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REVIEW

Power System Resilience: The Role of Electric Vehicles and Social Disparities in Mitigating the US Power Outages

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Abstract
Electrical power systems with their components such as generation, network, control and transmission equipment, management systems, and electrical loads are the backbone of modern life. Historical power outages caused by natural disasters or human failures show huge losses to the economy, environment, healthcare, and people's lives. This paper presents a systematic review on three interconnected dimensions of (1) electric power system resilience (2) the electricity supply for/through Electric Vehicles (EVs), and (3) social vulnerability to power outages. This paper contributes to the existing literature and research by highlighting the importance of considering social vulnerability in the context of power system resilience and EVs, providing insights into addressing inequities in access to backup power resources during power outages. This paper first reviews power system resilience focusing on qualitative and quantitative metrics, evaluation methods, and planning and operation-based enhancement strategies for electric power systems during prolonged outages through microgrids, energy storage systems (e.g., battery, power-to-gas, and hydrogen energy storage systems), renewable energy sources, and demand response schemes. In addition, this study contributes to in-depth examination of the evolving role of EVs, as a backup power supply, in enhancing power system resilience by exploring the EV applications such as vehicle-to-home/building, grid-to-vehicle, and vehicle-to-vehicle **or the utilization of second life of EV batteries**. Transportation electrification has escalated the interdependency of power and transportation sectors, posing challenges during prolonged power outages. Therefore, in the next part, the resilient strategies for providing electricity supply and charging services for EVs are discussed such as deployments of battery swapping technology and mobile battery trucks (MBTs), as well as designing sustainable off-grid charging stations. It offers insights into innovative solutions for ensuring continuous electricity supply for EVs during outages. In the section on social vulnerability to power outages, this paper first reviews the most socioeconomic and demographic indicators involved in the quantification of social vulnerability **to power outages**. Afterward, the association between energy equity on social vulnerability to power outages is discussed such as inequity in backup power resources **and power recovery and restoration**. The study examines the existing challenges and research gaps related to the power system resilience, the electric power supply for/through EVs, social vulnerability, and inequity access to resources during extended power outages and proposes potential research directions to address these gaps and build upon future studies.

Keywords Energy equity · Electric Vehicle (EV) · Microgrid · Power outage · Power system resilience · Renewable energy sources · Social vulnerability

Nomenclature

BESS	Battery Energy Storage System
B2G	Battery to Grid
DR	Demand Response
DER	Distributed Energy Resource
DG	Distributed Generation
DSM	Demand-side Management
EV	Electric Vehicle
ESS	Energy Storage System
GW	Gigawatt
CHP	Combined Heat and Power
HILP	High-impact Low-probability
WECC	Western Electricity Coordinating Council
MINLP	Mixed-Integer Non-Linear Programming

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NERC	North American Electric Reliability Corporation
CUI	Critical Urban Infrastructure
RES	Renewable Energy Source
V2G	Vehicle-to-Grid
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaic
P2G	Power-to-Gas
P2P	Peer-to-Peer
WT	Wind turbine
ENS	Energy Not Supplied
XFC	Extreme Fast Charging
CLPU	Cold Load Pickup

Introduction

The severity and frequency of natural disasters, such as ice storms, heat waves, and hurricanes has exponentially increased in the US. Disaster events incurred $2,541.1 billion in costs to the US economy, industry, infrastructure, and equipment by May 2023 [1]. Power outages caused by either natural or anthropogenic disasters have a significant impact on several sectors, including health services [2], data communication [3], urban safety and security [4], supply chain and logistics [5], and transportation and traffic management [6]. The power system is a key aspect of a city's resilience, which supports essential services from lighting to communication networks and healthcare facilities.

The occurrence of prolonged power outages in the US, both in the past and present, indicates that the reliability of the electricity supply has not received sufficient attention in terms of research and development, despite the existence of initiatives such as the Federal Energy Regulatory Commission (FERC) promoting "*Reliable Energy Supply*" [7]. For example, In 2022, California experienced 39 instances of unplanned power outages caused by severe weather and international attacks totaling 414 h, while Texas had 31 outages lasting 740 h, and Louisiana faced 16 outages amounting to 697 h [8]. An illustrative example is two recent significant disturbances and unplanned power outages in California in Tuolumne and Los Angeles on January 1st and April 14th, 2022, aggregating 4 h and 28 min outage duration. A considerable 167 megawatts were lost, and a total of 263,974 customers were affected [9]. In February 2021, Texas was hit by an intense winter storm, resulting in a substantial electricity generation failure that caused a power outage impacting more than 4.5 million households [10]. Blackouts are on the rise in other countries such as Pakistan, Bangladesh and China with even minor issues triggering a cascading effect throughout the nation's electricity networks [11]. These severe weather-related power failures have prompted many institutions and governments to acknowledge the urgent necessity of enhancing the power grid's resilience to extreme weather events.

Power systems encompass a range of elements, including generators, physical and cyber networks, control equipment, and loads, each possessing distinct attributes, making them vulnerable to various forms of extreme events. For instance, flooding can adversely affect generators, leading to power shortages [12]. Heatwaves, wind, and ice storms can damage transmission and distribution systems, resulting in blackouts and widespread failures [13]. A resilient power system should be able to respond quickly to disruptions and restore service, even during emergencies. Cities that have invested in grid upgrades, backup power systems, and alternative energy sources, such as renewable-based microgrids, battery energy storage systems (BESSs), and renewable energy sources (RESs), are better equipped to handle crises [14]. They become less reliant on centralized power sources and can maintain critical services, ensuring the city continues functioning even during challenging times. Despite efforts to augment the resiliency of power systems, there remains a significant lack of investigation into the distinct vulnerabilities of power systems to various natural and human-caused catastrophes. This encompasses understanding the specific impacts of different extreme events on power generation, transmission, and distribution infrastructure, as well as assessing the effectiveness of resilience measures in managing these vulnerabilities.

In addition to the power system, Electric vehicles (EVs) are pivotal for enhancing resilience, as they offer support during extended power disruptions. Specifically, EVs contribute to the power system resilience by supplying backup power during outages, storing RES surplus, and delivering additional services like managing frequency and ensuring voltage stability. The increasing adoption of EVs can be credited to progress in battery technology and the support provided by government subsidies [15]. The rapid expansion of EV sales has continued to increase their market share, climbing from approximately 14% in 2022 to 18% in 2023 globally [16]. The interconnection of EV transportation and power systems, particularly with the emergence of transportation electrification, presents EVs with opportunities to contribute to the power grid by offering ancillary services, supporting energy consumption of RESs and BESSs, and serving as backup resources [17]. Furthermore, with the growing availability of larger battery capacities, for instance, in mobile battery trucks (MBTs), and boosted driving efficiency, EVs can function as flexible loads at the grid's edge while meeting the mobility requirements of their users [18]. For instance, it is possible to balance the supply and demand of electricity and lessen the strain on the power system during peak periods or in the event of outages by leveraging the backup energy capacity of EV batteries and demand response (DR) schemes [19]. However, EV users may not be encouraged to share their batteries to participate in power restoration since they need their EVs for their own mobility and emergency services. Indeed, the more EV uptake and transportation electrification grow, the more charging facilities need to be provided for EVs. EVs have a significant contribution to boost power system resilience by acting as decentralized energy sources. Nonetheless, it is vital to consider that while EVs can be beneficial during such events, disadvantaged communities might face increased vulnerability to power outages due to their access to neither backup power nor EV charging stations. There is a lack of comprehensive research on integrating EVs to enhance power system resilience consisting of understanding technical, regulatory, and operational obstacles to effectively utilizing EVs for grid support during disasters. There is limited knowledge concerning how grid support activities impact EV battery life and overall performance assessing potential degradation effects from frequent charging and discharging cycles on EV batteries during power outages. Moreover, there is insufficient research on the infrastructure needs for supplying electricity to EVs on disasters including comprehending the essential infrastructure investments, such as backup power systems and charging infrastructure, required to guarantee dependable EV functionality during outages.

Although prolonged power outages can lead to significant economic and environmental harm, the potential humanitarian disaster caused by the disruption of emergency services and backup power can surpass the financial losses experienced [20]. Therefore, social vulnerability indicators in the context of multi-hazards are commonly employed to assess the varying susceptibility of populations to the effects of disasters leading to prolonged power outages. Researchers have conducted practical studies employing various indicators of societal vulnerability to analyze the consequences of disasters, such as mortality, financial losses, displacement, and reliance on public assistance [21]. Indicators such as demographics, land ownership, living conditions, socioeconomic status, health, risk perception, access to resources such as backup power, and exposure influence the susceptibility and resistance of populations to natural disasters. These indicators, known as determinants of social vulnerability, vary from place to place and affect people's ability to withstand and recover from hazard events [22]. People who are similarly exposed to hazards often experience different impacts due to variations in these determinants. Furthermore, these capacities can differ depending on the type of hazard faced. Therefore, it is crucial to identify the processes that contribute to unequal conditions and disproportionate burdens, affecting social vulnerability across various disasters and disruptions [23]. Current research lacks a thorough evaluation of the social vulnerability to power outages and how socio-economic factors, and resource accessibility shape the people vulnerability to outage impacts, including equity access to electrical services, healthcare, and transportation. There is a scarcity of research examining the intersectional dynamics of social vulnerability factors and their cumulative impacts on outage consequences. Studies on community-level resilience to power outages, particularly in disadvantaged and marginalized communities, are limited considering the equity access to EV charging infrastructure. These research gaps partly stem from limited access to information and data concerning how people cope with power outages.

Building upon a foundation of existing research, this paper provides a comprehensive review within the broader landscape of the interconnections between electric power system resilience, the electricity supply for/through EVs, and social vulnerability to power outages. The review of electric power system resilience investigates qualitative and quantitative evaluation metrics, and planning and operation-based enhancement strategies for improving power system resilience through various means including microgrids, RESs, ESSs, MBTs, DR schemes, and EVs. It is crucial to recognize the valuable contribution of previous review studies in this field.

The studies [24–31] have laid vital groundwork in understanding various aspects of power system resilience, including analyzing the impact of disaster-related power outages, quantifying their effects on generation, networks, and loads, and exploring strategies to enhance resilience. For instance, the paper [24] provides a thorough examination of literature concerning power system resilience from diverse perspectives. It begins by reviewing established safety concepts within power systems considering large-scale power outages. Definitions and complex features of resilience within the power system domain are then explored. The study further delves into recent frameworks, resilience curves, and quantitative metrics proposed for assessing power system resilience, alongside a summary of strategies aimed at enhancing resilience. The paper [25] investigates the systematic review of power system resilience through four key dimensions: (1) assessing the effects of natural disasters on generation, networks, and loads; (2) measuring these effects to guide resilience enhancement endeavors; (4) suggesting adaptation strategies at both individual component and overall system levels, such as optimized scheduling of power sources; and (4) discussing future avenues for research. The scholar in [31] conducted a literature review concentrating on methods and modeling techniques utilized to evaluate the cost of power system outages and the value of enhancing outage mitigation or system resilience. Furthermore, it identifies key questions from stakeholders regarding resilience investments and aligns them with relevant models capable of addressing them. Comparing this paper with existing studies, the paper discusses the need for coordinated planning and operation strategies to supply power to EVs, highlighting the importance of updated public policies and addressing social inequities in power outage management. By synthesizing existing literature and providing recommendations for future research directions, this study contributes significantly to the ongoing efforts to enhance power system resilience, integrate EVs into the grid, and address social vulnerability to power outages. Our study builds on these insights, focusing on the interconnectedness of electric power system resilience, the power system resilience for and through EVs, and social vulnerability to outages. We identify research gaps and suggest future directions, providing recommendations for standardized resilience definitions, qualitative and quantitative metrics, assessment methods, and enhancement strategies. Additionally, we address energy justice concerns, particularly regarding access to emergency services and backup power during outages. Our deliberate choice of these dimensions reflects their significant role in addressing the complex challenges posed by power disruptions, especially how they intersect and impact different societal segments.

The rest of this paper is organized as follows according to the illustration in Fig. 1. Second section discusses the systematic review approach used to evaluate the existing literature on the quantitative and qualitative resilience metrics for electric power systems, as well as enhancement strategies for electric power system resilience. Third section examines the EVs, as assets or liabilities for the electric power grid in the electric power systems. Fourth section discusses the existing quantification of social vulnerability indexes and the connection between social equity and social vulnerability to power outages. Finally, the conclusion is provided in fifth section.

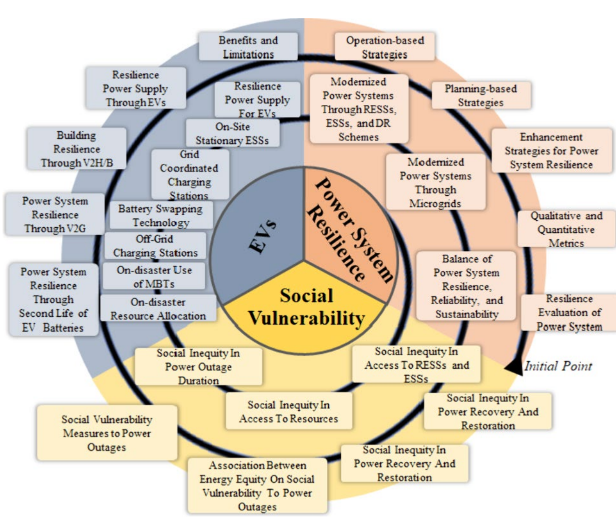

Fig. 1 The overarching structure of the paper

Review Methodology

This paper provides a comprehensive examination of contemporary approaches, metrics, and enhancement strategies related to three interconnected dimensions of (1) electric power system resilience in terms of evaluation metrics and planning and operation-based enhancement strategies for electric power system resilience through the advancements in modern power systems such as RESs, ESSs, sustainable microgrids, and control equipment, (2) EVs as a backup power supply contributing to power system resilience and resilience enhancement strategies and power supply for EVs during outages, and (3) social vulnerability to power outages by assessing the susceptibility of populations to the effects of prolonged power outages considering the equity access to backup power on disasters. The review methodology adopted for this paper involves a systematic approach to identify, select, and analyze relevant literature pertaining to electric power system resilience, EVs, and social vulnerability to power outages. The systematic review process is structured to ensure transparency and rigor in identifying key insights from the existing literature. Approximately 700 publications were initially identified, with around 400 chosen for careful reading based on a comprehensive examination of title, abstract, conclusion, and full text. Figure 2 illustrates the number and percentage of reviewed papers per section (electric power system, EVs, and society) per publication year. Table 1 illustrates the main keywords used for searching for various sections. Moreover, about 65% of the reviewed papers were screened through their title, abstract, and introduction parts while the rest were fully screened. Keywords were strategically combined into primary categories to capture relevant literature on electric power system resilience, EVs, and social vulnerability to power outages. The review process commenced with an extensive search of scholarly literature across various databases, including IEEE Xplore, ScienceDirect, Web of Science, Springer, Scopus, and relevant search engines. Figure 3 depicts the references of this review paper that have been collected through various databases consisting of IEEE Xplore, ScienceDirect, Web of Science, Springer, Scopus, and search engines. A set of predefined criteria was established to guide the selection of papers for inclusion in the review encompassing factors such as relevance to the topic, publication date, and the quality of research methodology employed. Papers were screened based on their title, abstract, and introduction to determine their suitability for further examination. Selected papers underwent a thorough assessment of quality to ensure the reliability and credibility of the findings. Criteria for quality evaluation included the rigor of research methods and the relevance of the research to the review objectives. Relevant data and insights were extracted from the selected papers and synthesized to identify patterns, themes, and key findings related to electric power system resilience, EVs, and social vulnerability. This synthesis

Table 1 The keywords used to search for the reviewed papers in each section

Section/Keywords	Keyword #1	Keyword #2	Keyword #3	Keyword #4	Keyword #5	Keyword #6
Electrical Power System Resilience	Power Outage Restoration	Quantitative and Qualitative Resilience Metrics	Microgrid	RESs and ESSs	Power-To-Gas (P2G)	Demand Response (DR)
EVs	Mobile Charging Station	Second Life of EV Batteries	Vehicle-To-Home/Building (V2H/B)	Charging Station	On-Site Stationary ESSs	Battery Swapping Technology
Social Vulnerability Index to Power Outages	Social Vulnerability Index	Social Energy Equity	Access To RESs and ESSs	Power Restoration	Backup Power	Power Outage Duration

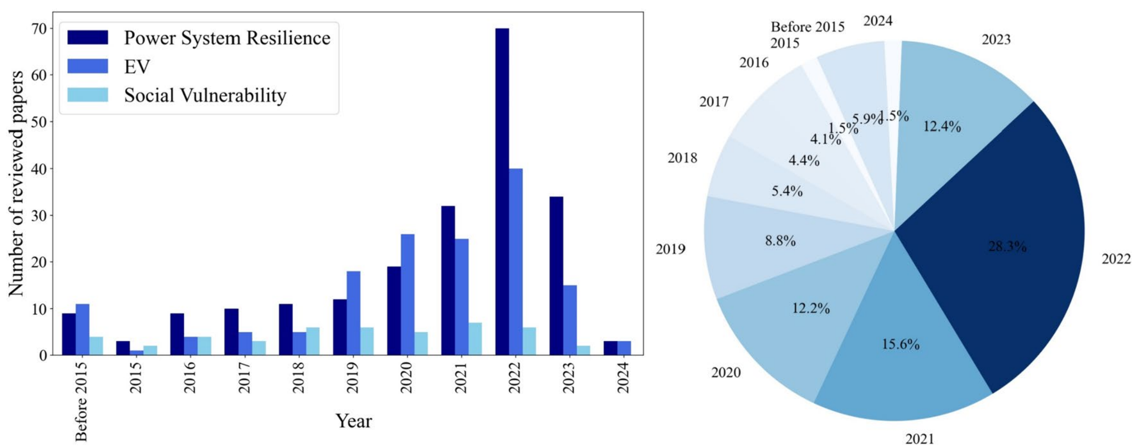

Fig. 2 The number and percentage of reviewed publications per publication year

process involved organizing extracted information to facilitate a coherent narrative and analysis. The review on power system resilience, the power system resilience for/through EVs, and social vulnerability to power outages operates under several key assumptions. Firstly, it assumes that the gathered literature provides a comprehensive representation of research on power system resilience, EVs, and social vulnerability. This is based on the thorough search methodology employed including major databases and relevant keywords (Table 1). Secondary, it assumes that evaluation metrics and enhancement strategies discussed are broadly applicable across diverse power system contexts, despite potential variations in regulations. Lastly, it assumes that reviewed studies accurately depict the power system resilience, EVs, and social vulnerability.

Electric Power System Resiliency: Challenges, Metrics, and Enhancement Strategies

In recent years, the electricity demand has seen a steep increase, largely due to factors such as robust economic, population growth, and urban expansion. This surge in electricity demand and the inability of the present energy network to sustainably supply this demand has led to multiple pressing problems, including a fossil fuel shortage, environmental degradation, and climate change, which are seriously obstructing the sustainable growth of society. These challenges are particularly evident in developing

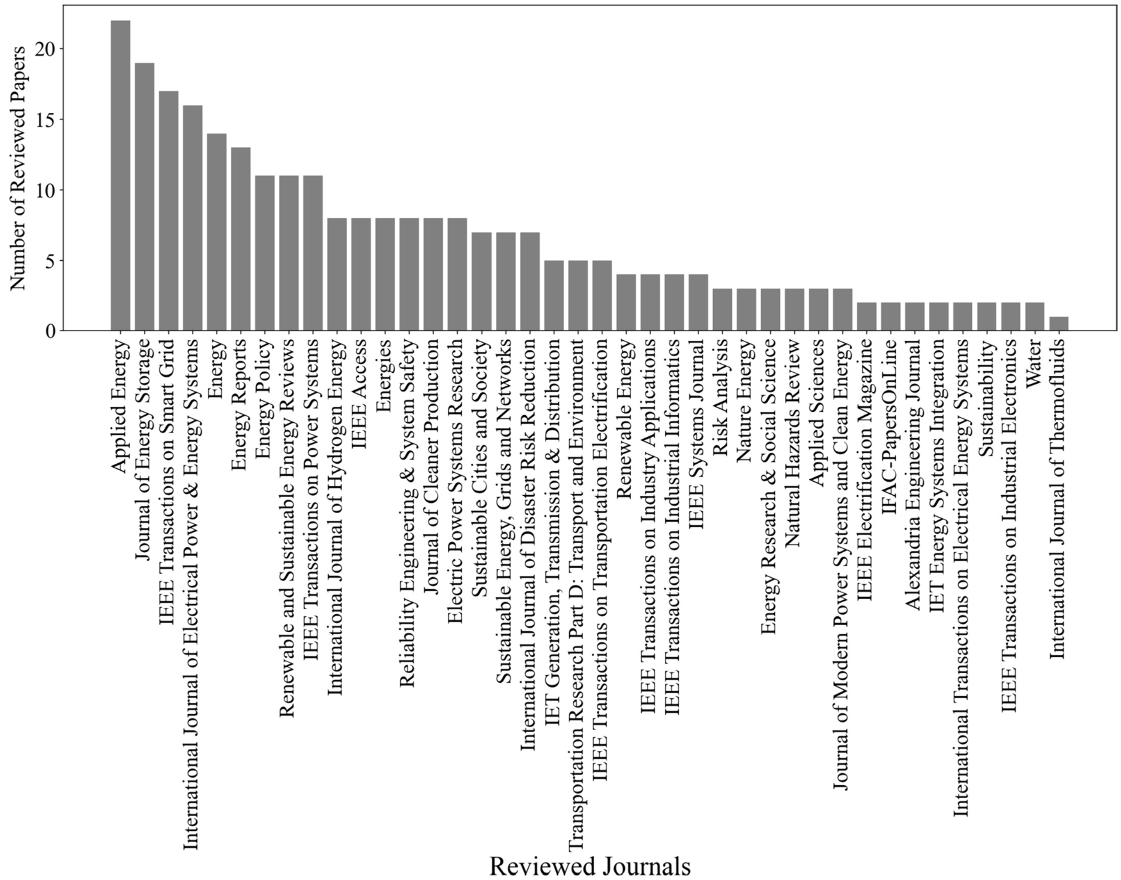

Fig. 3 The number of references of reviewed papers by each relevant journal

nations, with the US being a notable example. In the US, the accumulated electricity consumption by residential, commercial, industrial, and transportation sectors reached approximately 4,300 billion kWh in 2022, with a growth rate of 125.86% over the previous 30 years [32]. Electricity consumption in US cities reached 4.05 trillion kWh [33]. At the same time, the total installed utility-scale capacity of electricity reached 46.1 Gigawatt (GW).

The traditional electrical grid that was designed decades ago cannot accommodate this increased demand, leading to overloads, brownouts, and blackouts [34] since it is heavily reliant on fossil fuels, which are major detrimental contributors to climate change and air pollution. Advancements in power systems are crucial to meeting the escalating demand for electricity while enhancing the resiliency of power infrastructure against potential disruptions [27]. Modern power systems can be a potential solution since they contribute to sustainability goals, including reducing greenhouse gas (GHG) emissions, augmenting energy efficiency and reliability, and making optimal use of renewable energy resources (RESs) [35]. For example, developing smart grid technologies aiming at improving the efficiency and reliability of the power system can facilitate the integration of high RESs penetration and energy storage systems (ESSs) [36] enabling power infrastructure to cope with the rising electricity demand [37]. In addition, the integration of smart grid technologies and advancements in microgrids and distributed energy resources (DERs) enable power infrastructure to quickly identify and isolate outages, thus minimizing the possibility of cascading failures [38]. Demand-side management (DSM) programs, as a component of modern power systems, result in making the grid more responsive to changes in energy supply and demand. DSMs are an effective means of promoting a sustainable power system by curbing the consumption of energy during peak periods and lessening the need for fossil fuel-based power generation [39]. It is crucial to comprehensively comprehend modern power system capabilities to effectively manage and maintain power grids' operations and minimize the risk of power outages. This electric power system section aims to carry out a systematic review of (2.1) the resilience evaluation of the power system including the qualitative and quantitative metrics, (2.2) enhancement strategies for power system resilience, and (2.3) the balance of the power system resilience, reliability, and sustainability.

Resilience Evaluation of Power System

The term "resilience" was introduced by Hollin in 1973 to assess the capacity of an ecological system to adapt to shifts in its condition and influencing factors [40]. Resilience refers to a system's ability to resist and reduce the effects of disturbances caused by external events, as well as to maintain or restore its performance after the disturbance [41]. Power system resilience investigates how to restrict the extent, severity, and period of the possible events considering short and long-term actionable measures [42]. Short-term metrics refer to the operational actions applied in the phases of pre, during, and post-events, while long-term metrics mainly consist of infrastructure hardening and resilient planning [43]. In terms of the disaster occurrence time, resilience metrics are categorized into three groups: (1) resilience-based planning as long-term metrics enhancing power systems' resilience such as power system management and hardware designs, network reconstruction schemes, and underground cables [44], (2) resilience-based response [45] as short-term preventive actions like emergency and day-ahead measures, and (3) resilience-based restoration as short-term measures performing all system recovery actions [46]. To effectively gauge the resiliency of the power systems, many studies investigated the resilience evaluation metrics and planning approaches under the following two qualitative [47, 48] and quantitative categories [49–51]. Quantitative analysis, typically deriving from sources like historical data, design criteria, climate models, or lab tests, alongside qualitative evaluations, are based on the survey from experts, managers, operators, community leaders, and public decision-makers [52]. In the following, a review of qualitative and quantitative metrics used to assess the power system's resiliency is described in detail.

Qualitative Resilience Metrics

Qualitative resilience metrics assess the system's resilience by a set of descriptive metrics such as high, medium, and low accessibility, as well as availability [47], and are generally categorized into conceptual frameworks and semi-quantitative metrics. Conceptual frameworks study the fundamental resilience components including absorption, adaptive, and recovery capacity [48]. This subsection aims to uncover the usage of either conceptual or semi-quantitative approaches within the realm of research on the resilience of power systems. For example, the study [53] developed a resilience metric to assess the vulnerability of critical infrastructure and key resources of the power system. The scholars gathered data by conducting a questionnaire, obtaining over 1500 data points for each facility type, including non-residential buildings, electrical power substations, and transportation facilities. Following a thorough quality control assessment, the proposed resilience metric was constructed by aggregating the collected data into four levels of information employing multi-attribute theory, which facilitated the breakdown of resilience into its constituent attributes and subsequently organized them in a hierarchical structure. Another research study [54] built a qualitative resilience assessment metric focusing on the infrastructure failure interdependencies in electricity distribution and telecommunications based on experts' knowledge. The proposed framework, which comprises four stages (preparation, data gathering, analysis, and outcomes), was created and put into practice with the preparedness committees in Finland's regions. In the initial stage, the planning team outlined the threat scenario. Subsequently, representatives from the electricity distribution and telecommunications sectors involved in the study were asked to identify broader interdependencies and develop a scenario involving an intense storm and a widespread influenza pandemic. The second and third stages, involving data gathering and analysis, were carried out iteratively through multiple workshops involving up to fifty experts, until the collected and organized data met the required standards. Finally, the findings were presented in the form of system diagrams, which facilitate understanding of the points of failure between critical infrastructure and the dependencies' chains. The scholars in [55] concentrated on a qualitative risk management measure aiming at enhancing the value creation of risk management measure, a crucial aspect for decision-making and the formulation of strategies to mitigate the impacts of extreme weather events on the electricity distribution networks. To validate the proposed approach, the researchers conducted a case study involving the electricity distribution network in Finland. The stakeholder value of the risk management measure during the entire life cycle of critical infrastructure in the electricity network was evaluated by Analytic Hierarchy Process (AHP) to the evaluations established by 18 experts from distribution system operators. The AHP ranked the value criteria for comparing risk management measures, including the economic, environmental, and social benefits they provide, their influence on the maintainability, accessibility, and reliability of the electrical distribution network, along with its life-cycle costs (capital and operational expenses). The stakeholders were then divided into three groups, and they specified alternative risk management measures. The assessment results highlighted the following risk management measures, including the installation of underground cables, collaborative planning and training, information and communication technology systems, and establishing and disseminating situational awareness.

According to the literature, there is a research gap in proposing the qualitative resilience metrics from the stakeholders' viewpoints, particularly for modern power systems components such as ESSs, RESs, and critical infrastructure of smart grids and residential microgrids. For instance, qualitative resilience assessment metrics can be developed from occupants' and building owners' perspectives based on their critical equipment and vulnerability levels against disasters.

Quantitative Resilience Metrics

Quantitative resilience metrics evaluate the effect of various strategies to enhance operational resilience and infrastructure, such as reinforcing the power grid considering the resilience capabilities [56] including withstanding [57], absorptive [58], adaptive [28], restorative [59], as well as resilience dimensions, known as the 4Rs of resilience, namely robustness [49], redundancy [50], resourcefulness [51], and rapidity [60]. Recent research studies have paid particular attention to quantifying resilience metrics for both operational and infrastructure sectors using statistical analysis, such as the systematic online probabilistic resilience assessment framework [61], resilience-based risk assessment method [62, 63], system fragility-based approaches [64, 65], graph theory-based methods [66], simulation-based models [67], and fuzzy logic strategies [68, 69]. Quantitative resilience metrics are characterized by certain attributes that indicate the type, extent, and techniques employed in their creation as follows. These attributes provide information on the metrics' specific nature, scope, and methods used to develop them.

Stochastic vs. Deterministic Metrics Stochastic indicators consider the inherent uncertainty of parameters and events when it comes to evaluating a system's resilience, such as component failure and restoration time. On the other hand, deterministic metrics do not incorporate such uncertainties in their calculations, potentially leading to an overestimation of resilience. Deterministic models, such as power flow and short-circuit models, offer valuable insights into a power system's resilience by providing a baseline understanding of its behavior without uncertainties [70]. However, the lack of consideration for uncertain parameters in deterministic models can result in an overestimation of power system resilience. It is essential to consider both types of metrics to obtain a more comprehensive understanding of a system's resilience. A study [71] developed a stochastic resilience metric through the Choquet integral computation approach aiming at identifying viable paths for restoring a load by combining several individual parameters linked with nodes and links in the network, including path redundancy, source availability probability, and central point dominance. Another research [72] proposed a stochastic, energy-related, and operational measurement using a chance-constrained stochastic programing and a Markov chain-based operation model based on two levels of restoration: (1) the recovery of essential electrical loads and (2) the restoration of power system infrastructure, including the repair of damaged poles and lines. However, this research neglected the cascading effects of disruptions on other interconnected systems, such as water distribution and natural gas systems. The scholars in [73] proposed two sets of deterministic metrics to measure the resilience of both the operational grid and its infrastructure. The main goal of this research was to minimize the impact of high-impact, low-probability (HILP) events and ensure the power grid can quickly recover from power outages.

Cost vs. Energy vs. Time-based Metrics Cost-based metrics assess the financial impact of disruptions, energy-based metrics quantify the loss of power or energy following a disturbance, and time-based metrics evaluate how long it takes a system to recover. By using multiple metrics, the strengths and limitations of each approach can be balanced, leading to a more accurate assessment of resilience. For instance, the scholars in [74] developed a resilience-based importance measure of a node that is most influential over time, specifically on two aspects of vulnerability and recoverability. The proposed resilience measure evaluates the potential negative effect on the network's resilience when a particular node is disrupted/damaged and the potential positive effect on the network's resilience when that node cannot be disrupted. The study [75] proposed two measures of system resilience, including the time and the total cost, and discussed the critical factors to consider when analyzing resilience, such as the type of disruption, how components are restored, and the overall strategy for resilience. Moreover, researchers in [76, 77] developed a multi-objective model to maximize resilience, minimize restoration costs for interdependent power and water systems, and optimize transportation systems after natural disasters.

Infrastructural vs. Operational Metrics When evaluating the resilience of a power system, infrastructural measures focus on the effect of planning and infrastructure hardening indexes on enhancing the system's ability to withstand potential future disturbances. On the other hand, operational indexes concentrate on the actions taken to maintain or restore system performance during an imminent disruptive event. Evaluating both infrastructural and operational metrics provides a more holistic view of a system's resilience and helps identify potential weaknesses in the system's design and operation. For example, researchers in [78] presented a method for evaluating and enhancing the ability of critical infrastructure of the power transmission grid to withstand future disruptions over time. It specifically focuses on applying this approach to the IEEE RTS-96 power transmission grid located in Harris County, Texas, USA. But there are several other crucial mechanisms overlooked by the authors. These strategies are necessary to support a comprehensive analysis of resilience over the long term, including making changes to the network's structure, considering the interdependence of different components, and adding or retiring electricity generators, substations, and transmission lines based on economic, environmental, and reliability indexes. These strategies and mechanisms should have been discussed in detail to fully capture resilience's complex and nonlinear nature over time. Another research [79] used an operational metric to evaluate the resilience implications of incorporating microgrids into interconnected gas-powered networks, albeit in the context of distribution systems. In this study, the interdependent gas-power network was modeled using graph and network theories, and a resilience assessment was conducted to compare the efficacy of various microgrid integration scenarios in the network. Moreover, the study [80] utilized the same indicator to dynamically evaluate the effect of ice disasters on power transmission systems, with consideration given to both their location and strength. This study employed (1) a sequential Monte Carlo simulation approach evaluating the behavior of power transmission systems as a sequential time of events and (2) a fragility curve to describe the correlation between the probability of component failure in transmission systems and the intensity of weather events. However, this article did not investigate dynamic resilience evaluation metrics to assess the cost-based impacts of ice disasters on power transmission systems. The proposed resilience metric in [81] distinguished between operational and infrastructure impacts, allowing for more accurate modeling of the behavior of critical electrical infrastructure, tested on a 29-bus transmission network in Great Britain during extreme weather events. Some studies have focused too much on infrastructural metrics, overlooking crucial aspects like network structure changes, interdependencies, and asset management. On the other hand, operational metric-focused studies have not adequately explored the cost-based impacts and scalability of their approaches. To bridge these gaps, a holistic approach is needed, which integrates both infrastructural and operational metrics. This approach should consider the interdependence of various components in the system and assess the cost-based impacts of resilience strategies.

Dynamic vs. Static Metrics A system's resilience is often time-dependent, meaning its ability to withstand and recover from disruptions changes over time. Dynamic metrics take into account these changing conditions, while static metrics provide a snapshot of the system's resilience at a particular moment in time. Using dynamic metrics, researchers can assess how a system's resilience evolves over time and identify patterns and trends that can inform resilience planning and decision-making. The research in [81] introduced a new dynamic resilience metric to gauge the resilience of critical power infrastructure in the face of extreme weather events. The authors proposed a set of resilience metrics for operations and infrastructure that vary over time, relying on diverse dynamic indicators to quantify the resilience trapezoid. These metrics enable measuring how quickly and to what extent resilience drops during an event, how long the infrastructure remains degraded after the event, and how quickly it recovers to its pre-event state. Another study [82] investigated static data mining techniques for identifying abnormal behavior in distributed phasor measurement units using statistical and maximum likelihood estimation. This paper suggested an approach that prioritizes resilience through pre-event reconfiguration and islanding to mitigate the impact of unfavorable situations on the power distribution system, utilizing analyzed synchrophasor data. Scholars in [83] introduced two metrics including the single point of reduced availability and the double point of reduced availability, to evaluate the resilience of power systems that supply data centers. These metrics are designed to measure the system's capacity to maintain its operations even in the event of an outage.

Real data vs. Simulated Data Resilience metrics can be evaluated using different types of data, including historical data or simulated and synthetic data. Real data provides a more accurate assessment of a system's resilience, while simulated data allows researchers to explore hypothetical scenarios and assess the system's resilience in various conditions. Combining both types of data can enhance the validity and reliability of resilience assessments, providing a more robust understanding of a system's resilience. A research study conducted a numerical simulation to validate the efficacy of a resilience-based approach designed to identify post-disaster restoration strategies for secondary distribution networks in the modified IEEE 342-node low-voltage networked test system [84]. In more detail, the approach proposed in this study involved utilizing distributed generators (DGs) to restore service and provide power to critical electrical loads in a secondary distribution network. However, the authors neglected to consider electricity market models enabling owners of DGs to receive appropriate compensation for supplying electricity to critical loads during significant outages. Furthermore, inverter-interfaced DGs and electric ESSs were not considered in the restoration process. Some studies [85–87] applied the simulated data to evaluate the stochastic-based resilience metrics for different weather scenarios by the modified IEEE 33-bus, IEEE 37-bus, IEEE 69-bus, and IEEE 123-bus systems, respectively. The proposed models employed probabilistic metrics including value-at-risk and conditional value-at-risk, that quantify resilience in terms of the maximum loss of energy and the conditional expectation of energy loss for events beyond a prespecified risk threshold. However, the study [85] did not address the stochastic resilience metrics in optimal resource allocation planning to boost the power distribution grid's performance during HILP events.

Contrary to the abovementioned studies, some research such as [88–91], investigated the real data to assess the quantitative power system resilience. For instance, the article [92] focused on a unified resilience evaluation and operational enhancement of a simplified version of the Great Britain transmission network by assessing the impact of extreme weather conditions on the power systems. An innovative defensive islanding algorithm based on risk was also introduced to minimize the cascading effects that may arise during such emergencies. Another study [91] introduced two indicators, namely resilience risk factor and grid infrastructure density, to determine the US electricity grid resilience while ensuring environmental sustainability. It utilized Monte Carlo Simulations to categorize the US into four tiers taking into account both grid reliability and grid resilience. However, the authors did not consider the limitations of reliability metrics according to the standard IEEE bus systems. Acquiring data from real power systems is frequently challenging, leading to the widespread use of datasets like the IEEE test set. Obtaining real-world data poses difficulties due to privacy issues, proprietary data ownership, and security considerations. Access to real data would provide valuable insights into real operating conditions, system behaviors, and field challenges, empowering researchers to create more precise models.

Enhancement Strategies for Power System Resilience

Effective reinforcement approaches augmenting power system resilience for both electric transmission and distribution systems have built up considerable momentum in recent years [13, 93, 94]. This section presents efficient strategies for resilience enhancement, including the following two distinct categories of planning-based and operation-based strategies [25, 27].

Planning-based Strategies

Planning-based models focused on grid expansion planning examine strategies for strengthening transmission and distribution networks, including measures like upgrading electric poles to withstand flooding disasters [95]. Extensive research has been conducted on these models to enhance the grid's resilience in maintaining uninterrupted power supply [96–98]. These strategies are classified into five distinct categories as follows.

Undergrounding Distribution and Transmission Lines A study conducted in [99] developed a stochastic robust optimization model to identify a transmission resilience planning solution to diminish load shedding in the most economically efficient manner by the lines placed underground considering historical extreme weather events. Sequential Monte Carlo simulation solved the proposed stochastic model and was validated by a modified IEEE reliability test system and IEEE 118-bus system. Another study [100] proposed a stochastic multi-period mixed-integer linear programming framework to determine optimal locations for underground distribution lines and the effective coordination of mobile generators to provide a reliable power supply to critical loads during extreme events. The proposed framework in this research employed the linearized DistFlow approximation of alternating current (AC) power flow equations to represent the service restoration process by introducing binary variables to determine decisions related to undergrounding lines, configuring switches, and placing mobile generators for each period.

Upgrading the Physical Power System Components Hardening and upgrading the equipment and critical infrastructure such as transformers, circuit breakers, switchgear, and production and control systems [101], as well as installing backup distributed generators such as Combined Heat and Power (CHP), DGs, and diesel generators [66, 102], step up the automatic remote-control switches [103, 104]. For instance, the study [105] proposed an approach for determining the maximum capacity of the distributed generation when upgrading actions are performed considering the uncertainty and variability of demand and distributed power production. The approach considers the perspective of the distribution system operator and formulates the problem as a multi-objective optimization model to maximize distribution system capacity while minimizing the cost of upgrading. The upgrade options include the allocation of voltage regulators and conductor replacement, as well as the implementation of generation curtailment, support for reactive power in the distribution system, and voltage control through voltage regulators. The solution generates a set of upgrading plans, allowing the distribution system operator to select the most economically viable option that provides the necessary capacity to accommodate new distribution generation. As an alternative to peaking plants, this research [106] introduced a dual-layer control system that effectively coordinates CHP, district heating networks, and buildings to support grid flexibility. The control system enables the CHP unit to fulfill the heat requirements of local users while simultaneously providing frequency response services to the power grid. The numerical results demonstrate that the capability of the CHP system to provide frequency response is influenced by several factors, including the capacity and ramping rate of the CHP unit, limitations in the temperature supplied by the district heating network and the temperature within the buildings.

Optimal Placement and Size of Backup Power Such as BESS [107] and power generations [108]. For example, the scholars in [108] proposed the utilization of the Benders Decomposition technique for determining the optimal placement and size of ESS. They employed the conditionally precise convex optimal power flow approach, accounting for the stochastic nature of load and RESs. However, a limitation of the Benders Decomposition method was the inability to formulate optimization problems without dual variables to reduce the solution space. In [109], a bi-objective optimization problem was addressed, aiming to minimize both the total costs associated with the investment and operation, as well as the loss of load expectation. The ε-constraint approach was initially applied to obtain a set of Pareto solutions, and then a fuzzy technique was utilized to select the most suitable solution from this set. In more detail, 500 load scenarios were initially generated from a probability distribution function. However, due to computational constraints, the number of scenarios was reduced to just 5 using a scenario reduction algorithm, with assigned probabilities for each scenario. Another study [110] introduced a meta-heuristic pathfinder algorithm to effectively integrate solar photovoltaic (PV) systems into the multi-lateral distribution system for boosting resilience aiming at addressing the optimal distributed generation allocation problem. The study [111] explored the utilization of various operators from evolutionary algorithms by a hybrid grey wolf optimizer to address the problem of optimal allocation and sizing of different types of distributed generation technologies to minimize losses. The case studies conducted focus on practical systems, namely the IEEE 33-bus, 69-bus, and Indian 85-bus systems.

Encrypted Critical Data Communication There is a growing and profound integration between modern power systems' digital and physical aspects. This study [112] addresses the challenge of maintaining secure state estimation and reconstructing attacks in cyber-physical power systems when they are compromised by cyber-attacks. In this study, the traditional small signal model for cyber-physical power systems was initially developed to account for disturbances and cyber-attacks. They then proposed the use of an intermediate observer to achieve secure state estimation and reconstruct the attacked states by determining the linear matrix inequality technique. Research showed that false data injection attacks are significant threats to the energy management routines of cyber-physical power systems, showcasing their potential to cause substantial disruption. To this end, the study [113] proposed a data-driven attack strategy based on robust linear regression considering appropriate conditions of measurement data. Another study [114] highlighted the importance of cybersecurity of integrated energy systems and identified vulnerabilities in the cyber defense of heating systems. The authors presented three distinct methods for heat load redistribution attacks, focusing on manipulating indoor and supply temperatures within the secondary heating network. By employing a framework that integrates optimization dispatch and simulation, they demonstrated that the heat load redistribution attacks exhibit latency and transitivity properties, posing significant threats to the security, user comfort, and economic aspects.

Integrated Energy Systems Such as multi-carrier energies (heat, thermal, and electricity) [115, 116]. The study [117] proposed a multi-stage strategy integrating multi-level decentralized reserves aiming at enhancing the resilience of the electricity-gas integrated energy system against disasters. Another research study [118] demonstrated the application of dynamic simulation for modeling and evaluating the resilience of an integrated energy system against extreme weather events. Various approaches to resilience evaluation are examined, and the most appropriate one is selected and adjusted to create a metric that can be utilized with dynamic simulation outcomes. Subsequently, as a proof of concept, a model of an integrated energy system encompassing the gas, heat, and power sectors is presented and assessed using the proposed metric. To illustrate how alterations in the system's architecture influence resilience, two modifications are tested. A similar study [119] proposed a bi-directional flow model for a coordinated regional-district operation of an integrated energy system to boost resilience against extreme conditions. To prove how regional and district-integrated energy systems can boost resilience, a tri-level two-stage robust framework is built to accommodate random outages impacted by natural disasters in both the natural gas and electricity generation and distribution systems considering power-to-gas technology (P2G).

The research findings in power system resilience enhancement highlight several fields that need further investigation. For example, there is a need for sophisticated cybersecurity frameworks to counter the increasing complexity of cyber-attacks on cyber-physical power systems. Additionally, research should prioritize the optimization of coordination and control for multi-carrier energies within integrated energy systems considering decentralized RESs and ESSs.

Operation-based Strategies

Operational enhancement strategies focus on leveraging cutting-edge optimization techniques to make the most of the available resources and assets against extreme events and failures. Operation-based distribution system strategies include power network configuration, automated control, the formation of microgrids, load restoration-based models, and the employment of mobile battery resources and stationary energy storage.

Power Network Configuration Modifying the network control and topology reconfiguration to enhance resilience and decrease energy losses considering the network constraints by leveraging hybrid AC and Direct Current (DC) loads [120], using renewable distributed generations, BESSs, and EVs [121]. For instance, this study [120] proposed an optimal power distribution configuration to minimize energy losses caused by electrical resistances in primary distribution networks. The paper aims to reduce technical losses and take advantage of the advancements brought about by distributed RESs. Another study [122] addressed the power network configuration through EVs. This study proposed an innovative economic dispatch using Benders decomposition for achieving optimal configuration and operation of EV aggregators equipped with smart meters considering the controllable EV charging loads and RESs in the power system context.

Micro-grids' Control and Formation Research documented the significant contribution of resilience-oriented planning of micro-grids, such as low-voltage or medium-voltage grids, in both islanded and grid-connected modes to the power system resilience enhancement [123–126]. Micro-grids proactively schedule their generation resources to boost network resilience, enabling feasible islanding mode and the survivability of critical loads during a disaster or disruption [127, 128]. Moreover, many studies proposed power outage management and micro-grid dispatch scheme under the unexpected outages incurred by failures, cyber-attacks, and severe weather [129–134]. For instance, the objective of the study [123] is to enhance the energy resilience of a hospital by implementing a microgrid composed of a PV system, ESS, and a backup diesel generator by evaluating two scenarios. The first one examines the economic viability of the microgrid when there is no grid outage. Meanwhile, in the second scenario, the optimization takes into account both economic profitability and the capacity to endure a 24-hour outage during the month with the least radiation. This led to a net increase of 24 h in energy resilience compared to the standard approach and a utility cost reduction of $147,354 for the hospital. The scholars in [124] presented the development of a mixed logic dynamic framework and a stochastic model predictive control technique to enhance the autonomy of the microgrid while achieving a rapid transition response utilizing a hybrid ESS incorporated by both hydrogen and batteries.

Load Restoration HILP events mostly bring about extended outages and loss of critical loads, thus, severely affecting customers' safety. The importance of customers' safety and supply power for critical infrastructure calls for restoring critical loads at a reasonable restoration time [135]. To this end, many research studies have sought to restore both local and critical loads by utilizing DERs [55], DSM systems [136], switching operations and multiple local resources coordinated dispatch [137], post-disaster emergency response strategies (e.g., top-down, and bottom-up restoration models) [138], and EVs such as vehicle to home (V2H) [139]. For instance, the research study [140] proposed an advanced feeder restoration approach to restoring critical loads leveraging DERs during disasters. The main objective of this research was to propose an optimal allocation of DERs as mixed-integer linear programming to (1) lessen the restoration time, (2) maximize the amount of restored critical loads and the resilience to post-restoration failures. The simulations were conducted on an IEEE 123-node feeder with 5 DERs supplying 11 critical loads and the IEEE 906-bus feeder with 3 DERs supplying 17 critical loads. A similar study [141] introduced a novel framework for restoring critical loads considering the availability of DERs and determining the optimal path for restoration. The research objective was to maximize the reliability of the restoration plan aiming at minimizing the reliability of the restoration plan to decrease the possibility of post-restoration failures. To do so, this paper presented a distributed approach model incorporating min/max-consensus and bias min-consensus algorithms. This framework facilitated information exchange among neighboring nodes using a peer-to-peer (P2P) communication protocol.

Mobile and Stationary Battery Resources Optimal deployment and reconfiguration of mobile ESSs contribute to the active distribution systems in terms of fast rapid restoration of the critical loads and resiliency enhancement strategies [142]. The research explored cost-effective planning, scheduling, optimal routing, and on-disaster allocation of mobile ESSs (EV fleets, truck-mounted mobile ESSs, and mobile energy emergency generators) to enhance power resilience [143]. For instance, the scholars in [142] investigated the deployment of mobile ESSs and diesel generators in integrated electrical-heating networks to boost resilience, self-sufficiency, load restoration, power quality, and reduce operating costs. The proposed model was tested on an IEEE 33-bus electrical system equipped with some buses with CHP. Another article [144] concentrated on enhancing the resilience of a distribution network against earthquakes, with a particular emphasis on road traffic and interruption time as the main challenges in the early hours after the event by using mobile ESSs. This article modeled the impact of earthquakes on the distribution network, taking into account not only the immediate impacts but also the potential collapse of adjacent buildings onto power poles, utilizing fragility curves. The model presented was addressed through optimization using mixed-integer linear programming and was tested on a section of the Tehran distribution network.

More extensive investigation into operation-based distribution system strategies is essential to enhance the efficiency and resilience of power systems. By conducting further research with real datasets, power grids can be better equipped to endure and bounce back from extreme events and breakdowns, safeguarding vital loads and reducing customer disruptions. The existing models for power network configuration often struggle to fully grasp the intricate interplay among various distribution system elements, resulting in less robust setups that are more vulnerable to failures.

Balance of Power System Resilience, Reliability, and Sustainability

Reliability is the ability of a power system to deliver electricity continuously and without interruption to end-users. The sustainability of a power system refers to the ability of a power system to provide reliable and affordable electricity while minimizing its environmental impact, preserving natural resources, and supporting social and economic development [145]. The nexus of power system resilience, sustainability, and reliability recognizes the interdependence of these three critical aspects of modern power systems. Achieving a balance between them requires a comprehensive approach that considers the potential trade-offs and synergies between resilience, sustainability, and reliability. For example, enhancing the power system resilience through gas-fired backup power systems (e.g., large-scale CHP) can be unsustainable in case they rely on non-renewable resources [145]. Grid modernization can enormously contribute to maintaining the nexus of power system resilience, reliability, and sustainability [146]. It involves deploying advanced technologies such as smart microgrids, ESSs, RESs, DR schemes, advanced metering infrastructure, and cybersecurity measures to increase the power grid's flexibility, efficiency, and responsiveness.

Modernized Power Systems through Microgrids

Although current US electrical power systems can provide reliable service under normal and low-impact contingencies, they still struggle to maintain continuity during unexpected and high-impact events [147]. This highlights the fact that while existing power systems are considered reliable, they are not necessarily resilient. Various studies such as [92, 148, 149] have proposed solutions to enhance power system resiliency, encompassing the integration of DGs, microgrid implementation, and line reinforcement. Among these solutions, microgrids have gained popularity for their ability to enhance resiliency, owing to their capacity to accommodate RESs and their ability to function independently during system contingencies [150, 151]. Microgrids, classified into basic autonomous, fully autonomous, and networked microgrids, are created by isolating the affected region from the main grid and dividing it into self-sufficient microgrids through tie switches. For example, the scholars in [152] focused on the design of a robust current control system for a networked DC microgrid with multiple constant power loads, addressing a novel time-constrained denial-of-service attack. The research study [153] investigated developing a statistical framework to assess the resilience of grid-connected microgrids in serving critical loads during islanding scenarios. The study utilized a Markov chain to calculate the probability of meeting critical load requirements over a 7-day period. The resilience metric incorporated asset-level reliability data and evaluated the performance of a military microgrid with 5250 kW diesel generation compared to a hybrid microgrid with different energy sources. An optimized control algorithm was also developed to enhance survivability, minimize fuel usage, and reduce curtailed critical load. Another study [154] presented a resilient model utilizing mixed-integer second-order cone programming for optimizing the scheduling of microgrids (on an enhanced IEEE 33-bus benchmark test system) during islanded operation. The model focused on minimizing operational costs and load shedding that experienced scheduled interruptions from the main grid. The proposed model incorporated uncertainty through a robust approach, allowing the microgrid operator to balance performance and tolerance for uncertainty. The results demonstrate significant cost reductions and the prevention of unexpected load shedding when managing uncertainty effectively. In certain cases, microgrids can be interconnected to assist in powering the essential loads of other microgrids in the network having trouble with the power supply [151]. This makes microgrids an effective local or community resource for bolstering power system resilience through the concept of P2P energy trading systems [155, 156]. Moreover, microgrids can serve as a black-start resource for restarting main generators that have been disrupted by natural disasters [157]. For example, the study [156] investigated the application of blockchain technologies and auction mechanisms for enabling independent P2P energy trading within microgrids by developing two frameworks using smart contracts, incorporating continuous double auction and uniform-price double-sided auction mechanisms. The performance of these frameworks was evaluated through A/B (split) tests using real-world data. The findings suggested that integrating blockchain technologies and agent-based systems in a P2P platform holds promise as a complementary solution to the centralized energy grid.

Integrating and adjusting local RESs through microgrids can yield financial and socio-economic advantages [158].

Microgrid operation offers a valuable means of enhancing power system resilience through local, community, and black-star resources. The research [159] introduced a hierarchical model with three stages to enhance decentralized renewable-based microgrids' resilience. The model incorporated proactive steps to anticipate windstorms, optimized power generation scheduling, and reconfigured distribution feeders by the distribution system operator to reduce costs. Moreover, this paper considered uncertainties associated with load demand, wind speed, and solar radiation, and its performance was assessed using a distribution network consisting of 118 buses. Microgrids can support the startup of large generators that have shut down caused of a major event, providing a black start resource. Figure 4 illustrates a comparison between the restoration procedures of conventional and microgrid systems. In fact, the presence of microgrids near power plants can aid in the black start of conventional generators during blackouts [160].

Some other formations of microgrids can increase the short-term resiliency of power systems. Implementing dynamic microgrid formulation following power outages can improve the resilience of affected areas by ensuring self-sufficiency of local loads. For instance, the research [161] focused on developing a computerized tool that can effectively monitor, reconfigure, and control the topology of a DC microgrid. In their work, they presented the double bar bus DC microgrid utilizing event-driven and service-oriented architecture, along with real-time metering using nonuniform time sampling for neighborhood optimization. The objective was to create a system capable of assessing the resilience of the microgrid and dynamically rebuilding partitions to improve resilience during operation. The research gap is the shortage of studies investigating the economic and socio-economic benefits of microgrids under different uncertainty scenarios.

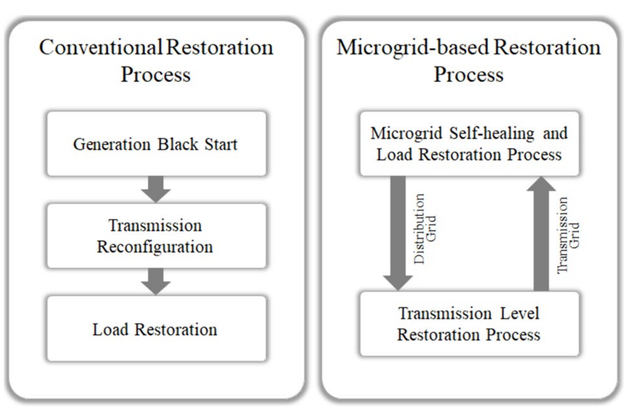

Fig. 4 The comparison of traditional power systems and microgrids during the restoration process

Advancements in Power System Resilience via RESs and ESSs

The shift towards deep decarbonization of power systems detracting GHG emissions and transitioning to cleaner energy sources is crucial in achieving carbon peaking and neutrality. To achieve this goal, RESs have emerged as a model for sustainable and integrated energy development that involves the integration of the distributed generation, ESSs, backbone grid, and microgrids to transform the energy supply composition [162]. Nevertheless, with the advancement of intelligent and eco-friendly power systems, they encounter growing unpredictability and complexity. Deep decarbonization of power systems requires transitioning from a centralized power generation model to a more decentralized and flexible system [163]. This transition involves not only replacing fossil fuels with RESs but also adopting new business models and regulatory frameworks to support the integration of distributed generations and microgrids. The national capacity expansion of RESs has been observed to follow an S-curve pattern. However, weather-related risks and cybersecurity threats can make energy systems fragile and susceptible to failure [164]. To ensure a steady and reliable supply of RESs, researchers have studied some momentous factors such as energy security [165], flexibility [166], reliability [167], and resilience [168] to enhance their performance through methods of concept definition and quantification. As an example, the study [169] investigated energy security through various ESSs, including pump hydro storage, thermal ESS, batteries, adiabatic compressed air energy storage, and gas/liquid bulk storage relevant to the energy transition. The findings indicated that thermal ESS offers the highest level of energy security, followed by batteries and gas/liquid storage. Moreover, the aim of the research [170] was to evaluate the impact of integrating variable RESs in the process industry to enhance energy flexibility. The assessment involved analyzing different scenarios and utilizing a simulation model to measure the specific reduction in CO_2 emissions. The following reviews the contribution of RESs and ESSs to power system resilience.

RESs can diversify the fuel mix of the power system, reducing the dependence on fossil fuels and increasing the system's resilience to fuel supply disruptions. This strategy can also boost energy security by reducing the reliance on imported fuels and decreasing the vulnerability of the power system to geopolitical tensions or market fluctuations [171]. Scholars in [172] proposed a trilevel max–min robust optimization framework equipped with large-scale RESs for implementing precautionary and responsive measures both prior to and following hurricane events. This study aimed to improve the resilience of active distribution system operation and tested on a modified IEEE-33/69 bus distribution system considering the uncertainties derived from the intermittent renewable production and multistage extreme contingencies. The study [173] evaluated a resilient thermal network for mountain communities powered by RESs in Italy that relies on biomass CHP and district heating systems based on two resilient energy system configurations. The proposed framework involved upscaling the energy system components to ensure that end-users receive the required energy supply during failures or extreme events. Another research [174] has proposed a resilience planning framework for distribution systems against natural disasters by determining the optimal locations for tie lines and dispatchable distributed ESSs and RESs including PVs and wind turbines (WTs). This paper developed the resilience planning model by taking into account two types of faults, including open circuit and short circuit faults, to create a more accurate simulation of natural disasters.

RESs can be integrated/paired with ESSs, such as batteries, pumped hydroelectricity, and thermal storage systems, which are used to store surplus energy when it is available and release it when needed. This approach provides a reliable power source during peak demand or periods of low-RES production of RESs. ESSs can also augment the stability and quality of the power supply, particularly in regions with high renewable energy penetration. The study [175] presented a decentralized approach to enhance the resilience of microgrids by determining the appropriate sizing and placement of mobile ESSs. Several studies have investigated the potential of various types of ESSs such as thermal ESSs, to boost the flexibility and resilience of power systems [49, 176–178]. For instance, the authors in [124] presented a model based on model predictive control for electricity network planning that considers hybrid ESSs. The study employed a multi-scenario algorithm to specify the state of charge of ESSs, and the results demonstrated the positive impact of hybrid ESSs on system resilience. Another study [143] concentrated on a resilience-oriented approach for the outage management of a 33-bus active distribution system using mobile ESSs. The study utilized four resilience measurements to quantify the system resilience, and the results showed a significant improvement in resilience due to the use of mobile ESSs and distribution feeder reconfiguration. The research [179] employed a mixed-integer linear programming model to analyze the impact of ESSs on distribution system resilience in the face of storms. This study applied fragility functions to create fault scenarios and demonstrated that ESSs lessen the forced load shedding in critical loads. It should be mentioned that equipping microgrids with RESs and ESSs plays a significant role in enhancing power system resilience and network recovery [180]. For instance, the researchers in [168] developed a resilience enhancement framework for renewable energy hybrid microgrids across various building types by calculating the probability of surviving an outage under different configurations of PV, WTs, ESSs, and generators. According to this study, adopting renewable microgrids with ESSs will play a vital role in the transition to the resilient smart grid of the future. The paper [181] introduced a multi-objective model for planning microgrids coupled with RESs to promote community resilience and environmental sustainability by exploring the integration of energy and water technology hubs. The proposed model focused on the optimal trade-off between three economic and environmental measures: cost, GHG emissions, and water consumption. The study [182] examined through the IEEE 17 and 69 bus test network, explored the improvement of resilience in isolated microgrids against potential cyberattacks aimed at curtailing critical loads. The resilience of the microgrid was enhanced through the diversified deployment of intelligent electronic devices, the optimal reconfiguration of the power network, and the strategic positioning and sizing of distributed energy resources in the design and operation phases. The authors in [183] presented an integrated tri-level mixed integer optimization framework aimed at enhancing the resiliency of multiple microgrids during extreme events considering two models of the defender-attacker-defender aiming at identifying the best possible solutions to reduce load-shedding. In the first model, measures to improve the system's robustness were examined, and worst-case scenarios with the highest load-shedding were calculated to perform reconfiguration and decrease load-shedding. In the second model, the study identified the most effective reinforcement plan and the most adverse attack scenario, achieving optimal placement of distributed generation to meet demand during the islanding mode of microgrids.

Research showed that RESs can be designed to be more resilient to natural disasters and other hazards. For example, WTs can be built to withstand hurricane-force winds, and PVs can be designed to withstand hail and high winds. The study [184] proposed an optimal resilience design of grid-connected integrated electricity and natural gas systems for residential communities on the capacity of an on-site PV system. Major conventional techniques for the placement of renewable distributed generations have focused on minimizing power losses [185], enhancing voltage profiles [186, 187], and maximizing cost savings [188]. Although, the authors in [189] introduced a new optimization framework to identify the optimal number, location, and assignment of renewable distributed generators for the single-source capacitated distributed generation location coverage problem in a utility-based off-grid microgrid during a major grid disturbance. This study considered total investment and operation and maintenance costs, travel distance for electricity distribution, power outage levels resulting from large-scale grid disturbances, and levels of excess renewable penetration that can lead to reverse power flow problems.

Power System Resilience through P2G and Hydrogen ESSs

The over-reliance on intermittent RESs, such as wind and solar power is a potential challenge. During dunkelflaute events, the electricity generation of RESs may be significantly reduced, leading to potential energy supply issues. One way to address the intermittency of RESs and ensure reliable power supply is to utilize the new power generation technologies such as P2G and hydrogen ESSs. This is done by transferring excess electricity from abundant generation of RESs to regions experiencing low generation due to dunkelflaute conditions [190]. The study [191] quantified the aircraft's electrical load based on passenger travel behavior and developed corresponding models for auxiliary power unit load characteristics and EV charging profiles using flight schedules and sequencing algorithms. To optimize the total costs of hydrogen-integrated ESS for airports, a mixed-integer linear programming approach based on life cycle theory was proposed. However, despite the potential advantages of hydrogen ESS in terms of resilience during power failures, this aspect remains largely unexplored in existing academic research. Therefore, the paper introduced a resilience assessment method and proposed improvement measures for hydrogen-integrated ESS. Another study [49] introduced a two-layer framework to enhance the resilience of a 118-bus active distribution network, comprising four microgrids with hybrid ESSs, electric buses, and a direct load control program. The model considered uncertainties in RESs generation, demand, and electric buses' mobility and employed a robust optimization approach to address them. In the first layer, individual planning for each microgrid was conducted while the second layer involved the control center's planning for the main network based on the microgrids' requested programs. The results demonstrated that the inclusion of hydrogen and electrical ESSs significantly reduces forced load shedding during emergency situations, and the utilization of electric buses for network recovery contributed to a resilience index increase. This article [192] investigated a conceptual integrated energy-mobility system centered around renewable-to-hydrogen stations and tank truck fleets. The renewable-to-hydrogen stations utilize renewable energy sources to power the grid while simultaneously charging a hydrogen ESS capable of performing power-to-hydrogen and hydrogen-to-power operations. The operational framework of the integrated energy-mobility system was analyzed, and preprocessing technologies were developed to simplify the modeling process. A joint optimal scheduling model was then formulated, incorporating renewable generation contracts, power-to-hydrogen and hydrogen-to-power operations. The research study [193] introduced a framework to enhance the resilience of microgrids using the power-to-hydrogen technology and their ability to operate independently. The study developed a model for resilient microgrid operation, where compressed hydrogen produced by power-to-hydrogen systems can be utilized to generate electricity. The model was formulated as a bi-objective optimization problem, aiming to minimize operational costs and maximize resilience by reducing active power exchange with the main grid, minimizing ohmic power losses, and increasing hydrogen storage in tanks. To address the complexity of this mixed-integer nonlinear optimization problem, a solution approach combining goal programming and Generalized Benders Decomposition was proposed. The results revealed that the resilience approach, while slightly increasing operational costs, ensures that there is no load shedding during main grid failures. The researchers [194]in addressed the growing interconnection between electricity and natural gas systems, brought about by the widespread use of natural gas for power generation and electricity-driven gas compressor stations. The study introduced an interdependent electricity-natural gas system that involves the spread of failures in both directions (bilateral and looped), along with a bidirectional energy exchange between the two systems. To bolster the resilience of the interconnected electricity and natural gas system in the face of natural disasters, the paper introduced a three-tier robust optimization framework that integrates strategies before and after the disaster occurs. The approach incorporated preventive planning strategies, such as the reinforcement of interdependent electricity-natural gas system transmission components to mitigate the impact of disasters. Moreover, fast-response power generating units, gas storages, and power-to-gas technology were utilized to cope with the aftermath of disasters.

Power System Resilience through DR Programs

Both DSM and DR programs are considered effective strategies for augmenting the resilience of power systems. DR programs are divided into incentive and price based and are usually executed through various methods, such as direct load control, time-of-use pricing, ancillary services, interruptible programs, peak time rebate, and real-time pricing [195]. DR programs allow customers to adjust their electricity consumption patterns in response to various factors, such as electricity prices [196], weather conditions [197], or grid reliability concerns (the reliability of DR programs is not guaranteed due to the inherent uncertainty in generation and storage units, and users' behaviors) [176, 197]. The importance of efficient and flexible DR schemes in modern power systems has increased due to their ability to enhance flexibility, reliability, and resilience [198]. The rise of distributed energy resources and the growth of EV uptake has made DR schemes critical for managing the variability and uncertainty of these resources [199]. For example, the authors in [200] have investigated a DR program with the capability of smart charging/discharging plug-in EVs (PEVs) to increase the reliability of the radial distribution network. The numerical reliability analysis based on the loss of load expectation and expected not served was carried out by leveraging the load profile, load peak, voltage profile, and energy loss. Furthermore, the growing occurrence of extreme events and other emergencies underscores the importance of emergency DR programs in ensuring the continued operation and resilience of the power system [201, 202].

The research paper [203] utilized the darts game theory algorithm for optimal microgrid formation to identify the trade-off between the power loss, load-shed power, and restoration cost considering the impact of the emergency DR program to enhance the distribution network resiliency. A similar study in [204] introduced a multi-objective restoration model to enhance the resilience of an electricity distribution network by minimizing load shedding during the restoration process while minimizing restoration costs. The framework includes the establishment of microgrids, utilization of DERs, and implementation of DR programs to enhance flexibility in the restoration of distribution networks. These DERs comprise generators powered by fossil fuels, along with RESs like wind and photovoltaic units, in addition to BESSs. DR programs encompass load options that can be shifted, curtailed, or transferred. The multi-objective model, as proposed, was addressed using the ε-constraint method, and the most suitable solution was chosen through the fuzzy satisfying approach. The efficacy of this model was validated through experimentation on both 37-bus and 118-bus distribution networks. The proposed model in [205] introduced a risk-constrained stochastic framework that addresses uncertainties in energy and reserve scheduling for a resilient microgrid with DSM. The framework optimizes system operation in both normal and islanding modes, considering uncertainties in islanding duration, load prediction errors, RESs, and electricity prices. The proposed scheme incorporates a security-constrained power flow method and a conditional value-at-risk metric to balance economic and security requirements while controlling profit variability.

The Role of EVs in Power System Resilience

EVs are becoming increasingly important in the energy system as they offer several benefits, such as reducing GHG emissions, oil dependence and improving air quality in urban areas [206]. Beyond these benefits, EVs can also contribute to enhancing the power system's resilience, making them a crucial component in the energy sector [207]. EVs enhance power system resilience as mobile energy storage units. Their batteries can store excess energy during low-demand periods and supply it to the grid during peak hours or emergencies [208, 209]. In the event of a power outage, EVs can serve as a reliable backup power source for critical load restoration [210, 211]. This function is particularly important in areas with frequent power outages or in locations with vulnerable grids to extreme weather events like hurricanes or tornadoes. Section 3 describes in detail the significant role of EVs in creating a more resilient and sustainable power system as flexible energy storages, backup power, and contributor to the stabilization of the grid during prolonged power outages.

EVs as Assets or Liabilities for the Electric Power Grid

EVs: Benefits and Limitations

According to the US Environmental Protection Agency (EPA), among other sectors such as industry, agriculture, commercial and residential, US transportation is the main source of GHG emissions [212]. EVs as sustainable alternatives to fossil fuel-powered vehicles offer a multitude of benefits, encompassing both environmental and economic advantages including zero tailpipe emissions, contributing to improved air quality and GHG emissions reduction, lower operating costs, and less maintenance contributing to long-term cost savings [213]. Research broadly investigated various technologies to boost the transportation systems' sustainability and to decrease GHG emissions through the application of biofuels/bioenergy [214], hydrogen vehicles [215], fuel cells [216], and all types of EVs (Battery Electric Vehicles (BEVs), Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV), and Fuel Cell Electric Vehicle (FCEV)) [217]. The past two decades have witnessed global development and advancement of EV industrialization. As worldwide EV manufacturing and production grow, the prospects of transitioning to zero-emission transportation have risen, and their cost has fallen. The average EV price in the US has increased by over 13% compared to the previous year, hit $66,000 in 2022 [218].

The financial incentives for medium and heavy-duty vehicles, such as purchase-based (down the upfront net purchase cost) and use-based (decrease in EV operating costs, offering additional federal tax credit, financial assistance, etc.), are vital to diminish emissions and make progress toward climate targets. The US government legislated *BUILD GREEN Act* to invest around $500 billion over ten years in greening public transportation infrastructure by installing EV charging infrastructure and expanding renewable energy generation capacity nationwide [216]. Electrification of the transportation system has considerable national benefits by (1) creating approximately 960,000 direct and indirect jobs (installation of solar and wind energy capacity, battery storage, catenary for commuter rail, and EV charging infrastructure), (2) human health (the entire bus and railroad fleet replacement bring about approximately 4,200 fewer deaths annually) [219], and (3) reduced GHG emissions (21.5 million metric tons of CO_2 lessened annually). The growth in annual CO_2-equivalent emissions of the worldwide transportation sector may reach 21,000 mega-tones in 2050, a 75% increase in comparison to 2020 when broader and more ambitious policy portfolios are not made [220].

A deep understanding of the obstacles hindering the widespread adoption of EVs is crucial to recognize their immense societal, economic, and environmental advantages, as well as their significant contribution to strengthening the power system. This comprehension allows for valuable insights into the process of EV uptake and the consumers' needs [221]. The obstacles to widespread EV adoption are discussed as follows based on EV users' point of view as well as policymakers' perspectives.

EV Users/Consumers' Points of View Researchers survey EV users to understand their opinions on individual barriers to EV adoption. For instance, a study in 2012 created questions to rank the uptake indicators and concluded that driving range, price, lack of charging infrastructure, and safety are the most significant barriers to EV uptake [222]. They realized that EV uptake is associated with factors beyond environmental impacts and per-mile running expenses. Moreover, they found that the respondents ranked EV prices higher than their environmental impacts [222]. In 2022, another study conducted by a pilot survey with 50 participants showed that the performance of EVs has been boosted and they are easier and more stable to drive and operate than before, while the concerns over their adoption intentions have remained unchanged [223]. Research [224] categorized the barriers to EV adoption from consumers' point of view into (1) sales conversion inability, including supply and choice of vehicles and dealerships, as well as lack of trust in technology, (2) living with the technology such as cost of purchase and ownership, charging infrastructure, driving range, recharge duration, and (3) desirability consisting of soul and character of the vehicle, repair, culture, lack of fun (such as the absence of gear shifting), emotional attachment, and others.

Policymakers' Viewpoints The obstacles to widespread EV adoption in categorized into five classes, including technical, policy, economic, infrastructure, and social. The research has shown that several obstacles still hinder the large-scale use of EVs, such as a lack of financial support [225]. Policymakers generally separate technical concerns from social ones but technical obstacles to EV adoption are challenging as social barriers [226]. The study [226] mentioned a major barrier is a technology and policy resistance, where government incentives promoting EV adoption may inevitably disrupt the oil companies and automobile companies that have made significant investments in supply and production infrastructure for internal combustion engine vehicles. Another study [227] highlighted the non-cost barriers. It indicated that limited outreach activities and awareness are the most crucial factors restricting EV uptake, followed by user perceptions, limitations in standardization, a dearth of diverse EV models, and the absence of supportive regulations. The research study [228] conducted semi-structured interviews with policymakers and car dealership representatives in Ireland. This research indicated that EV deployment progress is hindered by a lack of consistent promotion and awareness campaigns, excessive reliance on fiscal instruments, and weaknesses in an incentive system. Moreover, based on the conducted survey, the policymakers recommended strategies such as (1) implementing an emissions-based taxation system that exempts EVs from taxes, (2) promoting the utilization of PHEVs and HEVs, as an intermediate step towards the eventual transition to a fully zero-emissions market, and (3) increasing public awareness around EVs by creating a social norm through mandatory EV driving lessons.

Yet, the US government seems to pay more attention to tackling the technical and infrastructure EV uptake barriers. The new National Electric Vehicle Infrastructure (NEVI) Formula Program made by President Biden's Bipartisan Infrastructure Law has dedicated \$7.5 billion in EV charging infrastructure, \$10 billion in clean transportation, and over \$7 billion in EV battery components [229]. However, no funding has been allocated for education and public awareness. In short, policymakers mention other barriers to large EV adoption such as (1) lack of publicly accessible chargers [230], (2) EV driving range [231], (3) failure of efficient integrated energy management systems for EV and charging stations [232, 233], and upfront purchase cost [234, 235]. The research has not adequately investigated the most barriers to EV adoption from policymakers, given their varying priorities and potential conflicts of interest.

To take full advantage of EVs, more serious barriers to large-scale EV uptake should be addressed such as sustainably used battery recycling [236] and battery manufacturing [237], constructing or upgrading new charging stations coupled PV-energy storage with multiple charger types [238], and smooth integration of EVs with RESs and power systems [239]. Due to the interdependency of transportation electrification and power systems, the utilization of EV batteries as ancillary services, backup resources, and supplying electricity for EVs during a disaster should be addressed. Despite all the EVs' hurdles mentioned above, research has shown that they can make a significant contribution to power system resilience during outages as follows.

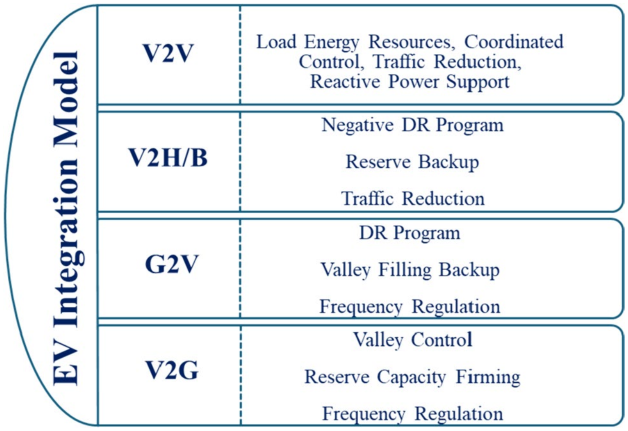

Fig. 5 Various EV integration modes with the electricity grid

Resilience Power Supply through EVs

EVs can help the grid's resiliency by modulating their charging level, smoothing peak curves, and filling load valleys [240]. Besides, EVs can offer diverse services to the power system by utilizing various charging methods, including vehicle-to-home or building (V2H/B), vehicle-to-grid (V2G), as well as one-way controlled charging (V1G) [241]. As Fig. 5 shows, EVs are integrated with the electricity grid in four manners. The required EV charge is supplied in the grid-to-vehicle (G2V) manner, while EVs as flexible loads, provide ancillary services such as capacity firming and reserves in V2G mode. Vehicle-to-Vehicle (V2V) enables the energy exchange method to charge EVs without the need for on-site chargers. It is performed through both wire/cable and wireless. In Vehicle-to-Home/Building (V2H/B), a bidirectional EV charger is utilized to supply electricity from an EV to a building/house via a DC-to-AC converter system. During a power outage, transportation electrification can benefit the power systems through EVs as flexible loads such as V2G and V2H applications [242]. Indeed, EV batteries can be aggregated aiming at injecting into the grid edges to address immediate local/regional critical loads during prolonged power outages. In addition, EVs can be grouped to energize a larger critical load such as distribution substations and efficient grid restoration [243]. To realize EV participation in the power systems (V2G), considerable utilization of EVs plus the owners' willingness are needed [244]. A survey conducted in [245] by experts in the US figured out that the most valuable integration mode is G2V, and the most crucial integration issue is battery degradation. The following subsection expounds on the resilient enhancement strategies via EVs to supply electricity for homes/buildings, disrupted critical loads, and damaged microgrids.

Buildings' Resilience Enhancement via V2H/B As backup resources, EVs can energize buildings and microgrids during and after power outages with the advent of V2B technology. Moreover, as self-healing resources, EV batteries provide electricity to survive critical loads and recover normal operation. EVs can operate as backup power [246] or an offline uninterruptible power supply [247] during a power outage to maximize the backup duration in buildings. Buildings under the demand response schemes combine the operation of the V2B, wind turbine, diesel generator, and PV system to minimize the energy costs [248, 249] and mitigate the power volatility in the RESs, providing an opportunity to increase self-consumption of PV system [250]. Research has paid attention to the V2H/B and integrated PV-EV under the home energy management system. For instance, the work in [251] augmented home resilience by leveraging PEVs to energize the building during a power outage while maintaining a minimum level of comfort level. Researchers in [252] have proposed the optimal resilience operation of buildings' energy management under both off-grid and grid-tied modes by leveraging the battery swapping technology, EVs, reserve battery, and PV system. One similar study developed a home-centralized PV system to obtain optimal appliance automation and reduced residential energy demand. A study considered the application of V2H technology, PV system, and EVs [253], and the research [248] pointed out that commercial usage of V2H can maximize locally generated RESs. Research [254] designed a novel home energy management system in nearly-zero energy buildings to optimally coordinate smart household appliances, RESs, EVs, and on-site storage facilities.

Power Systems' Resilience Enhancement via V2G EVs can contribute to the resilience enhancement of the power systems by leveraging EV self-healing capability [255], EV batteries as black-start resources [256], and as reactive power [257]. Moreover, EVs can support the grid to boost frequency regulation during the restoration phase [258] and survive critical loads during and after prolonged power outages [259]. Research [260] proposed a hybrid approach aiming at improving the resilience of the power distribution system with the combination use of PHEVs and PV systems. Another study [261] proposed an autonomous load restoration architecture based on IEC 61,850–8 – 1 GOOSE communication protocol to augment feeder-level restoration in the power distribution network.

Recently, MBTs as mobile energy storage systems and electric buses have been widely employed in the resilient restoration of power distribution systems because of their flexibility [262]. For instance, the paper [263] proposed dispatching truck-mounted mobile emergency generators for resilient emergency responses to natural disasters to survive critical loads by forming multiple microgrids. The proposed framework determined pre-positioning (prior to disaster) and real-time allocation (on disaster). The research study in [264] investigated the power restoration strategy by utilizing EVs in a parking lot for a low-voltage distribution system at the time of a power outage. The proposed strategy aimed to develop a weight factors allocation for priority-based scheduling of the appliances of residential consumers while satisfying the operational constraints. In addition, the researchers in [265, 266] introduced routing and scheduling of mobile ESSs coupled with intermittent RESs to ameliorate the resilient restoration of the power distribution network. Researchers in [267] mentioned that the power system could rent some electric buses due to their large capacity and model the electric bus dispatching and restoration scheduling problem to boost the resilience of power systems against meteorological disasters. But a serious problem that has been blurred in the research is "how to make incentivized mechanisms for EVs to participate in ancillary services?". The paper [268] investigated a fair incentive mechanism to encourage EV owners to participate in the load restoration of a modified IEEE 33-bus distribution system during a disaster. This study applied the asymmetric Nash bargaining theory to pay EVs through the contribution indicator. There is a huge research gap in making incentivized mechanisms aiming at persuading EV users to participate in the restoration phase.

Resilience Enhancement via Second Life of EV Batteries Batteries are key components of the power system's resilient enhancement strategies through EVs. The sustainable management of lithium-ion batteries after they have been useless has caused some concerns because of fast EV uptake [269]. The used lithium-ion batteries sustain considerable energy capacity when no longer usable for EVs since their residual capacities are degraded to 70–80% [270]. Innovative approaches to handling end-of-life electric vehicle (EV) batteries present significant opportunities for economic advancement, environmental stewardship in recycling and disposal to mitigate battery accumulation in landfills, preserving value, and sustainably managing raw materials [271]. The second life of EV batteries can contribute to energy infrastructure resilience in energy arbitrage, grid support by dispatchable RESs, and electricity demand load-leveling [272]. The usage of second-use batteries can lessen GHG emissions and costs in normal operation and provide electricity for critical loads in emergencies [273]. However, their deployment heavily depends upon heterogeneous local conditions, optimal logistics (priority routing strategies), site selection, and the demand for these batteries [274].

Research [275] designed a techno-economic assessment of second-life batteries to maximize the energy self-independence of the local energy community. This research regarded self-consumption maximization of PV energy, load shifting and grid balancing needs, and the exploitation cost of second-life batteries. The article [276] performed a techno-economical assessment of second-life EV batteries as a backup power to recover wind farms. The research work in [277] proposed deploying the second life of the EV battery as stationary energy storage in a residential building under six scenarios in the presence of demand-side management and self-consumption maximization of the PV system. The scholars in [278] developed a mixed ESS as a backup resource, including grid-connected vehicles and second-life batteries to replace the traditional ESS for forced outages and short-notice maintenance.

Resilience Power Supply for EVs

There are two reasons that a reliable power supply should be provided for EVs. The first reason is the growth of EV uptake and electrified transportation. In 2030, it is anticipated that the United States will have approximately 26.4 million electric vehicles on its roads [279]. . Secondly, power outages have the potential to disrupt the power supply for EVs and their charging infrastructure, especially grid-connected charging stations. Consequently, a loss of power supply for EVs, utilized for both personal and public transportation purposes, can impede mobility and essential services like public transportation and emergency response vehicles (e.g., fire trucks, police cars, and ambulances) during such events [280]. However, the government and agencies did not set regulations towards power supply for EVs, unlike gas-fired vehicles, where policies are in place along designated evacuation routes and emergencies [281].

One of the most crucial steps toward resilience enhancement strategies for EVs is to minimize the effects of power outages by anticipating the energy required for critical urban infrastructure, as well as determining the available on-disaster energy resources. The emergency preparedness plans are divided into short and long-term plans [282]. Long-term plans take steps to lessen the vulnerability during the mitigation phase. These preparedness actions acquire more time and investment and focus on figuring out how various types of disasters affect the buildings, infrastructure, transportation sector, people's lives, etc. [27]. . For instance, the study [283] utilized a planner-attacker-defender model to ensure the optimal performance of the power system under nominal operations and attacks, leveraging the combination of long-term capacity expansion and switch installation. Moreover, the proposed model optimized the investment in power system reconfiguration. A long-term resilience-oriented transmission expansion planning framework was proposed in [284] aiming at (1) determining the size of the power outage and its cascading effect by applying an iterative algorithm and (2) minimizing the impact of cascading outages in terms of power load curtailment. The second category of the emergency preparedness models is short-term plans utilizing the optimal allocation schemes for available resources during a disaster [29]. For example, the scholars in [285] investigated the resilience-oriented pre-hurricane resource allocation leveraging the generation resources such as electric buses, diesel oil, and BESSs to serve the critical outage loads of an IEEE 123-bus system. The resource allocation problem was formulated as a mixed-integer stochastic nonlinear programming considering the uncertainty derived from the magnitude and locations of fault.

The research studies on resilience enhancement strategies for EVs are mainly divided into three phases according to the disaster timeline (1) *pre-disaster recovery planning*: an opportunity for communities to respond to disasters and manage vital recovery issues rapidly, for example, keeping the essential services up and running. There are several pre-disaster strategies such as on-site energy storage in charging stations [286] and deployment of off-grid charging stations integrated with RESs [287, 288], (2) *on-disaster strategies*: the immediate execution of the emergency operations during a disaster to save lives, protect property, and satisfy basic human requirements through charging network during short-notice mass evacuations [289, 290] and resource allocation approaches with different priorities to supply the power for EVs and emergency services [291], (3) *post-disaster strategies*: designing effective strategies for restoration process (including three steps of start-up generation, reconfiguration, and load restorations) to restore the power system as fast as possible considering the Cold Load Pick-up (CLPU) phenomenon and EVs recharging demand [292]. CLPU phenomenon, more likely occurring after a disaster, is called when the load demand is greater than the regular system operation and is predicted by model-driven methods (challenge: information should be gathered from whole loads/equipment) [293] and stochastic methods (limitations to collect the load performance such as EV loads) [294]. Resilience enhancement strategies for EVs are listed in detail as follows.

On-Site Stationary ESSs Failure to manage the charging demand prudently may result in increased daily peak demand because of transformer and feeder overload, accelerating transformer aging, and increased power losses [295, 296]. A BESS can provide considerable benefits to the charging stations including (1) acting as a power buffer to make money for charging station owners (store in BESS during low-energy demand hours and discharge it during high-energy prices) [297], as well as reducing the effect of the extremely fast charging station on the power quality of power distribution network [298], (2) optimized energy arbitrage value and peak shaving [299]. Recently, several EV service providers such as Tesla and EVgo, are unveiling charging stations equipped with BESS under a solar-powered canopy to support fast, super, and ultra-fast chargers. The research has broadly addressed the optimal size of BESS in charging stations to minimize the operational cost of charging stations, stress on the grid [300], and average waiting time in charging stations [301]. Moreover, some researchers proposed the incorporation of RESs with BESS within EV charging stations by determining their size and type to (1) minimize the energy cost associated with the charging infrastructure [302], (2) reduce the cost of energy of the EV charging stations and the negative environmental impact [303], and (3) consider the EV power demand and EV typologies with various battery capacities [304]. Research in [305] modeled the sizing of BESS for E-bus fast charging stations by convex programming, considering the EV drivers' satisfaction levels and electricity costs. Some researchers have considered the economic benefits of BESS in charging stations. For instance, the paper [306] applied a multi-objective optimization to determine the trade-off between maximized energy arbitrage and daily income in the EV market and minimized loss during the BESS operation cycle. In addition, research [307] proposed the optimal scheduling model to minimize the charging station operating costs under the limitations of equipment power, EV travel demand, and BESS status.

Recently, several studies have paid attention to resilience enhancement strategies using BESS. For example, [308] proposed a resilience-constrained operation strategy by BESS to assure the survivability of critical loads after a power outage. Research [309] developed a quantification methodology from energy resilience perspectives considering photovoltaic generation and electrochemical BESS integrated into large buildings (such as offices). Moreover, the study in [310] proposed an optimization model for PEV commitment considering the time-of-use demand response scheme, PV system, and BESS.

Grid-Coordinated Operation of Charging Stations Charging stations should be capable of providing sufficient electricity for their operations and the ever-increasing EV charging demand. Moreover, charging stations are coordinated with the upstream network to fulfill the EV demand since BESS is inadequate and inflexible. The connection of charging stations to the upstream network may be affected by power outages. To this end, charging stations operate in islanded mode and RESs integrated with charging stations are conducive to augmenting the power quality and ensuring the stability and reliability of the distribution network. The fluctuations of RES generation necessitate the presence of BESS embedded in charging stations [311]. Figure 6 illustrates the operation of charging stations integrated with BESS, RESs, and the grid. Ethernet switch boxes, equipment units, as well

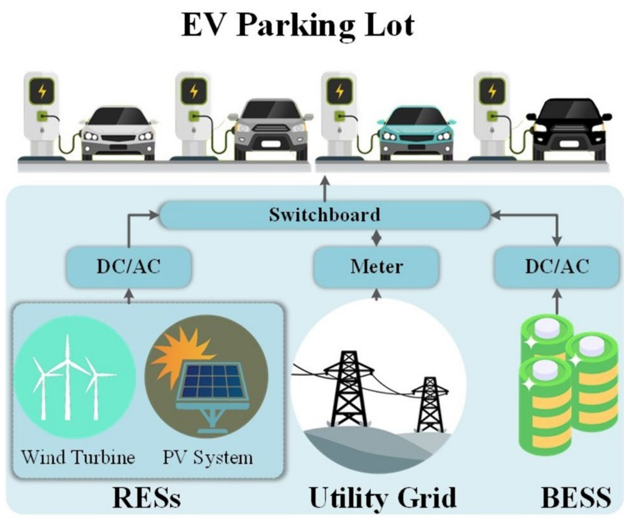

Fig. 6 The integration of charging stations' equipment including BESS, charging points, and RESs

as meters are embedded in charging stations, which control the maximum charging current, feeder connection, and data communication [312].

Some research highlighted the benefits of integration of BESS and RESs under the energy management system of charging stations since RESs provide frequency regulation, peak load shaving, load leveling, and spinning reverse [313]. For instance, research [314] investigated the multi-functional capabilities of a grid-connected solar PV system with BESS to meet the exceeded demands of residential buildings and EVs. Another research [315] has proposed a bi-level technique to optimize the size of charging stations and RESs by minimizing (1) Energy Not Supplied (seamlessly minimizing the power loss and boosting the system voltage magnitude) and (2) the operating cost of PEVs charging and discharging. Research [316] proposed an optimization framework for the techno-economic feasibility of solar PV parking lots coupled with PEV infrastructure with the aim of minimizing the cost of retrofitting parking lots (net present cost). Similarly, the authors in [317] developed an optimization framework to determine the optimal sizing of PV and BESS in extremely fast charging considering the EV coordinated charging strategy, investment and maintenance cost of PV and BESS, purchased energy from the utility grid, and EV demand. Apart from solar, wind can be coupled with BESS in charging stations to help support the V2G system; however, wind energy installation in charging stations is mainly beside the sea with wider regions accessibility [318]. The study [319] designed a grid-connected hybrid system (PV and wind) to fulfill the load demand of EVs and a small shopping complex. The proposed model minimized the levelized cost of electricity and the power supply loss considering the energy exchange to the utility grid. The paper [320] investigated an interval-based framework to identify the feasibility of leveraging wind energy to supply electricity to EV charging stations considering the time interval over which wind speed is averaged, various turbine manufacturers, and standard high-resolution datasets of wind speeds.

Battery Swapping Technology Deploying battery-swapping technology as an alternative means of replenishing EVs offers several advantages. These consist of eliminating charging duration, potential development into a larger ESS, mitigating the burden of uncontrolled EV charging on the power system, and lowering initial purchase costs [321, 322]. Tesla rolled out a new 90-s battery swapping technology in the US but ultimately gave it up because of the cost and utilization challenges [323]. Moreover, large-scale deployment issues remain a bottleneck for this technology, such as limited accessibility, energy estimation, safety responsibility, high maintenance costs of swapping stations, not being compatible with EVs, insufficient subsidy policies, and last but not least, lack of standardization made by automakers [324]. Research has paid less attention to establishing battery swapping stations as a long-term resilience enhancement strategy, for instance, during a mass evacuation. However, many studies focused on battery swapping station configuration, demand analysis, battery management mechanisms, and operation policy optimization to minimize operating costs and maximize revenue.

There exist three mainstream operating scenarios; *(1) centralized charging with battery dispatch*: consisting of a centralized battery station with BESS and a battery dispatch van for station-to-station and EV user-to-station. The research investigated the grid interaction potential with centralized battery stations, such as multi-energy resource integration and battery-to-grid management [325, 326], EV route planning [327, 328], and battery dispatch route planning [329, 330], *(2) distributed battery swapping station*: this type of charging stations can lessen battery transportation costs and power grid load in comparison to the centralized battery swapping stations. Researchers have investigated the closed-loop battery inventory system, placement, and sizing of distributed battery swapping stations [331, 332], optimal operation of battery swapping stations with PV systems [333] considering battery degradation [334], planning and investment [335], real-time operation management [336], and *(3) micro-battery swapping stations*: connected to micro-grids and supplied by RESs such as PV and wind turbines, and comprising battery storage system, battery charging system, converter devices, control equipment of battery-to-battery (B2B) and battery-to-grid (B2G) energies. Researchers paid more attention to the optimal energy management of micro-battery swapping stations [337], and real-time pricing strategies [338].

Sustainable Off-Grid Charging Stations Grid-connected charging stations lessen the operating cost and service reliability. Although, prolonged power outages, and thereby disconnection to the grid, affect the charge service reliability and power supply to EVs. Therefore, charging services cannot rely entirely upon on-station RESs and BESS due to a small battery, generation sizes, and uncertainty. Moreover, the energy source of the grid-connected bi-directional charging stations is a fossil fuel which is not environmentally friendly, and there is a need to shift from grid-based to clean off-grids because of frequent natural events. Sustainable off-grid charging stations have been developed to reduce the charging stations' dependency on the grid by leveraging the RESs (mainly PV and wind) at remote locations where the grid's reach is impossible. PV off-grid charging stations are more feasible as compared to wind-based energy because of fewer conversion stages to generate power [339]. Research [340] designed an off-grid PV charging station by assessing the life cycle assessment. Researchers in [341] designed a stochastic planning model formulated as multi-objective linear programming for green stand-alone charging stations powered entirely by RESs. The proposed model optimized the capacity and technology of BESS and RESs while minimizing the investment cost of off-grid charging stations considering the uncertainties derived from RESs and EV electricity demand. The study [342] proposed an optimal robust sizing of a solar-powered charging station coupled with BESS to minimize the delivery cost of charging services and improve resiliency. Researchers in [343] designed optimal mass evacuation planning for EVs before a natural disaster (Florida case study), considering the off-grid charging stations and limited charging facilities. Research [344] designed an off-grid charging station powered by solar panels for EVs and hydrogen vehicles, considering the uncertainties posed by solar energy, and the energy demands of EVs and hydrogen vehicles. Hydrogen vehicles are charged through an electrolyzing water system that is converted to hydrogen.

EV Cold Load Pickup after Outages A critical issue at the load restoration stage is Cold Load Pickup (CLPU), an over-current condition that occurs when a distribution circuit is re-energized after an extended period of power outage [345]. To model the CLPU at the load restoration stage, the effect of power outage duration should be considered since the attribute of CLPU is influenced by the ambient temperature and thermal loss over the power outage duration [346]. EVs can contribute to the CLPU after a power outage since CLPU is usual for any load interacting with the energy storage component [292]. The study [347] proposed a Monte Carlo simulation method to anticipate the CLPU derived from EV recharging on the distribution transformers. Some researchers focused on gauging the actual power outages and reconnections, aiming at allowing behaviors' prediction of real distribution feeders [294]. Researchers pay insufficient attention to the prediction of EV CLPU after a power outage. Moreover, considerable researchers have concentrated on the role of EVs, as a grid supporter, in power restoration of distribution networks after black-out [348], and they ignored the CLPU prediction models of EVs in post-disasters.

On-Disaster Utilization of MBTs The unchangeable geographic sites of the fixed charging stations have some hurdles such as higher charging fees, stress on the grid while charging EVs, lower resiliency in case of power outages, defective match according to the distribution of the EVs, and restricted expansion of the EV charging capacity beyond the grid constraints [349]. MBTs equipped with charging units and BESS can constitute mobile charging stations having the potential to target the accessibility and affordability issues of charging stations by Spatiotemporal dispatching of the required electricity for EVs. Moreover, MBTs can contribute to EV demand fulfillment during emergencies or disruptions. Recent research has witnessed the advancement in the conceptual design of MBTs with the aim of decreasing the RESs' curtailment while restricting the public costs of BESS. For instance, the study [350] designed a logistics system for battery shipment by MBTs between BESS and charging stations to enable the independent operation of charging stations. Research [351] proposed an optimal MBTs' dispatch based on a quantified function of EV demand prioritization demand considering several factors such as saturation of charging stations, distance, and socio-economic indexes. The researchers in [352] formulated the day-ahead optimal operation of MBTs as a mixed-integer non-linear programming (MINLP) to serve multiple charging stations in meeting the EV demands during overload and on-peak hours.

On-Disaster Resource Allocation to EVs Resource allocation, also known as resource scheduling, allocates fully or partially available resources to several critical activities during a disaster or a short-term disruption. Scarce resource allocation among various claimants has been a hot and active research topic in different fields. Researchers have proposed various resource allocation techniques, such as proportional sharing [353] and allocation based on several rules including the Talmud Rule, Equal Award Rule, Equal Loss Rule [354], and Fairness-oriented Scarce Resource Allocation Rules [355]. Other energy resources may need to be utilized to fulfill the EV demand during a power outage because of the failure of charging stations' services and restricted power supply. The resource allocation for EVs, similar to microgrids' load shedding, has fairness-related and prioritization challenges [356]. To this end, researchers have attempted to tackle these challenges. For example, researchers in [357] developed a multicriteria EV prioritization framework with the aim of fairly assigning available electricity resources to EVs during power outages. It pointed out that two parameters of social welfare and community well-being become parameters of paramount importance during power outages. In this study, EV prioritization is carried out based on three indexes of social welfare, community well-being, and individual EV satisfaction, with the combination of five decision variables including trip purpose, EV occupants, electricity gap, departure time, and customer behavior. Research [355] modeled a fair load-shedding problem connecting households to electricity supply based on several fairness factors, such as fair connection duration, the required electricity amount, and the demand. This study mentioned that regardless of fairness, some households may suffer more than others. Researchers in [358] exploited the EV user's preferences and their criterion of charging selection in terms of economic concepts. This paper categorized the charging preferences of EV users into three types of radical, conservative, and balanced. Recent studies have applied the fairness-oriented charging of EVs during a disaster considering several factors and priority criteria such as EV charge needed along with departure and sojourn times [359], state-of-charge (SOC), slack time for charging and allocated energy [360], and most urgent deadlines relative to their residual service time [361]. Moreover, a multi-server fair queueing model aiming at fair power-sharing for EVs with limited capacity has been investigated [362]. Although, research neglected the fair resource allocation for EVs during emergencies considering all potential resources, such as mobile battery trucks and their optimal dispatches to respond to charging services on time.

Social Vulnerability to Power Outages

As mentioned earlier, the consequences of power outages on the economy, environment, healthcare, and people's life have pushed the government and researchers to address the identification of vulnerable systems and failure points aiming at proposing enhancement strategies for power system resilience. While extended periods without electricity can cause considerable economic losses and environmental damage, the potential human catastrophe resulting from the breakdown of essential services can outweigh the financial damage suffered [363]. For instance, apart from economic losses, a winter storm in Texas, in February 2021, deprived millions of residents of electricity for 5 days. This situation tragically caused numerous fatalities due to factors such as carbon monoxide poisoning, severe cold, and worsening pre-existing illnesses [364]. After the catastrophic impact of Hurricane Maria on Puerto Rico in 2017, over 4,600 people died, with more than a third of these fatalities being linked to the lack of timely or continuous access to healthcare services [365]. Researchers introduced the notion of social vulnerability in the field of disaster management in 1970. They acknowledged that vulnerability encompasses not only infrastructure and technology but also socioeconomic elements that influence society's resilience [366]. Social vulnerability refers to a combination of demographic factors determining the extent to which communities, people, and their livelihoods are at risk during a disaster. It is commonly defined by three components: exposure, sensitivity, and adaptive capacities [367]. Exposure relates to the proximity and environmental characteristics of a location, while sensitivity measures the potential harm to people and their places. Adaptive capacities refer to the ability of a system to adjust, moderate effects, and cope with disruptions. The social science community broadly agrees on the key factors influencing social vulnerability, which encompass limited access to resources, political power, and representation, as well as social capital, beliefs, customs, physical limitations, and the type and density of infrastructure and essential services [368]. This section aims to review the existing literature on quantifying the social vulnerability against disasters and power outages and the impact of energy justice and lack of access to reliable electricity resources on the social vulnerability considering the socioeconomic measures.

The Quantification of Social Vulnerability Measures to Power Outages

Extended power outages can have various potential consequences, including health and safety risks, food spoilage, and disruption of healthcare and essential services such as water, food, heating, or cooling. Understanding households' vulnerability to infrastructure service disruptions provides valuable insights for prioritizing enhancements in infrastructure resilience to mitigate societal impacts. It is important to note that the residents are not equally affected, as socioeconomic and demographic factors significantly determine the severity of individuals' experiences during such outages. The most affected people are often those who are medically vulnerable or disadvantaged, facing difficulties in both preparing for and coping with the aftermath of these events.

The quantification and evaluation of social vulnerability in the context of power outages and disaster management has been broadly investigated by researchers. For example, a widely cited study [368], as a prominent and systematic effort in social vulnerability analysis, quantified a social vulnerability index to assess the vulnerability of all us counties to environmental hazards. This paper used county-level socioeconomic and demographic data related to both social inequities and location characteristics related to the built environment to quantify a social vulnerability index such as personal wealth, age, the density of the built environment, race, occupation, infrastructure, medical services, education, and so on. Through a factor analytic approach, a total of 42 variables were condensed into 11 independent factors. These factors were combined in an additive model to generate a summary score representing the social vulnerability index. The obtained results indicated distinctive spatial patterns, with clusters of highly vulnerable counties observed in metropolitan areas in the eastern regions, southern Texas, and along the Mississippi. The study [369] answered the question "Who is at risk when the power goes out?". This study utilized the Truven Health Market-Scan database to determine the population of privately insured individuals who relied on electrically powered durable medical equipment to sustain their lives, concentrating on geographical locations, age groups, and genders of individuals. The impact of power outages on health can be significant, with certain populations being more susceptible. A similar study [370] conducted a study focusing on New York City residents, particularly older adults (aged 65 and above) and people with household members dependent on electric medical devices or requiring assistance with daily activities. A telephone survey was conducted, and preparedness was defined as having a three-day supply of drinking water, non-perishable food, and a functioning flashlight. Out of all respondents, 58% were prepared, and 46% expressed concerns about health during power outages. Among respondents with electric-dependent household members, preparedness levels were higher (70%) compared to those without such members (56%). However, only 40% of this group reported being registered with utility companies for early outage notifications.

Some researchers have explored the relationship between socioeconomic factors and the economic consequences of power outages using heuristic models to gauge the effects of power outages and load reduction on consumers [371]. For instance, the purpose of the study [372] was to empirically evaluate how susceptible households are to power disruptions during disasters. The authors utilized a service gap method to describe the vulnerability of households to interruptions in infrastructure services. They employed empirical survey data gathered from Harris County, Texas, following Hurricane Harvey to ascertain the importance of different factors influencing household vulnerability. Several factors were considered in developing the social vulnerability model, including socioeconomic factors such as age, income level, minority status, and health issues, and other factors including availability of power supply, previous hazards experienced, level of necessity, access to reliable information, service expectations, social connections, and length of residence. The researchers used a stepwise algorithm to select the most relevant variables. Among the different models tested, the accelerated failure time logistic model demonstrated the best fitness in estimating household susceptibility to power disruptions caused by a disaster. The model revealed that having backup power, the household necessity for the service, race, and access to reliable information were the most influential factors affecting household susceptibility to power disruptions. The study [373] presented a comprehensive framework that merges a geospatial power system operation model with spatial considerations of social and economic indices, including population, economic activities, essential services, and facilities such as hospitals, emergency response centers, police departments, fire stations, schools, and daycare centers. The framework allowed for the simulation of system component failures and restoration based on environmental conditions. The authors applied this framework to analyze the effects of planned or unplanned power outages. The case study demonstrated that controlled optimization helps reduce the societal costs of power outages by redistributing power shortages to regions with lower costs and partly shifting the costs to other factors. The scholars in [364] introduced a three-dimensional measure of social vulnerability that quantifies the extent to which an individual's life or livelihood is at risk due to prolonged power outages. The three dimensions of vulnerability include health, preparedness, and evacuation. To create a single metric for each dimension, principal component analysis, and a Euclidean norm model were employed. These three scores were combined using Pareto ranking to generate an overall vulnerability score. The study applied a case study approach focusing on Colorado state, utilizing data from the 2020 US Census and other relevant federal and state datasets.

Some studies showed that the impacts on health resulting from the power outage are not uniformly experienced across all socioeconomic groups [374, 375]. Indeed, certain socioeconomic and demographic factors can increase individuals' susceptibility to higher risk levels. For example, the purpose of the research [376] was to investigate the correlation between power outages resulting from Hurricane Irma and hospitalization and mortality rates among residents of nursing homes in Florida using state-administered surveys to assess the power outage status of nursing home facilities. Another study in [375] evaluated the potential health consequences of both citywide and localized power outages in New York City during the period from 2002 to 2014 within 66 electric grid networks, utilizing data from the New York State Public Service Commission. Both studies indicated that age is a crucial factor in determining an individual's ability to endure a prolonged power outage, and older adults are generally considered to be more vulnerable compared to other age groups. Similar to older adults, children are vulnerable to extreme temperatures, both cold and hot and power outages have a notable impact on them [377]. A study in [378] examined how the policies of RESs in Vermont address the issues of energy vulnerability. Utilizing an anti-resilience framework, this study incorporated 569 surveys and 18 interviews conducted across the state. The findings revealed that individuals who are low-income, non-white, and renters experience higher levels of energy vulnerability, characterized by inadequate access to affordable energy. Notably, low-income and renter respondents were more than three times as likely, while non-white respondents were seven times as likely, to report instances of lacking heating.

While many studies have focused on developing indices to measure social vulnerabilities in relation to various natural disasters, the literature on social vulnerability has largely neglected the specific context of prolonged power outages. The enhancement strategies for power system resilience in the face of natural disasters and cascading failures have primarily taken an engineering-centric viewpoint and overlooked the social aspect of the issue. In more detail. power system resilience studies typically rely on strategies that measure the impact of electricity service disruptions using metrics such as the energy not served or the value of the lost load. However, these metrics fail to capture the non-monetary consequences of power outages [379]. Moreover, the reviewed social vulnerability indexes are based on qualitative approaches, and researchers neglected to model the quantitative approaches for social vulnerability indexes against prolonged power outages. Most research studies investigated social vulnerability by leveraging socioeconomic and accessibility factors such as access to public and educational resources, medical care facilities, and backup power. However, to the authors' knowledge, the researchers have not considered broadly the impact of the distribution of RESs, and ESSs on the duration of power restoration for affected people.

The Association between Energy Equity on Social Vulnerability to Power Outages

The provision of electricity services enables access to fundamental amenities such as lighting, heating, and cooling, in addition to powering indispensable devices and appliances that are crucial in everyday life. Energy is intricately linked with social, political, and economic structures, making it a matter of social justice. These energy systems often disproportionately harm specific segments of society, particularly low-income communities, and ethnic groups [380]. A reliable and affordable electricity supply is also fundamental for the proper functioning of crucial infrastructure, including hospitals, schools, and public safety systems, without which people's lives, health, and safety could be compromised [381]. However, many people across the world do not have access to electricity. According to the IEA, the number of people without access to electricity increased in 2022 for the first time in decades (774 million people) [382].

After experiencing a slowdown due to the pandemic in 2020 and 2021, the number of people without access to electricity is increased in 2022. It is estimated that approximately 774 million people will be affected, which is 20 million more than the previous year. This increase will bring the number of people without access to electricity back to the levels witnessed in 2019. Much of the rise is expected to occur in sub-Saharan Africa, where almost 80% of those live in the dark and the number of people affected is approaching the highest level seen in 2013 [383]. The top-five countries with the lowest access to electricity in 2022 are the Central African Republic, Malawi, Burundi, Chad, and South Sudan. Yet, the vast majority of the US population has had access to electricity for decades, but some households may still face challenges in accessing reliable and affordable electricity [384].

Social Inequity in Power Recovery and Restoration Research has provided evidence of social inequities within the domain of power outages that disadvantaged communities face a higher occurrence of more prolonged power outages. These disadvantaged communities also bear a greater burden of the adverse consequences resulting from such outages. For instance, the study [385] indicated that the blackout caused by the hurricanes Irma and María resulted in an estimated excess of 1200 fatalities. These excess deaths predominantly affected individuals belonging to the most socioeconomically marginalized areas of Puerto Rican society. Current strategies employed by electric utility companies for restoring power after a disaster do not consider socioeconomic and demographic measures and political affiliation as factors when distributing resources for recovery. To this end, the scholars in [386] developed a novel method that utilized daily satellite nighttime light data allowing for tracking the restoration of electricity and both centralized and distributed power supply systems, including off-grid systems. The analysis covered all settlements on the island, monitoring the duration of power outages and recovery times and linking these measures to demographic information obtained from the census. The results indicated disproportionate extended power failures in rural municipalities, particularly in the northern and eastern districts. Unexpectedly, this paper identified significant disparities in electricity recovery among neighborhoods within the same urban area, primarily associated with housing density. Notably, low-income residents, who are most vulnerable to increased mortality and morbidity risks due to power outages, experienced longer outages because they resided in less densely populated, detached housing where electricity restoration lagged. Another study [387] analyzed data from four major service regions in Upstate New York during Super Storm Sandy, as well as daily operations. By employing non-stationary spatiotemporal random processes that link infrastructure failures to recoveries and associated costs, the results revealed that local power failures have a disproportionally large non-local impact on people. Moreover, extreme weather events do not necessarily cause vulnerabilities but rather amplify pre-existing vulnerabilities that may not be readily apparent in day-to-day operations. The researchers in [388] employed data/information regarding the deployment of power restoration crews, a fresh metric for evaluating government responsiveness, and a newly developed index for measuring social vulnerability. They examined the factors influencing government responsiveness following power outages and discovered that communities with affiliations to the ruling party tend to receive more attention from the government. Conversely, socially vulnerable communities are less likely to receive prioritized assistance during outage recovery efforts. This holds true even after accounting for factors like disaster damage, logistical challenges, economic considerations, and the restoration of essential services. The current policies for power restoration disproportionately affect marginalized communities, underscoring the importance of including power restoration for vulnerable communities as a key priority in restoration efforts.

Social Inequality in Power Outage Duration There is a clear demand for developing a social vulnerability metric tailored to address the unique challenges posed by power outages. For example, the scholars in [389] conducted a study on the duration of power outages at the census block group level in the US by gathering data from the U.S. Census, the U.S. Geological Survey, and a utility company's power outage database. This paper considered various factors, including the American Indian disadvantage as a correlate of average outage duration, to understand the causes of inequality in power outage duration. They realized there may be institutional bias contributing to this inequality. However, when they applied spatial error regression models, they found that unequal resilience and service inequalities within the study area can be more consistently explained by factors such as proximity to important facilities like hospitals, the average number of customers affected by outages downstream, and environmental conditions such as seasonal patterns. Some scholars investigated social vulnerability to power outages from an environmental justice perspective. For instance, the study employed an environmental justice framework to address whether pre-existing vulnerabilities in Puerto Rico are related to the rate of electricity restoration following Hurricane Maria. The scholars anticipated that areas identified as vulnerable to environmental injustice would experience slower recovery compared to less vulnerable areas. Regression analysis was utilized to assess how well three vulnerability indices (distributive justice, procedural justice, and justice as recognition), based on environmental justice variables encompassing factors such as the percentage of the non-white population, income levels, linguistic isolation, educational attainment, young individuals experiencing poverty, and seniors living in poverty, predict the restoration of electricity. The analysis yielded mixed evidence regarding the initial predictions. Alongside environmental justice factors, additional factors such as terrain and proximity to electric transmission lines also impacted the rate of recovery, adding complexity to the recovery narrative. Another similar study [390] employed Hurricane Irma's impact on Florida as a case study to investigate (1) the discrepancies in electric power outages and recovery rates between urban and rural counties, and (2) the length of power outages in counties subjected to tropical storm force winds compared to those exposed to the hurricane, (3) the relationship between the duration of power outages and socioeconomic vulnerability. The findings indicated that counties with a predominantly rural character, mainly served by rural electric cooperatives and municipally owned utilities, encountered prolonged power outages and notably delayed recovery and significantly slower and uneven restoration times. A research study [391] on the impact of Hurricane Sandy in New Jersey discovered variations based on ethnicity in terms of evacuation duration, power outage duration, self-reported personal/family/healthcare effects, and the utilization, need, and accessibility of federally qualified health centers.

Social Inequity in Access to Resources The consequences of a prolonged power outage are more severe when individuals or households are unprepared for such events. As described in the literature, disaster preparedness entails access to essentials such as clean water, food, medical supplies, backup power, and an emergency plan. It is associated with specific socioeconomic and demographic factors [370]. For example, the researchers in [392] conducted interviews with 42 individuals residing in Highlands and Orange Counties, Florida, following a hurricane. These interviews encompassed a diverse range of socioeconomic indexes, genders, ages, and neighborhood characteristics. The researchers realized that households with lower incomes living in disadvantaged areas experienced lower resilience during the storm. In fact, during power outages, individuals with lower incomes face limitations in acquiring non-perishable food, backup power, generators, and fuel, which in turn is linked to heightened stress caused by the blackout. When people plan to evacuate during an emergency or a prolonged power outage, various capacity-related factors can influence or modify their decision. Some research studies showed that higher household income [393] and access to resources [385] have been positively associated with the choice to evacuate.

On the other hand, lacking reliable transportation serves as a barrier [394] to evacuation. A study in [395] examined equity aspects related to community resilience following Winter Storm Uri in Texas, which resulted in prolonged power outages affecting over 4 million households. The research analyzed county-level data on outages and recovery to investigate significant associations between different county attributes and their share of outages during the recovery phase. Using satellite imagery and computer vision techniques. The findings indicated that a percentage of the linguistically isolated population and public transport users displayed positive associations with the group of census tracts affected by the outage.

Social Inequity in Access to RESs and ESSs The energy justice research highlights that disadvantaged and energy-poor households are disproportionately impacted by the inequities that arise during the transition to sustainable energy. Both academic literature and policies highlight the potential of renewable energy communities to promote people's involvement in the energy transition and foster a fair transition. For instance, the paper [396] examined data from 71 European renewable energy communities to investigate how they fulfill this social role by enhancing participatory processes to involve vulnerable groups and provide affordable energy for households in need. Moreover, the researchers evaluated how renewable energy communities align with the three core principles of energy justice (distribution, recognition, and procedure). However, it is worth mentioning that one significant consequence is that households already burdened by high energy costs face increased energy insecurity when prices rise due to the adoption of new technologies and expanded infrastructure such as RESs and ESSs. These vulnerable households face the risk of utility disconnection and experience mental and physical stress as they struggle to afford essential heating and cooling requirements [397]. But the government and utility companies have attempted to provide financial incentives to boost people's involvement in sustainable energy transition. For example, the Department of Public Service supported loan programs that enable low-income households to undertake energy efficiency improvements by providing subsidized interest rates for loans [398]. The study [378] indicated that despite Vermont's reputation as a leader in renewable energy, the current policies do not effectively distribute household transition benefits in a manner that addresses vulnerability equitably. The study further revealed that non-white respondents were seven times less likely than white respondents to have solar panels, while renters were three times less likely compared to homeowners. Interviews conducted as part of the study highlighted that household transition benefits primarily benefited high-income households. The authors argued that these disparities may be attributed to structural discrimination and policies that allocate household transition benefits based on disposable income and property ownership. This unequal distribution of "investment capital" has hindered access for non-white, low-income, and renting households.

Emerging grid resources like ESSs have the potential to offer significant environmental and societal advantages. The study [399] proposed a comprehensive framework consisting of four metrics to identify priority regions for deploying and dispatching ESSs by integrating spatial-temporal data on plant electricity generation, air quality standard exceedance days, and population characteristics obtained from the environmental equity screening tool. The main purpose it to replace marginal grid air emissions with high environmental and health effects considering location and time factors, densely populated areas with poor air quality, particularly during periods when air pollutant concentrations exceed regulatory standards. To demonstrate the effectiveness of our framework, the authors conducted a case study using ESSs, and DR program to identify regions where emissions reductions can have the greatest marginal benefits. Another study [400] examined the energy equity and community benefits of MBTs through an analysis of storage adequacy for three specific use cases: utility-scale networks of MBTs assets operating within the distribution system, MBTs assets utilized for community public transit, and behind-the-meter personal vehicle MBT assets. Each use case involved different battery capacities, charging schedules, and grid integration, necessitating an understanding of the associated equity co-benefits. The study [401] delved into various strategies for obtaining ESS from the viewpoint of customers. It explored how behind-the-meter programs can be organized in a fair manner, ensuring that customers don't face a financial disadvantage whether they opt for front-of-meter or behind-the-meter energy storage solutions. Additionally, the study looked at the possibility of providing higher incentives for low-income customers in underprivileged areas, ensuring they have equal access to the benefits of behind-the-meter energy storage schemes. Table 2 shows the summarization of the reviewed papers regarding the social vulnerability index.

Although the existing literature has widely investigated the impacts of access to RESs, ESSs, backup power, and emergency services and facilities during disasters, there is a gap in specifying the effect of EV adoption by low-income people in disadvantaged regions in power restoration duration. Moreover, the research neglected the role of equitable placement of EV charging infrastructure, such as off-grid charging facilities, in power outage management.

Table 2 The comparison of the recent studies concerning the social vulnerability index to power outage

Reference	Category	Main Contribution	Findings
[368, 372]	Social Vulnerability Index	Developed a social vulnerability index for US counties and households to assess vulnerability to power outages	Distinctive spatial patterns of highly vulnerable counties in Texas Identified backup power, household necessity for the service, race, and access to reliable information
[369, 370, 375]	Impacts of Power Outages on Health and Vulnerable Populations	Investigated the impact of power outages on health, focusing on the population of privately insured individuals	Varying levels of preparedness and concerns among older adults, emphasizing the need for increased preparedness and communication. Age is a crucial factor in determining vulnerability to power outages, children and older adults are generally more vulnerable. Low-income, non-white, and renter individuals experience higher levels of energy vulnerability due to inadequate access to affordable energy.
[380]	Access to Electricity and Energy Equity	How energy systems disproportionately harm specific segments of society, particularly low-income communities and ethnic groups	Examines the association between energy equity and social vulnerability to power outages.
[385–388]	Social Inequity in Power Recovery and Restoration	Social inequities in power outages and the adverse consequences. Tracking electricity restoration and recovery times in different regions, linking outage duration to demographic information. Assesses the determinants of government responsiveness in the wake of power outages, highlighting disparities in outage relief effort	Analyzes the government's prioritization of power restoration in relation to social vulnerability. Analyzes the government's prioritization of power restoration in relation to social vulnerability.
[389, 390, 392]	Social Inequity in Access to Resources and Preparedness	Power outage preparedness and resilience among households in Florida. disparities in power outages and the speed of restoration between urban and rural counties in Florida	Institutional bias and spatial factors contributing to unequal resilience and service inequalities during power outages The positive correlation between the duration of power outages and socioeconomic vulnerability.
[378, 396, 399–401]	Social Inequity in Access to RESs and ESSs	Frameworks to identify priority regions for deploying RESs and ESSs, considering environmental justice and population characteristics	The potential of ESSs to replace marginal grid air emissions with high environmental and health impacts. County-level data on outages and recovery to investigate associations with demographic characteristics. The impact of incentive levels targeted at low-income customers living in disadvantaged areas for equal participation in energy storage programs.

Conclusion

The well-being of millions of people affected by the cascading effects of disasters such as extended power outages, heavily depends upon the ability of critical infrastructures of electric power systems, to withstand and recover from these outages. Furthermore, the worldwide increasing demand for electricity has emphasized the significance of ensuring the power system's resilience in the face of disruptions. This paper initially discusses the importance of addressing the power system's resilience, followed by presenting the qualitative and quantitative resilience metrics. Then, this paper advocates for a systematic review of current literature, emphasizing the importance of utilizing advanced technologies to enhance the resilience of the electric power system including such as RESs, ESSs, MBTs, as well as off-grid green charging stations and isolated microgrids. The increasing EV adoption in transportation presents both challenges and opportunities for the power sector. With their larger batteries, EVs can contribute to the resilience of buildings, microgrids, and power systems by providing services to the grid during emergencies. The second part of this paper aims to discuss the substantial contribution of EVs as backup sources to the electric power system during prolonged power outages such as utilization of second life of EV batteries or other applications including V2G, V2H/B, and V2V. Moreover, the paper emphasizes the need for coordinated planning and operation strategies to supply EVs with power. The importance of EVs in various event phases and the need for updated public policies are highlighted. The last part of this paper aims to review the literature on the possible connections between resilience power system, EVs, and social vulnerability by addressing social inequity in power outage management, duration, and access to backup power and resources such as RESs, ESSs, and MBTs.

Future research in this field can concentrate on investigating the dynamic interplay between EVs and power systems during extreme circumstances like natural calamities or cyber-attacks. Future research can enrich existing literature by adopting an interdisciplinary approach, merging insights from economics and policy studies to gain a comprehensive understanding of the complex connections between power system resilience, EV integration, and societal vulnerability to power outages. Additionally, integrating case studies from various geographical areas can offer valuable insights into effective approaches for boosting power system resilience, leveraging EVs, and addressing social disparities during power failures. This study can be expanded by examining the role of backup power sources and EVs in meeting the electricity demands of critical infrastructure. Exploring the extent to which backup power, encompassing ESSs, RESs, and EVs, can contribute to re-energizing critical infrastructure, including hospitals, healthcare facilities, and emergency services, while considering energy accessibility equity, is crucial. Future research may delve into cutting-edge technologies like blockchain, artificial intelligence, and the Internet of Things (IoT), which have the potential to make power grid resilience and EV integration. Given the escalating frequency and severity of climate-related disasters, forthcoming review papers could underscore the significance of power system resilience and EVs in climate change adaptation, spotlighting strategies for mitigating risks and fostering adaptive capacity in response to evolving environmental challenges.

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Declarations

Ethical Approval No ethical approval was required as it did not involve the collection or analysis of data involving human or animal subjects.

Competing Interests The authors declare no competing interests.

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