various metrics used for resilience evaluation of EDS. Various complex network parameters for resilience evaluation are detailed in Section 5. Enhancing resilience through planning and operational techniques is covered in Section 6. Research gaps and future directions in resilience evaluation are identified in Section 7. Lastly, Section 8 concludes the thorough analysis of resilience.

1.1. Impact of natural disasters on power systems

Natural disasters, like storms and hurricanes, seriously threaten power systems, causing extensive damage and prolonged outages all over the world. Hurricane Sandy in 2012 affected 4.2 million customers who faced a 10-day power outage, and Hurricane Maria in 2017 affected 3.6 million residents in Puerto Rico [6]. In 2021, Cyclone Yaas made landfall on the coast of West Bengal, India, leading to widespread disruptions. The power supply was affected in 14 of the state's 23 districts, with outages lasting for 72 h [7]. In November 2023, Storm Ciarán left over a million people in France without electricity, highlighting the critical need for enhanced resilience in power systems [8]. It also affected the Channel Islands and southern England, leaving over a million people without electricity. France's northwest department of Finistère was affected the most, where winds exceeded 120 kmph (75 mph), and gusts surpassed 200 kmph (124 mph), resulting in power outages for 1.2 million people. The northwestern region of Brittany faced the brunt, with 780,000 affected individuals, while the southwestern county of Cornwall recorded 8500 people without power.

In the summer of 2010–2011, Queensland, Australia, faced extensive flooding, causing significant damage to six zone substations, as well as numerous utility poles, transformers, and overhead cables [9]. This, in turn, resulted in electricity disruptions for approximately 150,000 consumers. In December 2023, Cyclone Michaung struck with fierce winds, torrential rains, and severe flooding, severely disrupting life in Andhra Pradesh and Tamil Nadu, India. The storm caused widespread power outages across these states, lasting for 48 h [10].

Extensive losses have been experienced from the wildfire events where severe wildfires engulfed California in early September 2020, wreaking havoc on the state's solar power production and causing a substantial drop of nearly one-third in solar generation. As the state is heavily dependent on solar installations for almost 20 % of its electricity, this caused a significant setback [19]. In August 2021, Greece experienced severe wildfires triggered by an extreme heatwave [20]. The fires devastated 125,000 hectares of forest and farmland, as well as households. The occurrence of fires surpassed the 12-year average by 26 %, leading to an area burned that was 450 % larger than usual. The fires caused significant damage to the distribution network. For example, in Evia, seven medium voltage (MV) lines serving 13,000 customers were affected, and in Attica, nine MV lines affecting 38,000 customers were impacted. To meet power demand during the crisis, twelve mobile generators having a capacity of 2.12 MW were used until the network could be fully restored [20]. Several other events that have caused major blackouts with a significant loss in infrastructure and power supply worldwide are shown in Table 1, emphasizing the vulnerability of EDS infrastructure to natural disasters on a global scale.

Table 2 provides an overview of the significant impact of various types of extreme weather and natural disaster events that have affected the United States over a span of 44 years, from 1980 to 2023 [21]. It categorizes these events into several types: Flooding, Freeze, Severe Storm, Tropical Cyclone, Wildfire, and Winter Storm. In the last 44 years, there

Table 1
Major global events and their impact.

Event	Year	Location	Impact
Kobe Earthquake [11]	1995	Japan	2.5 M households
Ice Storm [12]	2008	China	2000 substations
Cyclone Tasha [13]	2010	Australia	150,000 customers
Tohoku Earthquake [14]	2011	Japan	4.4 M households
Hurricane Sandy [15]	2012	Caribbean & USA	4.2 M customers
Hurricane Maria [6]	2017	Puerto Rico	3.6 M residents
Hualien Earthquake [16]	2018	Taiwan	>1000 customers
Windstorm [17]	2021	Texas, USA	4.5 M households
Earthquake [18]	2023	Turkey/Syria	4.5 M buildings

Table 2
Extreme events affected the United States from 1980 to 2023 [21].

Disaster type	No. of events	Total costs
Flooding	44	$196.6B
Freeze	9	$36.4B
Severe storm	186	$455.2B
Tropical cyclone	62	$1379.3B
Wildfire	22	$142.4B
Winter storm	22	$98.3B
Total	345	$2308.2B

were 345 extreme weather events, incurring a combined cost of $2308.2 billion. This equates to an average of 7.84 events annually, with a financial impact of approximately $52.4 billion each year. This indicates a high economic toll of such events over the years. Also, an important observation reveals a concerning trend over the past decades: the number of high-impact weather events per year is on the rise. In the 1980s, there was an average of 3.3 events per year, but this figure climbed to 5.7 events per year in the 1990s. The upward trajectory continued into the 2000s, with the average annual number of events reaching 6.7. This increasing pattern peaked in the 2010s when events nearly doubled to an average of 13.1 per year. The data from the most recent period, the last five years leading up to 2023, reveals an even more stark reality, with a dramatic leap to 20.4 events per year. This consistent increase in the frequency of events each decade signals an urgent need for enhanced adaptation strategies in the face of escalating climate-related challenges.

In August 2023, heavy rain in Ottawa resulted in approximately 24,000 customers losing power. Within 3 h, the situation improved, with estimates indicating that fewer than 1000 customers were left without power [22]. After the heavy rain, Hydro Ottawa had about 225 work crews trying to restore power to those affected, and they worked to address over 725 different outages. The restoration process is generally a multi-day effort, but they managed to significantly reduce the number of customers without power within 3 h. The quick recovery is attributed to the efficient detection and restoration process that Hydro Ottawa follows, which includes assessing the damage, repairing main transmission lines, substations, and then local lines to homes and businesses.

Such incidents have a severe impact on energy infrastructure and the resultant challenge of maintaining electricity supply. These examples highlight not just the vulnerability of power systems to natural disasters but also the critical difference between reliability and resilience in EDS [23]. Reliability refers to the ability of the electrical grid to deliver power continuously under normal operational conditions, while resilience is about the grid's ability to prepare for, respond to, adapt to, and recover from adverse events that cause disruptions. In the face of extreme events, enhancing resilience means strengthening not only infrastructure against potential damage but also quick restoration capabilities, as demonstrated by Hydro Ottawa's rapid response following heavy rains. Building resilient power systems involves strategic planning, robust construction, and adaptive operational practices that could mitigate the impact of these disruptions, thereby ensuring a more secure and stable power supply in increasingly uncertain environmental conditions.

Table 3
Distinguishing factors between reliability and resilience in EDS [1].

Parameters	Reliability	Resilience
Definition & focus	Capability to provide continuous service under normal conditions	Ability to withstand, adapt to, and recover from disruptions; prioritizes critical services under extreme conditions
Measurement metrics	Uses established metrics like SAIFI, SAIDI, ENS, CAIDI, and CAIFI	Metrics are not well-defined; clear metrics are required
Influencing factors	Based on system design and operational effectiveness	Affected by network design, operational conditions, and control actions
Assessment timing	Calculated regularly under normal conditions	Evaluated before, during, and after disruptions in both planning and operational aspects
Load consideration	Considers all connected loads	Focuses on critical loads
Outage consideration	Excludes short outages (<5 min)	Considers all outages, regardless of duration

1.2. Reliability v/s resilience

The EDS is reliable but lacks resilience [24], highlighting two different yet interlinked aspects of system performance. *"Reliability primarily focuses on the ability of the system to deliver power without interruptions or disruptions during a routine, high-probability events such as minor faults, scheduled maintenance, or voltage fluctuations [25]."* This principle highlights the importance of proactive measures, redundant components, and continuous power supply to meet the daily needs of consumers. Metrics like system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), equivalent number of supply interruptions (ENS), customer average interruption duration index (CAIDI), and customer average interruption frequency index (CAIFI) quantify the frequency and duration of outages and are utilized to evaluate reliability [26].

Resilience, in contrast, focuses on handling low-probability, high-impact events like natural disasters or major equipment failures that could severely affect the EDS. Unlike reliability, which aims to prevent such events, resilience is about recovering from the events effectively in less span of time. Recovery includes adaptive approaches such as power backup, responsive emergency plans, and re-configuring systems to handle and recover from damage or changing conditions. Quantifying resilience is challenging and often requires an evaluation of the system's ability to cope with various extreme events. Thus, it becomes crucial to differentiate resilience from reliability, as shown in Table 3.

An effectively engineered and strategically planned EDS strives to achieve an equilibrium between reliability and resilience. This approach ensures that the system consistently delivers power under regular operating conditions while also possessing the capacity to quickly recover from infrequent yet catastrophic events. By striking this balance, the system safeguards both the daily power requirements and its ability to withstand and rapidly bounce back from extreme disruptions. Consequently, this balanced approach guarantees a continuous and stable electrical supply, ensuring a robust and dependable power distribution infrastructure [27].

2. Definitions of power system resilience

The term "resilience" is a concept with different interpretations across various fields such as engineering, organizational management, economics, psychology, and biology [28]. It originates from the Latin word "resilio," which describes an object's ability to return to its original state after being subjected to stress like bending, compression, or stretching [29]. The concept was first introduced by C.S. Holling in

1973, who defined resilience as *"a measure of a system's persistence and its ability to absorb changes and disturbances while maintaining consistent relationships between populations or state variables"* [30]. In 2002, Lachs et al. began focusing on restoring and preserving the stability of EDS under extreme events [31]. Despite numerous attempts, there is no universally accepted definition of resilience. Various organizations within the power engineering sectors have undertaken measures to define resilience and distinguish it from reliability. A chronological order of the various definitions of resilience is listed as follows,

D1 In 2009 [32], Haimes provided resilience definitions as *"the grid's ability to autonomously return to a standard and dependable operational state with minimal human intervention."*

D2 In 2009 [33], the United Nations provided a general definition of resilience as *"the capability of the system, society, or community when subjected to hazards to effectively withstand, absorb or adapt and reinstate from such hazardous impacts by maintaining and restoring back to its fundamental structures and functions."*

D3 In 2011 [34,35], the United Kingdom Energy Research Center (UKERC) defined power system resilience as *"the ability to withstand disruptions, specifically to recover rapidly from failures and being able to continuously provide economical power services to customers."*

D4 In February 2013 [36] , the definition of resilience by the United States Presidential Policy Directive-21 (PPD-21) within the context of critical infrastructure is given as, *"the term resilience means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents."*

D5 In August 2013 [37], a white paper which is the government's official and authoritative report, was published by the Executive Office of the US President, where it discussed the economic benefits of a more resilient power grid. This white paper is built upon a policy framework introduced in 2011 that introduced a four-pillar conceptual strategy including (i) enabling cost-effective smart grid investments, (ii) unlocking the potential of innovation in the electricity sector, (iii) empowering consumers and enabling informed decision making, and (iv) securing the grid, for the modernization of the electrical grid.

D6 In 2017 [38], from the power system's perspective, Panteli et al. define resilience as *"the system's capability to resist high-impact low-probability events, swiftly recover from such events and adjust its functioning and configuration to alleviate potential future impacts."*

D7 In 2019 [39], a joint work between the Department of Energy (DOE) and national laboratories is aimed at advancing grid modernization. The consortium adheres to a consistent resilience definition across all studies conducted under the Grid Modernization Initiative (GMI). This definition is stated as *"the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and rapidly recover from disturbances through flexible and comprehensive planning alongside technical solutions."*

D8 In 2021 [40], the North American Transmission Forum (NATF) defines resilience as *"the capability of the system and its elements to reduce damage and enhance recovery from unexpected disruptions within a reasonable timeframe."*

D9 In 2023 [41], the IEEE Task Force provided the subsequent definition of resilience, *"Power system resilience is the ability to limit the extent, system impact, and duration of degradation to sustain critical services following an extraordinary event. Key enablers for a resilient response include the capability to anticipate, absorb, rapidly recover from, adapt to, and learn from such an event. Extraordinary events for the power system may be caused by natural threats, accidents, equipment failures, and deliberate physical or cyber-attacks."*

The concept of power system resilience refers to the grid's ability to withstand and respond to adverse circumstances, such as disasters, accidents, equipment malfunctions, or deliberate attacks, ensuring continued supply to essential loads like hospital services, communication networks, national security, public transportation, trading markets, and industrial production. The IEEE Task Force outlines key elements of power system resilience as follows:

- Limiting the extent: Minimize the scope of damage to prevent a larger portion of the power system from getting affected by the disruptions.
- Limiting the impact: Reducing the overall impact on the power system, mitigating disruptions, and ensuring smooth grid functionality.
- Limiting the duration of degradation: Decreasing the time critical services that are affected is crucial for maintaining essential functions.

The absence of a universally agreed-upon definition for resilience in EDS suggests its relevance depends on the specific issue at hand. Nonetheless, considering key characteristics like anticipation, adaptation, and recovery from disruptive events could facilitate the standardization of metrics for evaluating resilience enhancement methods and informing investment decisions (Fig. 2). However, creating a universal resilience metric is difficult because of the varying characteristics of resilience-focused research and specifically defined objectives [1].

Acknowledging the occurrence of infrequent yet highly impactful events that may cause significant damage, it is noted that the preparation for such occurrences may be unfeasible and financially difficult, particularly when they are not easily predictable. This presents a challenge for both utilities and customers to prepare for extreme events. Consequently, the above-mentioned definitions converge on similar ground, focusing on the necessity for power system infrastructure to have the ability to withstand, recover, adapt, and prevent, often referred to as "WRAP". This acronym highlights four essential attributes: the strength to endure unexpected severe weather or malicious activities, the capacity for rapid response to restore community equilibrium, the flexibility to adjust to new operational conditions while ensuring seamless operation, and the significance of forecasting or prevention of futuristic incidents through data analysis or accurate predictions [1].

The definitions of resilience provide a clear understanding of the term and its key aspects. However, understanding resilience frameworks is essential to gaining insights into the objectives, methodologies, principles, performance analysis, outcomes, and government policies necessary for implementing strategies required for resilience evaluation and enhancement in EDS.

Fig. 2. Key aspects of a resilient system [1].

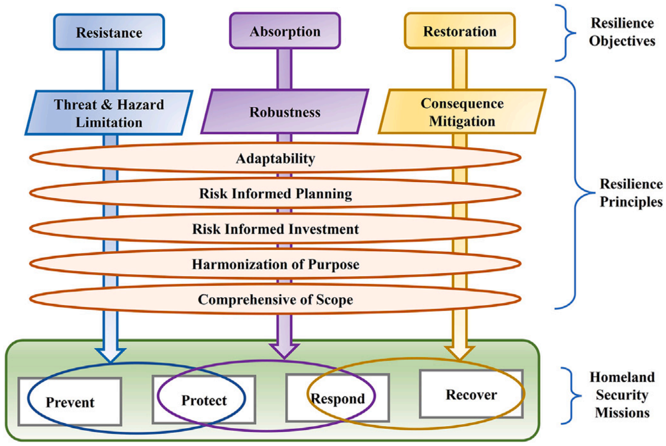

Fig. 3. Relationship among elements of resilience [33].

3. Resilience frameworks

Various frameworks that define and operationalize resilience across different contexts and institutions are discussed. It presents an in-depth analysis of frameworks developed by entities such as the United States Department of Homeland Security, Sandia National Laboratories, RAND Corporation, the UK Government, and the IEEE Task Force on Power System Resilience Metrics and Evaluation Methods. Each framework provides unique insights into how resilience could be integrated into infrastructure and societal systems, emphasizing a blend of operational practices, policy-making, and strategic planning.

3.1. An operational framework for resilience in 2009

In 2009 [33], an operational framework was introduced that is beneficial to the Department of Homeland Security (DHS) in the USA and various stakeholders, both public and private. It is a general framework for enhancing national safety and resilience by integrating resilience into the infrastructure and societal systems, with the goal of enhancing national safety. It systematically integrates the homeland security missions of prevention, protection, response, and recovery, aiming to create a cohesive strategy for resilience.

- Objectives: The framework establishes resistance, absorption, and restoration as the key end-states or outcomes, which collectively define the attainment of resilience as shown in Fig. 3. Unlike traditional views that may consider these objectives as sequential steps, this framework emphasizes their mutual reinforcement. Each objective supports the others, creating a dynamic and interconnected system where the success of one element contributes to the strength of the others.
- Principles: These principles serve as both educational tools and planning standards, guiding the design and selection of operational methods. They ensure that all actions taken, align with the inclusive goals of enhancing resilience, thereby providing a consistent approach across different homeland security missions.
- Ways and means: The framework includes a comprehensive range of policies, programs, and activities designed to build specific capabilities related to resilience. These methods are chosen based on their alignment with the framework's principles, ensuring that every implemented action contributes effectively to the resilience objectives. This segment details the criteria for selecting appropriate strategies and how they integrate into existing homeland security operations.
- Homeland security missions: The missions of prevention, protection, response, and recovery provide the operational context in which the framework's principles and methods are applied. Thus, it outlines how the framework enhances the integration of resilience-focused strategies into these missions, ensuring that policy and program solutions are not only developed but also implemented in a coordinated and effective manner across all aspects of homeland security.

This operational resilience emphasizes the need for a holistic approach where all components of the framework work to enhance the ability of homeland security to anticipate, withstand, and recover from adverse conditions and threats.

3.2. Framework developed by sandia national laboratories in 2014

In the effort to modernize the power grid and improve its overall performance, establishing a comprehensive framework and developing effective methods for quantifying resilience are of paramount importance [9]. This resilience framework is vital in offering detailed guidelines for evaluating the resilience of the system. The results from this evaluation serve as the foundation for resilience-centric decisions in both the operational and planning domains of the system. Furthermore, incorporating metrics to measure resilience improvements is crucial, allowing for a systematic assessment of different techniques and aiding in the formulation of investment techniques.

The Resilience Analysis Process (RAP) provides a systematic approach for resilience assessment and evaluating the efficacy of metrics aimed at enhancement. The RAP comprises six key steps to evaluate a system's performance, as depicted in Fig. 4. The first step in the RAP process involves establishing high-level resilience objectives, which form the foundation for the following steps. The second step entails defining the system under consideration, establishing resilience metrics, and delineating the scope and boundaries of the assessment. At this stage, stakeholder input is essential, guiding the analysis by incorporating their perspectives on potential consequences. The development of resilience metrics should include several critical factors [42], such as:

- Useful: Metrics created in this framework must be practical, supporting decision-making processes performed by human users, computational analytics, or a combination of both. They must cover a broad range, including system planning, real-time operations, and policy development.

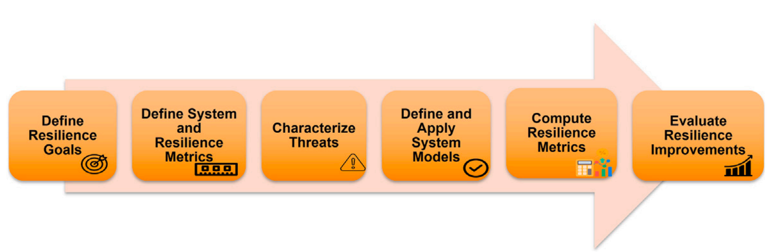

Fig. 4. Steps of RAP [42].

- Comparable: A robust metric must provide a suitable methodology for efficient comparative analysis and must have the ability for application across different systems.
- Applicable across operations and planning: Resilience metrics should be suitable for planning and operational applications, such as preparation for hurricanes during planning and real-time response strategies during operational phases.
- Applicable and scalable: The metrics must be adaptable across different times and locations, maintaining their relevance in spite of technological developments and the use of sophisticated methodologies.
- Quantitative and qualitative: The framework must support the creation of resilience metrics that have the ability to be used for both qualitative and quantitative analysis, providing flexibility in evaluation.
- Incorporate uncertainty: The resilience metrics must be developed using methodologies that quantify the inherent uncertainty in the results.
- Consider a risk-based approach: Metrics must account for a specific or group of hazardous events, vulnerable scenarios, and possible impacts on personnel, going beyond the immediate effects on the system.
- Consider recovery time: The metrics must include the outage duration, either directly or indirectly, as critical factors during evaluations.

The third step centers on recognizing potent threatening events. Following this, the fourth step entails estimating the degree of damage due to an event recognized in the preceding step. The fifth step incorporates data from the impacted components into system models to evaluate the present condition. The sixth step takes the results from the fifth step and quantifies and compares them with the resilience metrics defined in step 2. This method offers a thorough process for the assessment and enhancement of resilience, providing useful perspectives for decision-making and investment techniques.

3.3. Framework by RAND corporation in 2015

The RAND Corporation, USA, offers a framework for evaluating resilience in EDS. This framework acknowledges that resilience is not a binary state but encompasses several dimensions, such as the degree of service degradation, the speed of service restoration, and the completeness of recovery [43]. The framework includes essential components such as :

1. System design and operation: The resilience of the system is significantly affected by its design and operational practices. Elements such as redundancy, backup procedures, and recovery techniques are key in the determination of resilience, as illustrated in Fig. 5.
2. Cost-resilience trade-offs: Various responses to disruptions result in different levels of resilience and related costs. For example, investment in more advanced instruments during recovery could enhance resilience, as depicted in Fig. 5. This emphasizes the value of informed decisions on resource allocation.
3. Timescale considerations: Resilience is dynamic and evolves over time. Systems that are regularly maintained and upgraded tend to enhance resilience, whereas neglected maintenance may lead to a decline in system resilience. Long-term durability is a critical factor for consideration.

This framework recognizes that terminologies like reliability, robustness, recoverability, sustainability, hardness, vulnerability, fault tolerance, and redundancy are generally associated with resilience. But, for the specified purpose of resilience assessment in EDS, the goal is to capture main features such as service delivery, system design, system operations, disruptions, costs, and timescale [43]. Thus, the framework aids in evaluating progress, ensuring system resilience, and identifying methods for enhancement through resilience metrics. These metrics address various necessities at different decision-making levels, illustrating the role of input contribution towards appropriate results, as indicated in Fig. 6. This approach towards resilience metrics improves our understanding of attaining effective and efficient results [43].

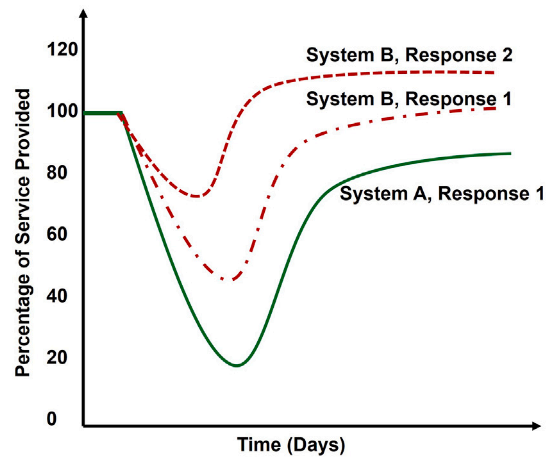

Fig. 5. Resilience curve for various systems and responses proposed by RAND Corporation [43].

3.4. UK government resilience framework in 2022

The UK Government Resilience Framework, issued by the Cabinet Office in 2022 [44], outlines a comprehensive strategy to improve the systems and capabilities that form the foundation of collective resilience. The framework emphasizes that *"resilience encompasses reliability and extends to include resistance, redundancy, response, and recovery as integral components"*. This policy document delineates the proposed metrics and techniques directed at improving the UK's overall readiness to handle and respond to different crisis situations and unexpected events. It acts as a guide, providing details of the government's plans to improve national resilience against a range of challenges, with an emphasis on strengthening the systems by supporting collaborative efforts across multiple sectors and domains. The key features and principles of the framework are as follows,

1. Principles: The framework is founded on three essential principles:
   - Developed and shared understanding of risks: It emphasizes a comprehensive understanding of civil contingencies risks, advocating for this knowledge to underpin all preparation and recovery efforts. This involves adapting the resilience system to face dynamic and complex risks.
   - Prevention over cure: The framework prioritizes risk prevention and the development of resilient systems over merely having robust crisis response capabilities. This involves integrating resilience into decision-making and investment processes.
   - Whole of society endeavor: Resilience is considered a collective effort involving transparency and empowerment of all societal sectors, including government, businesses, community groups, and the public.
2. Implementation: The framework outlines a broad set of measures centered around six main themes: risk, responsibility and accountability, partnership, community, investment, and skills. Each theme is designed to strengthen the system's resilience with specific actions planned for immediate and long-term implementation.
3. Partnership and community involvement: A strong emphasis is placed on partnerships with the private sector and community organizations. The framework seeks to enhance engagement with

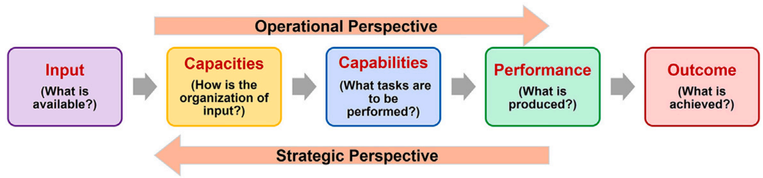

Fig. 6. Resilience implementation framework by RAND Corporation [43].

these groups to improve resilience practices and standards across various sectors.

4. Investment in skills and capabilities: The establishment of the UK Resilience Academy and the enhancement of the National Exercise Program are planned to ensure that individuals working within the resilience framework have the necessary skills and knowledge. This includes new training pathways and professional standards for those involved in resilience efforts.
5. Strategic deliverables by 2030: By the year 2030, the framework aims to have a dynamic understanding of both national and local risks, with improved governance and clear ownership of risks within the government. This includes better communication about risks to the public and integrating insights from UK and international experts into decision-making processes.
6. Transparency and information sharing: The framework highlights the need for better risk communication and transparency, aiming to make information about risks and resilience strategies more accessible and actionable for all stakeholders.

Overall, this framework focuses on prevention, collaboration, and continuous improvement as key elements in the UK's strategy to enhance national and local resilience against a range of emerging and existing threats.

3.5. A resilience framework by IEEE task force in 2023

In 2023 [41], the IEEE Task Force provided a resilience framework as shown in Fig. 7, illustrating a conceptual model for managing system response to extreme events, emphasizing the different stages and phases of crisis management. It delineates three primary stages: pre-event, during-event, and post-event, each with its associated phases that span from proactive defense mechanisms to post-crisis recovery and learning. The y-axis measures system performance, which is expected to decline during the event as the infrastructure and services are impacted, and then recover post-event as restoration efforts take effect.

The timeline along the x-axis shows that the duration of activities varies widely, from years of planning before an event to the immediate,

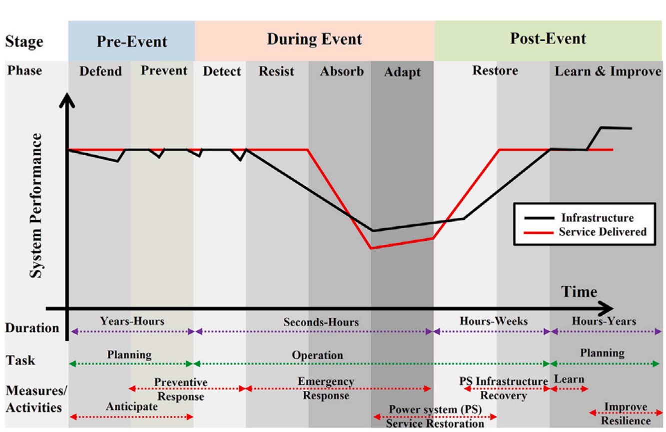

Fig. 7. Resilience curve proposed by IEEE Task Force [41].

operational responses during an event, and finally to the recovery and learning phase afterward. The two lines on the graph represent the performance of infrastructure (black line) and the services it delivers (red line), highlighting that while infrastructure may be designed to withstand events, the actual services provided may be more vulnerable and may recover at a different pace. At the bottom of the figure, tasks and measures or activities are further elaborated, indicating a shift from planning to operation, and back to planning. This suggests a cyclical process where lessons learned post-event feed back into pre-event planning, with an aim to enhance preventive measures and improve resilience. The model shows the essence of crisis management, underscoring the need for anticipation, rapid and effective response, and the continual improvement of systems in the face of adverse events.

It is to be noted that the frameworks presented in this review are proposed by international organizations and agencies that have designed them to provide high-level guidelines for resilience evaluation rather than in-depth implementation procedures. As demonstrated in works such as [42,43], these frameworks serve as foundational principles that must be adapted to specific contexts. This approach acknowledges the inherent diversity among electrical distribution systems, which vary significantly in terms of topological structure, geographical constraints, regulatory environments, available resources, and vulnerability to specific threats. It is emphasized in [9] that transitioning from theoretical frameworks to practical implementation requires system-specific engineering decisions and risk assessments.

The implementation necessarily involves system-specific considerations that extend beyond generalized frameworks, as highlighted by [33] and [45]. While various resilience approaches exist in the literature, such as for microgrid planning [46], for infrastructure assessment [47], and for seismic risk evaluation [48], these represent domain-specific methodologies rather than direct implementations of the comprehensive frameworks. The adaptation of these frameworks to specific EDS contexts remains largely proprietary within utility organizations, with comprehensive case studies rarely published in the literature. The IEEE Task Force framework [41], while comprehensive in its conceptual approach, requires contextual adaptation when applied to specific distribution systems. The RAP [42] provides the most detailed step-by-step methodology for resilience evaluation, offering specific guidance on defining resilience goals, characterizing threats, applying system models, computing metrics, and evaluating improvements, which makes it particularly suitable for adaptation to real-world EDS applications and scenarios.

4. Metrics for resilience evaluation

Traditionally, the evaluation of an electrical distribution system's performance over an extended period relies on reliability metrics such as SAIDI, SAIFI, and Momentary Average Interruption Frequency Index (MAIFI), etc. [49], which are designed to measure how effectively the system delivers power to all connected loads. However, in extreme adversity, prioritizing power supply to critical loads before addressing non-critical ones becomes crucial [41,50]. However, numerous quantifiable metrics for network resilience estimation have been proposed in the literature [1,51]. Some of the existing resilience metrics are detailed below, M1 In 2016 [1], a method to quantify the resilience of a power distribution system using percolation theory and complex network analysis is proposed, where resilience is estimated based on topological resilience, the failure rate of network equipment, power flow feasibility, and intensity of a threat. The resilience metric is given as:

$$\mathfrak{R} = \left[f_c, D, l_g, C_b, C_n, \Lambda_2\right] \tag{1}$$

where f_c represents the critical fraction of the complex network, D denotes the diameter of the complex network, l_g signifies the length of the graph, C_b stands for the betweenness centrality of the graph, C_n denotes the clustering coefficient of the network, and Λ_2 represents the algebraic connectivity of the network. These indices are then evaluated using the analytical hierarchical process (AHP) to compute a composite resiliency score, providing a structured way to prioritize resilience enhancements. The resilience score is obtained in the range of [0, 1] and could be evaluated at any given time instant. The methodology further employs a two-stage reconfiguration algorithm designed to optimize network responses to disruptions, maintaining service continuity by adapting the network layout strategically.

M2 In 2016 [52], a stochastic, energy-based, and operational resilience metric was developed to evaluate the system's ability to restore critical loads using microgrids. The system resilience is defined for the time period $[t_d, t_r^*]$ as:

$$\mathfrak{R} = \int_{t_d}^{t_r^*} \sum_{c \in C} w_c \cdot p_c(t)\, dt, \tag{2}$$

where, t_d and t_r^* are the restorative state and post-restoration state, during which a restoration strategy is applied, respectively. C denotes the set of critical load restored by microgrids; c denotes an arbitrary critical load in C, i.e., $c \in C$. w_c is the weight of a critical load c, and $p_c(t)$ is the active power of load c at time t. This metric is adapted in a stochastic post-hurricane framework to enhance the resilience of networked microgrids using mobile emergency resources, as well as for pre-hurricane resource allocation that includes electric buses.

M3 In 2018 [53], the quantification of the resilience of integrated energy systems is predicated on assessing the loss of functionality within the system. This approach introduces a loss matrix, which encapsulates the various scenarios where system services fail to be delivered during operational analysis periods. These scenarios consider both internal failure modes, such as equipment malfunctions, and external failure modes, such as environmental disasters. From this loss matrix, a consequence matrix is derived by assigning penalty costs to the instances of undelivered services. These costs reflect the impact of service disruptions from a financial or operational standpoint. The consequence matrix is subsequently normalized, establishing a resilience matrix. Within this matrix, the resilience of each element is characterized by its relation to the maximum possible penalty cost, which signifies a total loss of service. Lower values indicate higher resilience, as they represent a smaller proportion of the total potential cost attributed to service disruption.

The resilience of the system is characterized by the *Resilience Matrix*, which is defined as:

$$Resilience\ Matrix = \begin{bmatrix} Re_{1,1} & Re_{1,2} & \cdots & Re_{1,J} \\ Re_{2,1} & Re_{2,2} & \cdots & Re_{2,J} \\ \vdots & \vdots & \ddots & \vdots \\ Re_{I,1} & Re_{I,2} & \cdots & Re_{I,J} \end{bmatrix} \tag{3}$$

where $Re_{i,j}$ is the resilience index for the i-th operational temporal period and the j-th failure mode. The resilience index for each scenario is calculated as:

$$Re_{i,j} = \frac{P_i^{\max} - P_{i,j}}{P_i^{\max}} \tag{4}$$

where $P_i^{\max}$ in each scenario is the penalty cost if all functional services during operational temporal period i are lost, and $P_{i,j}$ is the penalty cost of lost functional services in operational temporal period i and failure mode j. This methodology normalizes the imposed costs to quantify the resilience index, providing a comprehensive measure of system resilience under various scenarios.

M4 In 2018 [51], the process for quantifying resilience in a system via the Choquet Integral involves the following steps:

(a) Identify the resilience parameters that influence the system's ability to withstand and recover from disruptions. These include branch count effect, overlapping branches, switching operations, repetition of sources, path redundancy, probability of source availability and penalty, and aggregated central point dominance.
(b) Assign weights $W_1, W_2, \ldots, W_n$ to each parameter, signifying their relative importance to the system's resilience.
(c) Calculate the interaction index I, which quantifies the extent to which parameters affect one another.
(d) Compute the Choquet integral to aggregate the parameters, considering their weights and interactions, and produce a comprehensive measure of the system's resilience.

The resulting measure is a single value in the range of [0, 1] and can be evaluated at any given time instant. It captures the system's robustness and adaptability, accounting for the complex interplay among various resilience factors.

M5 In 2020 [54], a resilience metric R_j is computed for different nodes in the distribution network to guide the optimal reconfiguration that maximizes system resilience. This metric is defined as

$$R_j = \frac{\alpha_1 \cdot \mathrm{bc}_j}{\alpha_2 \cdot \dfrac{d_{g,j}}{d_{\max}}} \times \frac{P_{\text{critical}}}{P_j} \tag{5}$$

where α_1 and α_2 are system-specific weights, representing the relative importance of the betweenness centrality and the path length factors, respectively. The term bc_j stands for the betweenness centrality of a node j, indicating its influence within the network. The variable $d_{g,j}$ is the geodesic path length from a given node to a generator, and $d_{\max}$ is the maximum path length found in the network. Finally, P_{critical} and P_j represent the real power demands of the critical loads and all the loads in the network at and downstream of node j, respectively.

An algorithm for system reconfiguration uses distribution phasor measurement units (D-PMU) data to monitor angular differences between buses and classify feeders at risk. By iteratively computing R_j for potential reconfigurations and evaluating power flow and stability, the algorithm identifies the optimal switching sequence that maximizes network resilience. This involves shifting critical loads to more resilient parts of the network and potentially shedding non-critical loads to ensure stability. Real-time adjustments are made based on updated data, ensuring the distribution network adapts dynamically to extreme events and maintains power supply to critical loads.

M6 In 2021 [55], criteria for resilience included topology-based and feasible-network-based parameters proposed for resilience measurement. The topology-based resilience metrics, denoted by $\mathfrak{R}_T$, include a vector of the following elements:

$$\mathfrak{R}_T = [D, ACB, \lambda_2, F_c, l_q, C_n, \rho, \mu] \tag{6}$$

where, D represents the diameter of the network, ACB is the aggregate betweenness centrality, λ_2 stands for natural connectivity, F_c is the critical fraction of nodes, l_q denotes the average path length, C_n is the clustering coefficient, ρ refers to the spectral radius, and μ signifies the algebraic connectivity. The resilience score is obtained in the range of [0, 1].

Concurrently, the feasible network-based resilience metrics, represented by $\Re_{FN}$, are comprised of:

$$\Re_{FN} = [BCE, OB, SO, RoS, PR, PoA\&PF, PNF, ACB] \tag{7}$$

where, BCE is the branch count effect, OB refers to overlapping branches, SO denotes switching operations, RoS represents the recurrence of sources, PR is path redundancy, $PoA\&PF$ stands for probability of availability and penalty factor, PNF is the possible network fraction, and ACB is the aggregate betweenness centrality. The resilience score is obtained in the range of [0, 1] and could be evaluated at any given time instant. These sets of metrics facilitate a multifaceted assessment of a system's robustness and adaptability to disruptions, considering both the topological structure and the operational capabilities.

M7 In 2022 [2], a resilience metric, named anticipate, withstand, and recover (AWR), is formulated for monitoring system resilience. The approach is designed to be applicable before, during, and after extreme events, covering the entire event progression. A conceptual resilience curve is presented, illustrating the expected outcomes of the proposed AWR metrics, including delayed impact, reduced impact, enhanced recovery performance, and better post-event performance. Factors impacting resilience are identified based on system characteristics and attributes at each stage of event progression. However, formulation and implementation of this resilience framework that spans before, during, and after an extreme event could introduce complexity. This complexity may pose challenges during the implementation phase, requiring significant resources and expertise. Three individual resilience metrics are evaluated for anticipation, withstanding, and recovery. All three metrics are normalized to a range of [0, 1] and can be evaluated at any given time instant.

- *Anticipate metric computation* $\Re_A$ – The real-world distribution system evaluates common hazards such as hurricanes, cyclones, floods, and earthquakes using this metric, which considers the system's susceptibility to these risks. Scores are assigned for each hazard, and a weighted total score is computed using the following formula.

$$\Re_A = \sum_{j=1}^{N} H_j W_j^H + \sum_{j=1}^{N} V_j W_j^V + \sum_{j=1}^{N} C_j W_j^C \tag{8}$$

where N denotes the total number of factors considered within each domain, $\Re_A$ represents the anticipation metric score derived from combining scores Hj, V_j, and C_j with their respective weights W_j^H, W_j^V, and W_j^C related to the hazard domain, vulnerability domain, and capacity domain, respectively. The above anticipation metric is based on the premise that early threats are identified and warning signs are accessible for calculating the anticipation metric scores.

- *Withstand Metric* $\Re_W$ – The withstand metric evaluates the system's capability to withstand disruptions:

$$\Re_W = [G, D, TIF, CLNL, R_\tau] \tag{9}$$

$$D_W = [1, -1, -1, 1, 1] \tag{10}$$

where $CLNL$ is the critical load not lost that measures the fraction of critical loads that remain operational, positively influencing resilience. G is the generation capacity, which indicates the available power capacity, enhancing resilience when higher. D is the demand at critical loads, which is the operational demand, that negatively impacts resilience when high. TIF is the threat impact factor that assesses the effects of disruptions on system topology, with lower values indicating better resilience. R_τ is the topological robustness that evaluates the network's ability to withstand events, contributing positively to resilience. Together, these parameters provide a comprehensive assessment of the system's ability to maintain functionality during disruptions.

- Recover Metric $\Re_R$ – The recover metric evaluates the system's capability to restore services following an incident:

$$\Re_R = [RG, RP, CLR, SO, TSO] \tag{11}$$

$$D_R = [1, 1, 1, -1, 1] \tag{12}$$

where CLR is the critical load restored that enhances recovery by ensuring a higher proportion of critical loads are restored, directly improving the system's ability to meet essential demands post-event. RP is the path redundancy that increases recovery resilience by providing multiple pathways for power delivery, thereby ensuring that critical loads have alternative routes for supply in case of failures. RG is the generation redundancy that contributes to resilience by ensuring the availability of multiple power sources, enhancing the reliability and stability of the power supply. SO is the switching operations that negatively impact recovery by introducing more complexity and potential delays in network reconfiguration, which could slow down the restoration process. TSO is the switching time, which also negatively affects recovery by increasing the time required to reconfigure the network, thus delaying the restoration of service to the affected areas.

M8 In 2024 [56], we have proposed a methodology that takes into consideration both the topological constructs from complex network parameters and the electrical service requirements. The proposed resilience metric ($\Re$) is determined as,

$$\Re = R \cdot W^T \tag{13}$$

where,

$$R = [PV_{CL}, N_{CLS}, A_{RoS}, p_m, N_{HC}] \tag{14}$$

$$W = [w_{PV_{CL}}, w_{N_{CLS}}, w_{A_{RoS}}, w_{p_m}, w_{N_{HC}}] \tag{15}$$

All five parameters in R are normalized in the range of 0 to 1 and then multiplied to their respective weights, denoted by $w_{PV_{CL}}$, $w_{N_{CLS}}$, $w_{A_{RoS}}$, w_{p_m} and $w_{N_{HC}}$ corresponding to the path variability, ratio of critical loads served, and average rating of service, percolation threshold, and number of nodes with higher information centrality, respectively.

A quantitative comparison of each resilience metric could not be conducted as there exist intrinsic differences in design, scope, and focus areas. Additionally, these metrics often rely on different units of measurement or scales, which makes direct numerical comparison unfeasible. The resilience metrics M1, M3, M4, M5, M6, M7, and M8 are unitless and are in the range of [0, 1] for M1, M4, M6, M7, and M8. For M2, M3, and M5, the minimum value for the resilience score is zero, and they do not have an absolute upper bound within the formula itself but are limited by the power limits of the network. Thus, a quantitative comparison is not possible. Therefore, a qualitative comparison is conducted covering all the specific dimensions of resilience. This approach allows for a better assessment of how each metric contributes to understanding and enhancing the resilience of power systems, as detailed in Table 4. This comparison ensures that the evaluation captures the multifaceted nature of resilience in EDS, providing an overview of each

Table 4
Comparison of resilience metrics.

References	Year	Electrical service parameters	Topological parameters	Operational metrics	Planning metrics	Considers RAP	Critical Load analysis	Considers IEEE task force definition & framework
M1 [1]	2016	–	Yes	Yes	Yes	–	Yes	–
M2 [52]	2016	Yes	–	Yes	–	–	Yes	–
M3 [53]	2018	Yes	–	Yes	–	–	Yes	–
M4 [51]	2018	Yes	–	Yes	Yes	–	Yes	–
M5 [54]	2020	Yes	Yes	Yes	–	–	Yes	–
M6 [55]	2021	Yes	Yes	Yes	Yes	–	Yes	–
M7 [2]	2022	Yes	Yes	Yes	Yes	–	Yes	–
M8 [56]	**2024**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**

metric's strengths and limitations. Each of the above metrics evaluates distinct aspects of resilience, such as operational and planning. Also, they use different topological and electrical service parameters. All of the above metrics except M8 have not followed the detailed steps set forth by RAP. As the IEEE Task Force definition and framework were introduced in 2023, none of the metrics available in the literature could consider it.

The proposed resilience metric M8 is the first metric that aligns with the RAP and IEEE Task Force frameworks by incorporating both quantitative electrical service parameters and qualitative complex network parameters. This combination enables a comprehensive assessment of the EDS resilience, addressing uncertainties, vulnerabilities, and recovery capabilities. The metric's adaptability and scalability make it applicable in various planning and operational scenarios, facilitating comparisons across different power distribution systems.

While this review presents various resilience metrics and frameworks, achieving standardization across these metrics remains a significant challenge. The diverse nature of resilience metrics, spanning topological, electrical, operational, and planning domains, creates inherent difficulties in establishing a unified measurement approach. As noted by [41], there is still no consensus on a comprehensive set of metrics to quantify power system resilience. The metrics presented serve distinct purposes such as some quantify network robustness [1,55], others assess energy-based resilience [52], while others evaluate load prioritization [54] or multi-stage resilience [2]. This diversity, while beneficial for addressing specific aspects of resilience, complicates standardization efforts.

Standardization is further challenged by variations in measurement units, scales, and the context-specific nature of resilience requirements across different electrical distribution systems. In [42], it is emphasized that resilience metrics must be comparable, applicable across operations and planning, scalable, and able to incorporate uncertainty—requirements that are challenging to satisfy simultaneously. Further complicating standardization is the observation by [53] that metrics must address both qualitative and quantitative aspects. Additionally, different stakeholders, such as utilities, regulators, and customers, may prioritize distinct aspects of resilience, further impeding standardization efforts.

Despite these challenges, promising approaches are emerging. Advanced mathematical techniques proposed in [51], like the Choquet integral, could be used to combine diverse metrics into more comprehensive measures. Overcoming standardization hurdles will require collaborative industry-wide initiatives to develop normalized metrics that maintain context-specific relevance while enabling meaningful cross-system comparisons. Such standardization would facilitate more effective resilience investment decisions and enable benchmarking across different electrical distribution systems.

5. Application of complex network theory parameters for resilience evaluation of EDS

Complex network theory (CNT) is broadly defined as the study of networks that display patterns of connection between their elements that are neither purely regular nor purely random. These patterns often reveal intricate topological structures that influence the network's functionality and behavior [57]. Complex networks are typically characterized by features such as a heavy-tailed degree distribution (most nodes have few connections, and a small number of nodes have many connections. This pattern results in a distribution where the tail is heavy or fat, indicating it declines slower than an exponential distribution), with high clustering coefficients (the likelihood that two nodes connected to a common node are also connected to each other), and short average path lengths (the average number of steps it takes to get from one node to any other node in the network) [58].

Complex network theory finds applications across a multitude of fields. In biology, it helps in understanding the intricacies of neural networks and genetic regulation [59]. In sociology, it provides insights into social structures and dynamics [60]. In the realm of technology, it's crucial for the design, analysis, and optimization of communication networks and the internet. By blending mathematics, physics, computer science, and specific domain knowledge, complex network theory offers a framework for understanding the structure and behavior of complex systems, making it a vital tool in the analysis of the interconnected world.

Numerous works have employed CNT to examine the resilience of critical infrastructures. The use of CNT for evaluating the resilience of sophisticated physical networks was initially proposed by R'eka Albert and Albert-L'aszl'o Barab'asi in 2002 [61]. In the field of power systems, complex network theory has been utilized to tackle various problems related to reliability and resilience. These problems include the identification of critical nodes [62,63], the development of restoration strategies for distribution systems [64], the analysis of connectivity loss [65], the study of reliability and disturbances [25], the assessment of unserved energy/load [66], the investigation of cascade effects [67], and the examination of blackout size [68].

Nguyen et al. identified critical nodes in an interdependent power network whose removal significantly disrupts its functions due to both the malfunction of these nodes and the resulting cascading failures in its associated communication network using a greedy algorithm with novel centrality functions based on the networks' interdependencies [62]. Rosas-Casals et al. performed an analysis of the topological structure and static tolerance of the September 2003 update of the Union for the Coordination of Transport of Electricity (UCTE) power grid, which covers thirty-three different networks, revealing some notable characteristics [63]. Although each power grid has an exponential degree distribution and most lack the typical small-world topology, their responses to node loss are similar to those seen in scale-free networks. The results indicate that the behavior related to node removal has a logarithmic relationship with the size of the power grid. This suggests that while larger sizes might increase fragility, growth could potentially mitigate this effect.

Network reconfiguration plays a fundamental role in restoring load efficiently following extensive power system blackouts. To address this, a network reconfiguration strategy that considers different prioritized objectives is proposed [64]. This strategy employs a preference-based

Table 5
CNT parameters utilized in recent literature for resilience assessment [70].

References	Parameters
[50]	D_g, ACB, λ_2, f_c, l_q, C_n
[55]	D_g, ACB, λ_2, f_c, l_q, C_n, ρ, μ_n
[2]	D_g, ACB, λ_2, f_c, l_q, C_n, ρ, μ_n
[1]	D_g, ACB, λ_2, f_c, l_q, C_n
[49]	p_m, C_n
[71]	p_m, f_c
[72]	λ_2, C_n, l_q
[73]	μ, ρ, λ_2, R_{eff}

D_g: diameter of the graph, ACB: average betweenness centrality, λ_2: algebraic connectivity, f_c: fraction of critical nodes, l_q: average shortest path length, C_n: average clustering coefficient, ρ: spectral radius, μ_n: natural connectivity, p_m: percolation threshold, μ: average degree, R_{eff}: effective graph resistance.

multiobjective optimization approach to develop effective network reconfiguration schemes. For connectivity loss, the power grid is analyzed from a network perspective to assess its capacity for transferring power between generators and consumers amidst disruptions. It showed that the grid is generally robust against various perturbations [65]. However, the findings indicated that disturbances impacting critical transmission substations significantly compromise the grid's operational efficiency.

Further in [25], a complex network was formed for the European transmission power grid to analyze that the network's topology is linked to its fragility, including a detailed examination of major malfunctions. It showed the critical relationship between the structural characteristics of the grid and its susceptibility to failures. In [67] the interdependence among systems and how it influences cascading behaviors is analyzed. This helps to predict and manage potential failures that could spread across interconnected networks, impacting everything from energy grids to communication infrastructures. Additionally, an overview of modeling power grids as complex networks, with an emphasis on their resilience and reliability analysis, is conducted in [68]. A failure originating from a small set of components could rapidly propagate throughout the entire network, potentially triggering a cascade of failures that leads to a grid blackout.

Assessing the resilience of EDS through CNT parameters is not to be viewed as an attempt to improve existing reconfiguration strategies. Rather, it offers a comprehensive insight that enables a deeper understanding of EDS, leading to enhanced operational performance and planning strategies. EDS typically exhibit radial topologies, where multiple loads rely on a single feeder branch, resulting in sparsely interconnected nodes. Weather-related disruptions affecting these critical nodes could greatly disrupt the continuous power supply to consumers [69]. Table 5, shows the extensive research efforts that have been made towards developing resilience metrics based on CNT parameters. These metrics analyze various network characteristics and assign weights to each characteristic to evaluate the resilience of the system.

6. Resilience enhancement techniques

As there is a critical need for enhancement of resilience in EDS, several techniques are employed. The techniques are implemented either during the planning of EDS or during its operation [70], as shown in Fig. 8.

6.1. Resilience enhancement planning techniques in EDS

Proactive planning-based resilience enhancement techniques are essential for EDS to withstand disruptive events and overcome adversities. These techniques encompass a wide range of measures, such as undergrounding distribution and transmission lines, constructing redundant power distribution routes, and upgrading critical infrastructure components using more durable materials [74–76]. EDS improves its capacity to sustain operational continuity during extreme events by investing in

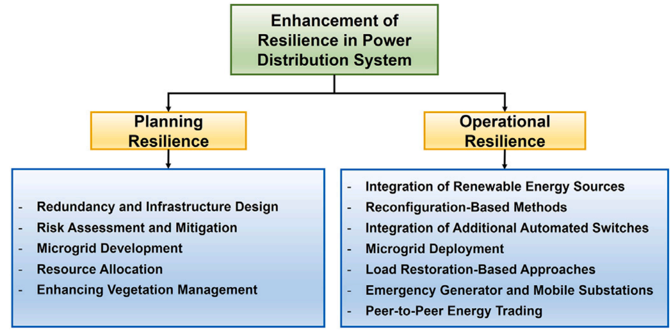

Fig. 8. Planning and operational resilience enhancement techniques [70].

Table 6
Recent resilience enhancement planning techniques in EDS.

Techniques	References
Redundancy and infrastructure design	[46,74–78,83–87]
Risk assessment and mitigation	[47,48,88–90]
Microgrid development	[91–98]
Resource allocation	[99–105]
Enhancing vegetation management	[79–82]

substations, integrating backup generators, and installing remote control switches [46,77,78]. Implementing effective vegetation management strategies helps minimize power outages resulting from fallen trees and branches [79–82], optimizing the placement and sizing of battery storage units and renewable energy sources enhances grid sustainability. These measures are crucial for the preparation of EDS to withstand disruptive events and ensure a dependable and continuous power supply to customers during challenging times. Recent works on various planning strategy techniques are summarized in Table 6. The application of resilience metrics in specific use cases for some of these works in each category is listed in Tables 7–11.

6.2. Resilience enhancement operational techniques in EDS

In power distribution systems, operational resilience techniques play a crucial role in minimizing the effects of adverse disruptive conditions, providing flexible strategies to minimize outages and ensuring a reliable electricity supply when faced with hazardous situations. These strategies encompass a range of methods, such as network reconfiguration, microgrid formation, the use of mobile emergency resources and energy storage units, integration of renewable energy sources, and peer-to-peer energy trading. Table 12 summarizes the recent works for these categories. The application of resilience metrics in specific use cases for some of these works in each category is listed in Tables 13–18. Network reconfiguration methods focus on optimizing the grid layout, whereas microgrid formations involve dividing the grid into smaller, self-reliable units that operate independently or in conjunction with the main grid. The deployment of mobile energy resources ensures a rapid response when faced with extreme events. Load restoration strategies accelerate the process of restoring supply after the disruptions have occurred, supported by DERs and dispatching trained repair personnel. Furthermore, situational awareness-based frameworks improve resilience by forecasting and responding to supply outages. P2P energy trading is incorporated into microgrids, which are localized and capable of independent operation from the main grid when faced with extreme events, thus improving the resilience of the community. Collectively, these techniques improve the reliability of EDS by providing continuous supply of power when faced with extreme events.

This review comprehensively examines both the structural and operational dimensions of resilience in electrical distribution systems, recognizing that effective resilience strategies must address both the

Table 7
Planning techniques for enhancement of resilience – Redundancy and infrastructure design.

References	Resilience evaluation	Application
[74]	$FCRE = \sum P_i \cdot C_i$ where, $FCRE$: fault chain risk expectation P_i: probability of fault chain i, C_i: consequences.	Enhancing resilience against hurricanes through fault chain analysis.
[76]	Resilience is achieved by minimizing total load losses using a trilevel optimization model. $\min \sum_{d\in D} S_d(h_{Pl}, h_{Ck})$ h_{Pl}, h_{Ck}: binary hardening variables, S_d: load losses.	Hardening lines and cables, maintaining connectivity during disruptions.
[46]	$RI_w = \frac{\text{Restored Load}_w}{\text{Total Load}} \times 100\ \%$ where, RI_w : resilience index for each outage state w.	Applied in planning to enhance network resilience using micro-grids for independent or collaborative operation.
[78]	$R(t) = \int (1 - L(t))\, dt$ where, $R(t)$: resilience at time t, $L(t)$: loss of function.	Seismic retrofitting analysis with Monte Carlo method
[77]	DRI_{load} = Load served during disruption / Total load demand DRI_{load} : load resiliency index	Multi-stage planning against hurricanes.
[75]	$\text{VoDA}_\epsilon = \frac{F^\epsilon_{\text{dro}}(w^{SP}, y^{SP}) - F^\epsilon_{\text{dro}}(w^{dro}, y^{dro})}{F^\epsilon_{\text{dro}}(w^{dro}, y^{dro})}$ $\text{VoMI}_\epsilon = \frac{F^\epsilon_{\text{dro}}(w^{RO}, y^{RO}) - F^\epsilon_{\text{dro}}(w^{dro}, y^{dro})}{F^\epsilon_{\text{dro}}(w^{dro}, y^{dro})}$ where, VoDA_ϵ: value of distributional ambiguity for a given ϵ, VoMI_ϵ: value of moment information for a given ϵ, ϵ: parameter for conservatism level or uncertainty set size in DRO models, F^ϵ_{dro}: optimal value function under DRO for a given ϵ, w, y: optimal first-level decisions, SP : stochastic programming model, RO : robust optimization model, DRO : distributionally robust optimization model.	Strategic planning in electrical networks for informed decision-making under uncertainty.

Table 8
Planning techniques for enhancement of resilience – Risk assessment and mitigation.

References	Resilience evaluation	Application
[47]	$R = \frac{1}{t_h - t_0} \int_{t_0}^{t_h} Q(t)\, dt$ where, $Q(t)$: functionality at time t, t_0: time of event occurrence, t_h: fixed horizon time.	Assessment of bridge network performance post-event, focusing on recovery speed and robustness.
[88]	$E_{unserved} = \sum(P_{out} \times duration)$ $C_{accum} = \sum(C_{repair} + C_{lost} + C_{op})$ where, $E_{unserved}$: load energy unserved, P_{out}: power outage in MW, C_{accum}: accumulated cost, C_{repair}: repair costs, C_{lost}: cost of lost load, C_{op}: operational costs	Minimizing the impact of floods on the power grid by optimizing substation hardening and evaluating the effectiveness across various flood scenarios.
[48]	$\lambda_{SP}(sp) = \nu \int_{\Omega\subseteq\mathbb{R}^n} P(SP > sp \mid IM = im) f_{IM}(im)\, dim$ where, $\lambda_{SP}(sp)$: mean annual frequency of exceedance for a performance metric, SP, exceeding a specific threshold, sp. ν: mean annual rate of significant earthquake events. SP: system performance metric, a scalar measure of system functionality or performance. sp: threshold value of SP, specifying the point beyond which system performance is considered unacceptable. IM: intensity measures, parameters describing the severity of ground motion during an earthquake. im specifically denotes a particular realization or value of these intensity measures. $f_{IM}(im)$: joint probability density function of the intensity measures, detailing their statistical distribution. Ω: domain of integration, representing the range of considered intensities for the study.	Seismic risk and resilience evaluation of the Chilean Electric Power Networks (EPN) at national, regional, and component levels, focusing on ENS and recovery times post-earthquake.

Table 9
Planning techniques for enhancement of resilience – Microgrid development.

References	Resilience evaluation	Application
[91]	$RI = e^{-\left(\frac{OF_{\text{a}} - OF_{\text{n}}}{B_{\text{at}} \cdot N_y}\right)}$ where, RI: resilience index, OF_{a}: overall financial outcome under attack, OF_{n}: overall financial outcome under normal conditions, B_{at}: attacker's budget, N_y: normalization factor.	Integrated into planning and optimization of MCMGs to enhance resilience against cyber-physical attacks, ensuring service of critical loads.
[92]	$\text{RESI} = \frac{1}{t_r - t_e} \int_{t_e}^{t_r} \left[\frac{\text{SPF}_0(t) - \text{SPF}(t)}{\text{SPF}(t)}\right] dt$ where, RESI: resilience index, t_e and t_r: start and end times of the event $\text{SPF}_0(t)$ and $\text{SPF}(t)$: system performance functions.	Optimization of microgrid resilience through optimal allocation of distributed energy resources and switches during HILP events.
[93]	$RI = \frac{A + B}{C + D}$ $A = \sum_{n\in CL}(u^{CL} \cdot P^L_{n,t} - P^D_{n,t} - P^F_{n,t}) \quad C = \sum_{n\in CL}(u^{CL} \cdot P^{L,CL}_{n,t})$ $B = \sum_{n\in NL}(u^{NL} \cdot P^L_{n,t} - P^D_{n,t} - P^F_{n,t}) \quad D = \sum_{n\in NL}(u^{NL} \cdot P^{L,NL}_{n,t})$ where, RI : resilience index, u^{CL}, u^{NL}: weighted coefficients for critical loads (CL) and normal loads (NL), $P^L_{n,t}$: load at node n at time t, $P^D_{n,t}$: directly controlled load, $P^F_{n,t}$: forced load shedding.	Enhancing resilience of microgrids via a two-layer optimization framework considering hybrid energy storage systems, electric buses, and direct load control programs.
[94]	$R(t) = \max\ \{\text{RF}(t), \text{FD}(t), \text{QD}(t)\}$ where, $R(t)$: resilience at time t, RF: rate of change of frequency, FD: lowest frequency post-disturbance, QD: quasi steady-state frequency deviation (deviation from nominal frequency).	Used to assess the resilience of microgrids under transient and static islanding conditions, ensuring operational security and survivability during unscheduled islandings.
[95]	$RankV_i = \max\{\frac{POPF_{ik}}{P_{\theta k}}\}$ for line i, $\quad DegV_i = \lvert\{RankV_i > \gamma\}\rvert$, $RankC_k = \max\{\frac{POPF_{ik}}{P_{\theta i}}\}, \quad DegC_k = \lvert\{RankC_k > \gamma\}\rvert$, where, $RankV_i$: resilience evaluation metric used in the analysis of microgrid topologies, $P_{\theta k}$: thermal rating of line k. $POPF_{ik}$: probability of failure of line i when line k is affected. γ : predefined safety threshold. $DegV_i$ counts the number of scenarios where the rank value exceeds γ. $RankC_k$: assesses the criticality of line k based on the impact of outages on line i. $DegC_k$: reflects the number of critical cases where the rank of criticality exceeds the safety threshold γ.	This methodology is applied to assess the resilience of isolated microgrid topologies by simulating various fault scenarios. It evaluates the performance of different topological designs under stress conditions, focusing on optimizing the positioning of assets to enhance system resilience against outages.

Table 10
Planning techniques for enhancement of resilience – Resource allocation.

References	Resilience evaluation	Application
[99]	$R = SOM\ (r_{ae}, r_{cl}, r_{gd}, r_{rl}, r_{cs}, r_{er}, r_{sub}, r_{path})$ where, R : resilience metric, SOM : self-organizing map, r_{ae}: average asset-level resilience, r_{cl}: sustainability of critical loads, r_{gd}: capacity and geographical distribution of DERs, r_{rl}: criticality of power lines, r_{cs}: cybersecurity of automation infrastructure, r_{er}: availability of energy reserves, r_{sub}: feasible islands, r_{path}: path redundancy.	Applied to dynamically evaluate and enhance system resilience by influencing operational and resource allocation decisions in real-time during extreme events.
[100]	$R = \frac{1}{T}\int_0^T F_{\text{network}}(t)\,dt$ where, R : resilience of infrastructure network, $F_{\text{network}}(t)$: functionality of the network at time t, T: planning horizon.	Application through a methodological framework using DDQN and agent-based modeling to optimize resource allocation for maximizing long-term infrastructure resilience.
[101]	$R_v = \frac{P(t_e) - P(t_o)}{t_e - t_o} - 1 \quad R_r = \frac{P(t_{trs}) - P(t_e)}{t_{trs} - t_e} - 1$ where, (R_v) : vulnerability Rate, (R_r) : restoration rate, $P(t)$: performance level of the system at time t, t_o : time at the onset of the extreme event, t_e : time at the end of the extreme event, t_{trs} : time when restoration is complete.	Applied to the IEEE 69-bus test radial distribution system to assess changes in system performance under extreme weather conditions, focusing on system aging and recovery dynamics.

Table 11
Planning techniques for enhancement of resilience – Enhancing vegetation.

References	Resilience evaluation	Application
[79]	$EVI = \frac{2.5 \times (IR - R)}{IR + C_1 \times R - C_2 \times B + L}$ where, EVI : enhanced vegetation index, IR: near-infrared reflectance, R: red light reflectance, B: blue light reflectance, $C_1 = 6$, $C_2 = 7.5$, $L = 1$ (adjustment parameter for soil reflectance).	EVI is used to monitor the recovery and decline of vegetation due to geological hazards and soil erosion in Shaanxi Province, analyzing spatiotemporal changes and correlations with climatic factors and human activities.
[81]	$SD_p = f$(soil properties, plant community, seed bank properties) where, SD_p: density of persistent seeds as an indicator of vegetation resilience. Structural equation modeling (SEM) and the plant-soil-seed bank quality index are used to assess the effect.	Used to evaluate the resilience of vegetation in degraded and restored grasslands by examining the changes in seed density and composition in relation to soil and plant community characteristics.
[80]	$QI = \sum_{i=1}^{n}(W_i \times SF_i)$ where, W_i : weighting factor for the indicator from principal component analysis, SF_i : indicator score, and n : number of selected variables.	Application of the resilience metric in the evaluation of long-term active restoration effectiveness in degraded grasslands.
[82]	$RI = \int_{t_0}^{t_0+t_c} Q(t)dt$ where, RI: resilience index, t_0: start of wind hazards, t_c: control period, $Q(t)$: system performance at time t. EENS $= \sum_i \sum_t P_{i,t}$ where, EENS: expected energy not supplied, $P_{i,t}$: power not supplied to customer i at time t.	These metrics are used to assess the effectiveness of vegetation management strategies when affected by wind hazards. By reducing the probability of tree failures through measures such as crown thinning, pruning, or removal of hazardous trees, the impact on power distribution systems may be minimized.

Table 12
Recent resilience enhancement operational techniques in EDS.

Techniques	References
Integration of renewable energy sources	[106–117]
Reconfiguration-based methods	[118–125]
Integration of automated switches	[126–128]
Microgrid deployment	[129–137]
Load restoration- based approaches	[138–144]
Mobile emergency generators	[145–151]
Peer-to-peer energy trading	[152–160]

physical robustness of infrastructure and the adaptive operational protocols necessary to respond to and recover from disruptions. It is worth emphasizing that all resilience metrics discussed (M1–M8) explicitly incorporate operational resilience considerations, highlighting the recognition of operational adaptability as a critical component of comprehensive resilience evaluation. This balanced approach reflects the understanding that structural improvements alone are insufficient without corresponding operational strategies to effectively respond to and recover from extreme events.

7. Research gaps and future directions

From the above literature review, the following gaps were identified,

G1 Lack of a universal resilience definition: Despite numerous efforts to define resilience within the power systems domain, a universally accepted definition remains elusive. Different organizations and researchers often emphasize various aspects of resilience, leading to diverse interpretations and a lack of standardization in resilience assessment and enhancement strategies.

G2 Absence of resilience metric that considers frameworks of both IEEE and RAP: Existing resilience metrics do not fully align with both the recent IEEE framework of resilience and the resilience analysis process. There is a need for comprehensive metrics that integrate both electrical and topological considerations to cover the operational and planning aspects of resilience.

G3 Lack of resilience metrics with electrical and topological parameters that cover both operational and planning of resilience: Existing resilience metrics tend to focus either on electrical aspects, such as service continuity and load prioritization or on topological features, like network configuration and robustness. A metric that synergizes both electrical service requirements and topological network properties to assess resilience holistically across different stages of power system operation and planning is lacking.

G4 Lack of application of resilience curve analysis for extreme events: While the concept of a resilience curve is well-established theoretically, its application to simulated or actual extreme events in power systems is limited. There is a gap in practical, empirical research applying resilience curve analysis to real-world scenarios to validate the effectiveness of resilience enhancement techniques and metrics.

G5 Insufficient emphasis on renewable energy integration and grid automation: Although renewable energy sources and grid automation are recognized as important elements of a resilient power system, more in-depth research is needed to understand their roles and impacts. This includes studying the effects of

Table 13
Operational techniques for enhancement of resilience – Integration of renewable energy sources.

References	Resilience evaluation	Application
[92]	$RESI = \sum_{s\in S, se\in SE}\left(\frac{1}{N_s}\sum_{i\in BUS}\left(\frac{P_L-(1-b_{curt})P_L}{P_L}\right)dt\right)$ where, $RESI$: resilience index, P_L: load at bus i at time t for scenario s and season se, b_{curt}: load curtailment binary variable.	Evaluating microgrid resilience during HILP events through DERs and operational strategies for various contingencies and scenarios.
[110]	$LPS = \max\left(P_m\right)$ where, LPS: largest amount of power supply, P_m: power that could be maintained during and after attack.	Employed during the quick restoration stage after malware attacks, with strategies to maximize power supply through system configuration and proactive cyber node protection.
[114]	$P^{+}_{EV,j,s} = \begin{cases} P_{EV,j,s}-\delta_1 & \text{if } s=t \\ P_{EV,j,s}+\delta_1 & \text{if } s=t' \\ P_{EV,j,s} & \text{otherwise} \end{cases}$ where, $\delta_1(t,t')$: shifted power, $P_{EV,j,s}$: original power exchange profile for EV j at time s.	Implementation of a distributed control strategy to reduce load curtailment in urban energy systems using EVs' charging and discharging capabilities.
[117]	$\psi_s = \frac{\psi^s_a+\psi^s_b}{2}$ where, ψ^s_a: proportion of energy demand supplied, ψ^s_b: economic impact of ENS relative to total operation cost.	Evaluation of SDN resilience in various scenarios with configurations of BDGs, BESSs, and DRPs, demonstrating enhancements in system resilience.

Table 14
Operational techniques for enhancement of resilience – Reconfiguration-based methods.

References	Resilience evaluation	Application
[120]	$DSR = \frac{\text{Load demand in reconfigured network}}{\text{Load demand in DOPF}}$ where, DSR: demand satisfaction rate, DOPF: distribution network optimal power flow	Optimizing network reconfiguration using sectionalizing switches during line outages.
[123]	$RSC = \frac{\text{Sum of load shed during fault}}{\text{Total system load}} \times 100\ \%$ where, RSC: resilience supply capability, measures how much of the load could be sustained during faults.	Employed to sustain critical loads during faults by isolating damaged parts and rerouting power.
[119]	$\mathcal{R} = \frac{1}{\int_{t1}^{t4}[P_{\text{target}}(t)-P(t)]\,dt}$ where, $\mathcal{R}$: resilience index, $P_{\text{target}}(t)$: target power at time t, $P(t)$: actual power at time t, t_1 : start time of performance degradation, and t_4 : time of performance full restoration.	Optimization of DER placement and sizing and power network reconfiguration to minimize critical load curtailment in response to cyberattacks.
[121]	$cpR = \frac{\sum_i (i\delta \cdot iP\Delta \cdot E_i\tau)}{\sum_i P_i}$ where, $i\delta$: load grade weight, $iP\Delta$: load loss at each node, $E_i\tau$: component failure probability.	Used in optimizing load reduction and network reconfiguration in response to earthquake intensities.
[118]	$RC = 1 - \frac{Q(t_0)-Q(t_f)}{Q(t_0)-Q(t_d)}$ where, RC: community disaster resilience, $Q(t)$: total origin destinations demand satisfaction ratio, t_0: pre-disaster time, t_f: post-disaster functional recovery time, t_d: post-disaster degraded state time.	Enhancing resilience through optimized network reconfiguration, including the implementation of strategies and elimination of road intersection.

Table 15
Operational techniques for enhancement of resilience – Additional Automated Switches.

References	Resilience evaluation	Application
[126]	$\Re = [BCE, PR, PoA\&PF]$ where, BCE: branch count effect, PR: path redundancy, PoA: probability of availability, PF: penalty factor.	Application of automated switches and DERs to enhance system resilience. The methodology uses AHP for resilience quantification.
[127]	$REI = E\left(\frac{\int_{t_0}^{t_4} RP_{\text{d}}\,dt + \int_{t_4}^{t_5}(RP_{\text{n}}-RP_{\text{d}})\,dt}{\int_{t_0}^{t_4} RP_{\text{n}}\,dt}\right)$ where, REI : resilience index, RP_{n}: normal operation function curve, RP_{d}: disaster impact function curve, E: expected value function, t_0 to t_5: assessment time intervals.	Assessment of resilience under typhoon scenarios, evaluating both information and physical systems' responses.

Table 16
Operational techniques for enhancement of resilience – Microgrid deployment.

References	Resilience evaluation	Application
[130]	$\Re = \left[\sum(P_{\text{out}}-P_{\text{in}})\right] \geq r\left[\sum_{n\in\Omega_{\text{HP}}} P_{L,n}\right]$ for $t \leq h$ where, $\Re$: resilience metric, P_{out}, P_{in}: power out and in at time t, $P_{L,n}$: power load at node n, Ω_{HP}: set of high priority nodes, r, h: resilience parameters.	To maintain power supply to high-priority nodes during outage periods.
[134]	$RI = \frac{\sum_{t=1}^{T} R_t \times W_t}{\sum_{t=1}^{T} W_t}$ where, RI : resilience index, R_t : restoration effectiveness at time t, W_t : weight of restoration at time t, T : total duration of restoration.	Used in hierarchical multi-agent reinforcement learning to optimize routing and repairing decisions in a coupled power-gas-transportation network.

Table 17
Operational techniques for enhancement of resilience – Load restoration.

References	Resilience evaluation	Application
[139]	$\mathrm{RI} = \min_{\omega\in\Omega_F}\{\alpha_{VL}(\sum_{i\in\Omega_B}\alpha_{l_i}\lambda_\omega^v(i) - P_{di}) + \sum_{i\in\Omega_B}(1-\alpha_{l_i})\lambda_\omega^i P_{di}\}$ where, RI : resilience index, Ω_F: set of fault scenarios, α_{VL}: weight of vital load, Ω_B: set of buses, α_{l_i}: load importance factor at bus i, $\lambda_\omega^v(i)$: vital load restoration rate under fault scenario ω at bus i, P_{di}: demand power at bus i, λ_ω^i: general load restoration rate under fault scenario ω at bus i.	Optimization of network partitioning in power system restoration after typhoon, focusing on minimizing load losses due to secondary faults, employing a multi-objective MILP model.
[140]	$R = \omega_1 R_{PG} + \omega_2 R_{PL} + \omega_3 R_{EI} + \omega_4 R_{EV}$ where, R : resilience metric, R_{PG}: restored active power, R_{PL}: load active power, R_{EI}: number of information flow lines, R_{EV}: number of virtual power plant (VPP) system transmission lines.	Resilience assessment applied in the VPP recovery process, incorporating evaluation at both the power grid and information network levels to measure changes in system resilience, primarily through energy flow dynamics.

Table 18
Operational techniques for enhancement of resilience – Mobile emergency generators.

Reference	Resilience evaluation	Application
[149]	Self-healing ability $= \dfrac{L_{\mathrm{Res}} - L_{\mathrm{Exp}}}{L_{\mathrm{Total}} - L_{\mathrm{Exp}}}$ where, L_{Res}: restored load after fault, L_{Exp}: expected load to survive without healing, L_{Total}: total load.	Evaluating the effectiveness of load restoration in faulted situations during islanded operations.

distributed energy resources in renewable integration and the implementation of automated switches on the resilience of EDS, especially under extreme event conditions.

G6 Need for dynamic and adaptive resilience enhancement techniques: Resilience enhancement methods must not only mitigate the immediate effects of disturbances but also adapt to evolving risks and vulnerabilities. Research is needed to develop dynamic and adaptive strategies that anticipate future challenges and incorporate flexibility to adjust to changing conditions.

G7 Insufficient integration of socioeconomic factors in resilience assessment: This review reveals that research in the literature has primarily focused on technical and operational aspects of resilience in electrical distribution systems, with limited attention to socioeconomic considerations. A truly comprehensive understanding of resilience must incorporate how power outages impact community welfare, public health, economic productivity, and social equity beyond grid functionality. It is emphasized in [43] that resilience frameworks should capture both technical performance and societal impacts, while [33] highlights the importance of a "whole of society endeavor" in building resilience. The UK Government Resilience Framework [44] explicitly identifies community involvement as a key resilience principle. Despite these recognitions, the literature shows a gap in methodologies for quantifying social impacts and integrating them with technical metrics. Although [88] addresses economic dimensions through cost accumulation models for outages, the broader social costs, including impacts on vulnerable populations, essential services, and long-term community development, remain underexplored in existing research.

G8 Limited consideration of infrastructure interdependencies and geographical context: A significant dimension that merits greater attention in resilience assessment is the interdependence between electrical distribution systems and other critical infrastructure networks. These infrastructure systems exhibit complex bidirectional dependencies like power outages, which can cascade to disrupt communication networks, water supply, transportation, and emergency services, while failures in these systems can impede power restoration efforts. In [134], some of these interactions are addressed in the context of coupled power-gas-transportation networks, and [118] examines relationships between power distribution and transportation for emergency services. However, comprehensive frameworks for modeling and enhancing resilience across interconnected infrastructure systems remain underdeveloped. Additionally, geographical context introduces another layer of complexity, as regional characteristics significantly influence both vulnerability to extreme events and socioeconomic impacts of disruptions. An initial exploration of geographical factors in seismic resilience evaluation is provided in [48], while an examination of the geographical impacts of hurricane damage is provided in [74]. It is documented in [21] how extreme events have affected different regions with varying impacts from 1980 to 2023, highlighting the importance of geographical context in resilience assessment.

Thus, there remain numerous opportunities for further exploration and development. This research points to future work that could extend across various dimensions, integrating deeper analyses, broader applications, and innovative technologies to enhance the resilience and efficiency of EDS. Here are some detailed directions for future work:

- Expansion of resilience metrics to include cybersecurity elements. As EDS has become increasingly digitized and reliant on smart technologies, incorporating cybersecurity metrics into the resilience framework is critical. Future work could develop integrated cyber-physical resilience metrics that consider both physical disruptions and cyber threats, providing a holistic view of system vulnerabilities. Implementing real-time monitoring systems that can detect, respond to, and recover from cyberattacks in conjunction with physical disruptions could significantly enhance overall system resilience.
- Another critical area of future work involves establishing a standardized time scale for resilience, particularly focusing on the speed of system recovery following disruptions. Such a time scale would facilitate the comparison of resilience across different EDS and the effectiveness of various enhancement strategies. Developing predictive models that estimate recovery times based on system characteristics, disruption types, and mitigation strategies could provide invaluable benchmarks for resilience improvement.
- A detailed analysis of dynamic thermal rating (DTR) systems represents a significant avenue for future investigation. DTR systems, which adjust the capacity of power lines based on real-time environmental conditions, could greatly enhance the efficiency and adaptability of EDS. Future studies could explore the integration of DTR systems into existing resilience metrics and frameworks, evaluating their potential to improve system responses to disruptions and increase overall operational efficiency.
- Incorporation of climate change projections and adaptation to climate variability. With climate change impacting weather patterns,

future research could integrate climate models with resilience planning. This would involve adapting the resilience metric to anticipate and mitigate the risks posed by increasing frequencies of extreme weather events. Resilience planning could also be performed for long-term changes through the development of strategic plans that account for predicted changes in climate over the next few decades, ensuring that EDS infrastructure investments are resilient to future environmental conditions.
- Enhanced integration of DERs with effective optimization models. Further refinement could be made to the optimization frameworks for the strategic placement of DERs, considering not only resilience and power loss but also economic factors, regulatory constraints, and community impact. Also, smart grid technologies could be used to dynamically manage the integration of DERs, enhancing the adaptability of the grid to changing load conditions and distributed generation capacities.
- Moreover, while this paper has explored several strategies for enhancing EDS resilience, including the integration of DERs, automated switches, and mobile energy storage systems, the potential for discovering and analyzing additional enhancement techniques is vast. Future research could delve into emerging technologies such as blockchain for secure energy transactions, advanced predictive analytics for disruption forecasting, and innovative grid designs that intrinsically improve resilience. Each of these areas holds promise for further strengthening the robustness and adaptability of EDS.
- Testing and validating the resilience metric in a variety of geographical settings, each with unique challenges and requirements, to enhance its adaptability and accuracy across different regions. And exploring the applicability of the developed resilience metric in other critical infrastructure sectors such as water supply, telecommunications, and transportation. This could involve customizing the metric to address the specific resilience needs of these sectors.
- The development of metrics that integrate socioeconomic factors with technical resilience evaluations could provide deeper insights into community-level impacts of grid disruptions and enable more holistic cost-benefit analyses of resilience-enhancing investments. By quantifying both direct economic losses and indirect social costs of outages, these integrated metrics would offer more compelling justification for resilience investments. Additionally, socioeconomic resilience metrics could help prioritize enhancements that maximize both technical performance and community well-being, particularly for critical infrastructure serving vulnerable populations or essential services. This approach would address the current gap in the literature and advance the understanding of resilience as a multidimensional concept spanning both technical systems and the communities they serve.
- Testing and validating the resilience metric in a variety of geographical settings, each with unique challenges (coastal, mountainous, urban, rural) to enhance its adaptability and accuracy across different regions. Additionally, exploring the inclusion of EDS resilience frameworks with other critical sectors such as water, telecommunications, and transportation would advance cross-domain resilience understanding. This exploration should address not only sector-specific adaptations but also the critical interdependencies between these systems. Integrated approaches that model cascading failures across infrastructure boundaries could lead to coordinated resilience strategies that optimize investments and minimize the propagation of disruptions across interconnected systems, ultimately improving societal resilience to extreme events.

These future directions not only aim to extend the current research but also strive to make the resilience metrics function within broader EDS management practices, ensuring that electrical distribution systems are robust, adaptable, and sustainable in the face of both expected and unforeseen challenges.

8. Conclusion

This review offers a comprehensive examination of resilience in the context of electrical distribution systems. The recent increase in extreme weather events has exposed the vulnerability of EDS, emphasizing the need for resilience. The review distinguishes between reliability, which focuses on disruptions during normal operating conditions, and resilience, which addresses low-probability, high-impact events. The literature review explores various definitions of resilience in EDS to identify the key characteristics of a resilient system. Several frameworks on resilience are analyzed, and a critical review of resilience metrics and methods is presented. The application of complex network theory parameters in EDS resilience evaluation is also explored. Resilience enhancement techniques, including planning approaches and operation-based methods, are detailed, showcasing the complexities of improving EDS resilience. Finally, the review identifies research gaps, challenges, and future directions in the field of EDS resilience. The examination of these aspects paves the way for future research on developing more robust and adaptive systems to enhance the resilience of EDS in the face of increasingly extreme weather events and other disruptive incidents.

CRediT authorship contribution statement

K. Victor Sam Moses Babu: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Divyanshi Dwivedi:** Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Pratyush Chakraborty:** Writing – review & editing, Supervision. **Pradeep Kumar Yemula:** Supervision. **Mayukha Pal:** Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, 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.

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Data availability

Data will be made available on request.

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