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REVIEW

Resilience-Driven Planning and Real-Time Control Strategies: Challenges and Solutions

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Abstract

This paper reviews the existing definitions of grid resilience and its metrics at distribution and transmission levels, while investigating resilience requirements and assessment methods. The paper also focuses on methods to enhance grid resilience through planning and real-time control strategies. It has been found in the review that, to date, there have not been a commonly agreed definition and methods to assess power system resilience and that it is essential that the grid operators have coordinated solutions addressing the power system resilience from generation to transmission, distribution and local systems and distributed energy resources. Main suggestions for future research on grid resilience could include development of resilience metrics and resilience-readiness assessment framework, development of methods to integrate resilience into the long-term planning of the power systems, development of a co-simulation of interdependent systems, and most importantly, real-life demonstrations and validations of resilience solutions.

Keywords Power system resilience · Flexibility · Resilience-driven planning · Real-time control · Resilience enhancement

Introduction

The transition to the decarbonized energy systems poses many challenges to grid operators. The challenges are due to replacing conventional dispatchable power generation with the intermittent weather-dependent, power-electronics interfaced generation as well as increased electricity demands by electrification in heat, transport and industrial sectors. The challenges are also due to that the power delivery grids at both transmission and distribution level are not developing fast enough to cope with the fast changes in generation and demand sides. At the same time, extreme weather events are occurring more frequently, and the threats from physical and cyber-attacks, earthquakes, warfare and other types of crises to power and energy systems are growing. More serious attacks on power plants, substations, transmission lines, etc., in Ukraine in the on-going war today have large impacts the country's energy supply system. This could lead to sustained power outages interrupting electric services in large areas.

The most recent large power blackout in Spain and Portugal happened very suddenly and within a few seconds leaving people in major cities of both countries without electricity and significant service interruptions in metros, airports, urban traffic system, hospitals, etc. [1]. Even though the root causes of the blackout are still under intense investigation, this event highlights the need for increased resilience of energy systems, that is the ability to withstand and recover from disturbances. These are great challenges faced by both transmission system operators (TSOs) and distribution system operators (DSOs) as to how to plan and operate the grids in a more intelligent and coordinated way to ensure continuous and stable energy supply while resilient to critical and extreme conditions.

Resilience is not a new concept. It is gaining increased attention from TSOs, DSOs, and authorities [2, 3]. What exactly is grid resilience? What are the metrics of grid resilience at TSO level, at DSO level as well as at the system level? What are the requirements and how to assess resilience? How to achieve the required level of resilience and at what cost? How will the cost be financed, by whom and what implications do these have on end-customers? These

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are a few key questions to which the answers are not quite clear today.

This paper attempts to review the current state of the art on the challenges and requirements in planning and operation of the power system to ensure high degree of security of supply, robustness and resilience to benefit the customers and the society. Specifically, the main contributions are the following:

i) Definitions of resilience, resilience metrics and assessment methods.
ii) Discussions on main resilience-driven planning and operation approaches for enhancement of resilience in distribution and transmission grids.
iii) Discussions on main real-time resilience control strategies for resilience enhancement.
iv) Suggestions for possible future research directions.

Resilience Definitions, Metrics and Assessment

Definitions

Table 1 summarizes the main resilience definitions by different organizations. Those definitions can differ depending on the perspective and operations of each organization. Those definitions point to a common agreement in that resilience reflects the ability or the characteristics of the grid to anticipate, withstand or protect against and quickly recover from disturbances derived by high-impact low-probability events. To improve grid resilience, it is necessary to improve all or most of these characteristics.

Factors Affecting Power System's Resilience

As European countries emerge from the recent energy crisis, several challenges to the energy transition and the overall security of our energy system remain. In the following subsections, the most important challenges that affect and threaten the power system's resilience are discussed.

Physical Attacks

The physical attacks on the electricity supply infrastructure have been reported, leading to extended power outages. For example, in 2022, electricity substations were attacked in Pierce County, USA and North Carolina, USA leading to 15,000 and 45,000 people out of power, respectively [9], while in May 2025, an alleged arson disrupted the electricity supply in Southern France, affecting more than 160,000 households [10]. The increasing occurrence of physical attacks on the electricity infrastructure and their consequences should be studied for the provision of scenarios for alternative electricity supply [11].

Cyber Attacks

The increased penetration of distributed energy resources (DERs) such as solar PVs, batteries, heat pumps and electric vehicles (EVs) increased the risk of cyberattacks as such devices could be exploited as an entry point into a data stream that feeds the energy system. Thus, as the number of such entry points increases, so does the risk that malicious actors will start manipulating the data generated. Therefore, enhancing cybersecurity of the power system is important the enhancement of grid resilience [12]. An illustrative successful cyber-attack example on power systems is the cyber-attack on the Ukrainian power system in December 2015, due to which more than 50 substations were affected, and about 225,000 Ukrainian customers lost power supply [13]. As a result of the increased number of cyberattacks on power systems and the potentially high impact of the successful ones, research efforts have focused on the investigation of methods for power systems' fortification against malicious cyber attacks [14].

Table 1 Summary of resilience definitions according to different organizations

#	Definition	Organization
1	*"Power system resilience is the ability to limit the extent, severity, and duration of system degradation following an extreme event."*	CIGRE Working Group C4.47 [4]
2	*"[The resilience is] the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capacity to anticipate, absorb, adapt to, and/or rapidly recover from such an event."*	US Federal Energy Regulatory Commission (FERC) [4]
3	"Grid resilience is the ability to withstand grid stress events without suffering operational compromise or to adapt to the strain so as to minimize compromise via graceful degradation"	Pacific Northwest National Laboratory (PNNL) [6]
4	"Resilience is the ability to withstand and mitigate the extent, severity and duration of system degradation following an impactful event"	ENTSO-E [7]
5	"Resilience of the power system reflects the impact of severe events. It is a way of describing the power systems ability to deal with extraordinary disturbances, high-impact low-probability (HILP) events, or rapidly changing external conditions"	ISGAN [8]

Table 2 Recent natural disasters and their effect on power system infrastructure

#	Event	Location, year	Effect
1	Storm	Australia, 2016	Blackout. 1.7 million people are without electricity [15, 16]
2	Hurricane Maria	Puerto Rico, USA, 2017	Electricity outages in electricity service persisted for months [17]
3	Typhoon	China, 2015	More than 4 million people are without power supply for several days [18]
4	Cold/Storm	Texas, USA, 2021	Large-scale blackouts. Over 4 million people are without electricity. Interruption of water and gas supplies. Dramatic increase in electricity prices [19]
5	Ice storm	China, 2008	Extensive damage to power system infrastructure is affecting many people and subsequently leading to billions of dollars of economic losses [20].
6	Earthquake	Chile, 2010	
7	Hurricane Harvey	USA, 2017	
8	Wildfires	Australia, Brazil, USA	A large part of their power systems has been affected with large financial damage [21].

Table 3 Resilience-related operational, policy and regulation challenges and requirements

Type	Challenge/requirement
Operational	Secure restoration of the power system [11]
Operational	Increased power system absorption and resistance [11]
Operational	Grid operators (TSOs and DSOs) should assess their operational planning considering extreme events and planned outages including steady state, transient, stability, and short circuit analyses [22]
Operational	Grid operators (TSOs and DSOs) should have a documented contingency plan for grid resilience [22]
Operational	European TSOs should comply with EU's Cyber Resilience Act to maintain an adequate cybersecurity level [23]
Operational	The existing grid planning approaches today only consider N-1 reliability criteria [11]
Operational	Studying extreme events is outside of common industry practice, where planning studies tend to focus on ensuring reliability to a set of common or credible contingencies [17]
Operational	Power system interconnectivity could more easily lead to cascading [24]
Operational	Transition from a system based on dispatchable generation towards a system based on mostly weather-dependent generation [23]
Operational	Increased individual ownership of resilience assets decreases the possibility of coordinated actions for improved grid resilience [25]
Operational/ Regulatory	None existed standardized metrics for assessing grid resilience, especially in the distribution level [26]
Regulatory	No specific resilience-related framework for power systems [27]
Economic	Difficult to secure the financial feasibility of resilience-related management of power systems [28]
Policy	Difficulty in coordination since different nations may have different, and sometimes contradictory, regulatory environments and incentives [11]

Climate Changes and Natural Disasters

The increasing frequency and severity of extreme weather phenomena that lead to sustained power outages interrupting electric services in large areas highlight the need for enhanced power systems' resilience. Therefore, increasing power system's resilience against HILP events such as natural disasters is of paramount importance. Table 2 summarizes the recent natural disasters that had major impacts on the power system infrastructure.

Operational, Policy and Regulation Challenges and Requirements

Since the resilience topic has been increased in significance recently, many regulatory, policy and operational challenges and requirements have emerged. Table 3 summarizes the most important challenges and requirements in both transmission and distribution grids. They are categorized as Operational, Regulatory, Economic and Policy.

The above-mentioned challenges related to the power system's resilience reflect the current situation. The resilience related challenges are expected to increase in number and intensity over the next years. The global temperature is expected to increase by 1.5 °C by 2030, leading to an increased frequency of natural disasters (i.e., extreme hot temperatures, agricultural droughts, storms, floods, increased wildfires, increased cold and snow periods), which will affect the entire Europe. Since power system assets are exposed to the natural phenomena, the increased frequency of extreme weather conditions will affect the entire chain of power system elements in generation, transmission, and distribution. Hence, European entities should adapt to the new environmental conditions by engineering solutions to withstand the extreme weather in the entirety of power system infrastructure, i.e., generation, transmission, and distribution [29].

Resilience Metrics

There are no established standards and regulations for grid resilience [2]. It is important to develop metrics and methods to quantify resilience, and the planning methodologies to compare e.g., different investment alternatives for resilience improvement to meet a certain requirement (targets) of grid resilience. Metrics for analyzing system performance can be divided into four categories: (1) per-stage performance metrics for the system's response to a particular stage of the disruption; (2) per-scenario performance metrics for power system's resilience to a particular scenario; (3) per-event performance metrics, hence, an aggregation of the per- scenario performance metrics for a single event, weighted by the probability event occurrence; and (4) asset-level performance metrics for the vulnerability and criticality of specific component failures.

A widely used method to predict or quantify system's resilience under high impact low probability events is the grid performance curve (GPC) and its variations [24]. The GPC can be assessed using various performance metrics such as (1) percentage of total or critical loads; (2) number of supplied critical loads; (3) number of survived or failed loads; and (4) technical metrics (voltage and frequency) [26]. If a single metric were to be used to measure resilience it would be "the expected availability of the required capability," that should be calculated as the probability weighted sum of the availability summed across the considered disruption cases [21].

E.DSO tries to identify the most significant climate metrics that can be attributed to the different stages of the curve. For this reason, E.DSO defines five main resilience features (robustness, redundancy, reliability, response, and recovery) to which 71 different resilience metrics are specified. The defined metrics have been categorized as leading (resilience-oriented planning or a measure of the network/asset pre-evet state) or lagging (event impact or a measure of the network/asset during or post event state), while it is also defined to which main resilience feature those metrics are connected, as well as with which climate hazard(s) they are associated to [30].

National Renewable Energy Laboratory (NREL) quantifies the resilience by providing performance-based metrics that quantify the consequences that could be avoided through resilience investments, such as: (i) Customer outage time; (ii) Load not served; (iii) Number or percentage of customers experiencing an outage; (iv) Number of critical services without power; (v) Time to recovery; and (vi) Cost of recovery [31].

The impact of extreme events on power systems can be effectively quantified by the resilience assessment at facility- and system-levels. Facility-level resilience assessment evaluates the damage probability of the power facilities during extreme events, while system-level resilience assessment mainly evaluates the impact of power system infrastructure damage on the power system operation [18]. Table 4 summarizes the most recent methods developed for the evaluation of the power system resilience.

Resilience-Driven Planning

A recent paper [33] and a planning guide by Siemens [34] have presented new methods for urban grid planning to consider DERs, EVs, etc. However, resilience has not been considered as one of the planning goals. The existing grid planning approaches only consider N-1 reliability criteria. The new approaches for resilience enhancement can include: (i) "pre-event" in the planning phase (hardening the grids); (ii) "during-event" in the real-time (real-time monitoring and control) and (iii) "post-event" in the recovery phase; which will ensure that the grids or part of the grid will survive after sudden and large disturbances. At the same time, in the current condition, it usually takes a long

Table 4 Recent methods for the evaluation of power system resilience

Method	Entity	Comment
A Resilience grading strategy, based on barrel theory [18]	Researchers	Fair resilience assessment decision-making for resilience enhancement strategies.
Power system resilience evaluation method based on the power support ability of power sources and network topology [15]	Researchers	Full consideration of the characteristics of modern power sources and grid topology are considered, resulting in improved evaluation accuracy.
Comprehensive grid resilience assessment framework including a topological perspective focusing on high wind incidents [32]	Researchers	The assessment evaluation framework generates a resilience index that can accurately reflect grid status during adverse climate conditions. The proposed framework can be applied to all types of power networks.
An integrated modeling framework capable of evaluating system performance using physics-based engineering models [17]	Pacific Northwest National Laboratory (PNNL)	The developed framework can evaluate bulk electric system infrastructure upgrades and operational decisions based on their impact on power system resilience.
Web-based geospatial application called EGRASS (Electrical Grid Resilience and Assessment System) [17]	Pacific Northwest National Laboratory (PNNL)	The developed tool can make recommendations for improved distribution system resilience.

time to expand the grids in a classical way by considering only new transmission lines, cables, substations etc. The grid operators would then need to consider non-wire options in their planning, i.e., flexibility provided by DERs in distribution grids enabled by intelligence and controls, ICT/IoT platforms, island operation of microgrids, etc. The balance between the wire and non-wire options needs to be decided by the planning framework. For the distribution grid planning by the DSOs today, the grid planning is based on N-1 reliability criteria, i.e., the grid should function within the acceptable limits when one of the grid elements is disconnected due to a disturbance or a fault. Resilience-driven planning, on the other hand, will plan the grid to be able to withstand many severe disturbances, i.e., N-X criteria, with X being the elements destroyed by the disturbances; to maintain the continuity of supply for as many customers as possible; and to be able to quickly restore the supply of disconnected areas. The capability of islanded operation of microgrids would be an efficient solution for security of supply, i.e., to use the already existing resources, as compared to traditional wire-solutions with high redundancy. In the following subsections, the possible solutions to enhance resilience in the transmission systems and distribution networks will be reviewed.

Resilience-Driven Planning of Transmission Systems

The European TSO organization, ENTSO-E identifies some resilience-driven planning solutions that can be employed towards contributing to maintaining a high-level of resilience of the power system [7]:

i) **Power system flexibility** that can be exploited in different time scales (i.e., both long-term as well as closer to real-time) to compensate for the loss of dispatchable power plants.
ii) **Increased interconnection with distribution and other energy sectors** with increased cross-sector observability and awareness, hence, providing better threat and risk assessments.
iii) **Infrastructure and investments**, as the evolution of planning methodologies allows for a more accurate resilience assessment and cost-benefit analysis.
iv) **Resilience-driven market design**, through the provision of incentives to market actors.

ENTSO-E envisions leveraging market mechanisms to ensure system resilience and efficient use of infrastructure. For a more effective market design TSOs should identify, define, quantify and communicate long-term system needs to guide market design evolutions and stimulate technology and business innovation, while the electricity market design must be able to better reflect the physical reality of the grid. A resilience-driven market design needs to properly reflect grid constraints and operational challenges via e.g., requirements, price signals and products, including new ancillary services, new congestion management approaches coordinated with DSOs, and new grid tariff structures [7]. Some of the products that could be traded in such markets would be Frequency Containment Reserve (FCR), Automatic Frequency Restoration Research (aFRR), Manual Frequency Restoration Research (mFRR), Fast Frequency Reserve (FFR), Black Start, Reactive power and voltage control, Redispatch, etc., while the relevant stakeholders (suppliers, balance responsible parties, power exchanges, TSOs, DSOs, aggregators, etc.) could exploit, e.g., hydro, renewables, CO_2 neutral thermal generation, heat pumps, electric vehicles (EVs), battery energy storage system (BESS) and demand response technologies to participate in the markets.

Moreover, EURELECTRIC concludes TSOs should adjust to the expected deterioration of climate conditions, through accordingly adapting power system planning. To this end, they recommend the development of more accurate forecasting of weather conditions, so that renewable-based generation is precisely estimated, as well as increased use of storage, thermal, flexibility and interconnection back-up for renewables. EURELECTRIC recommends adaptation of transmission assets to the new conditions such as provision of alternative power network paths, i.e., increased meshing and increased grid automation and digitalization level to promptly reconfigure and restore the grid. In addition, the redundancy in system design accounting for dependencies could be beneficial, as well as resource sharing between neighboring system operators [29].

Grid-forming (GFM) technology could also play a vital role in improving system resilience by combining operational, structural, and recovery aspects in grids with high penetration of renewables. For example, BESS with GFM can provide: (i) real-time grid stabilization (i.e., frequency regulation, voltage support, fluctuation mitigation); (ii) operational continuity during events (i.e., energy backup, peak shaving, autonomous reconfiguration); (iii) faster post-event recovery (i.e., prioritized restoration, black-start support); and (iv) Long-term structural adaptation (i.e., investment deferral, resilient RES integration, operational flexibility) [35]. Furthermore, authors in [15] propose a method that can efficiently evaluate power system resilience, which can be applied to different grid planning scenarios and can be a useful tool for power system operators for grid planning as well as dispatching decisions.

Resilience-Driven Planning of Distribution Networks

The European DSO organization, E.DSO, identifies that grid hardening, hence, strengthening MV and LV grids through targeted investments would be crucial to increase distribution network's resilience and efficiency, and expanding distribution networks. Moreover, the extensive deployment of smart meters enables accurate detection of LV imbalances, facilitating the implementation of data-driven solutions to increase flexibility and resilience of the network. A specific solution to mitigate voltage unbalance and increase LV network resilience is the LV Network Smart Balancer [36].

For increased grid resilience, DSOs need to consider grid hardening, non-wire options, i.e., the flexibility from distributed energy resources (DERs) as well as from multi-carrier coupling. To this extent, the multi-energy synergy of electricity and natural gas distribution systems (EGDS) offers potential for resilience in extreme events [28]. Moreover, authors in [25] propose the peer-to-peer (P2P) energy transactions to increase the resilience of distribution networks in the long-term. According to this approach, prosumers that are equipped with DERs could support the power supply system in a local manner by forming P2P transactions, hence, increasing the distribution system resilience. Furthermore [37], explores the contribution of EVs and vehicle-to-grid (V2G) technology to increase the resilience of India's distribution network planning. According to their research, EVs reduce dependency on traditional fuels, while they serve as mobile power sources which are vital for essential services during extreme events.

Real-Time Control for Resilience Enhancement

Many real-time control strategies for enhancement of grid resilience at various levels in the power systems have been investigated in the literature. This section presents the main strategies in transmission, distribution and microgrid levels.

Smart Islanding in Transmission Systems

A novel risk-based defensive islanding algorithm has been proposed in [38] which can be used to enhance the system resilience by splitting the network into stable and self-adequate islands [39]. proposed a new controlled islanding method for a hybrid AC/DC grid which finds an optimal islanding solution in real time such that the power exchanges between islands are implemented via a VSC-HVDC link to reduce the generation-load imbalance. Other proposed methods include, e.g., a constrained spectral clustering-based methodology for intentional controlled islanding of large-scale power systems by [40] and a two-step spectral clustering-controlled islanding algorithm by [41], and power system reconfiguration method based on multilevel graph partitioning presented by [42]. In Sweden, the Swedish TSO has increased its activities to strengthen electricity security where the island operation has been one of the solutions when the national power system fails. It is primarily about being able to supply essential societal functions and facilities that are important for the total defense with electricity [43].

Black-Start Support from Renewable Sources

The transition toward the renewable based energy system will lead to the reduced black-start capability from fossil generators which currently provide black-start capability. Renewable based generation will need to provide black-start capability in the renewable dominated system [44]. has carried a comprehensive review into this aspect and identified the challenges. It was found that converter-connected renewable energy sources (RES) could provide black-start services with high speed of self-starting, ramping and dynamic response and they can start using internal energy storage systems or diesel generators due to low demand for auxiliary power. However, there are challenges with RES, especially when it comes to the grid-following mode which is currently used in most RES today. If RES can be equipped with grid-forming capability, they can act as black start units. With the development of grid-forming inverters, grid operators must consider how RES can be used to aid in black-start and consider increasing the required communication and coordination between DSOs and TSOs when performing grid restoration [45].

Flexibility for Grid Resilience

In [8], how flexibility can be used to enhance the grid resilience, in both planning and operation phases, have been discussed. It was discussed that flexibility could be developed and utilized for the operation and planning of the power system as well as for stability support. The integrated flexibility will directly impact the resilience of the power system, thus flexibility solutions intended to provide resilience support must be reliable and secure to provide the trust required for operation and planning. A comprehensive list of projects focusing on flexibility and resilience has been reviewed. SCCER-FURIES Dynamics project [46] has shown that converter-based resources have the potential to overcome the challenges caused by the replacement of conventional synchronous generators based sources and to maintain or even improve the overall system resilience, including (i) system support during faults near the distribution grid feeder;

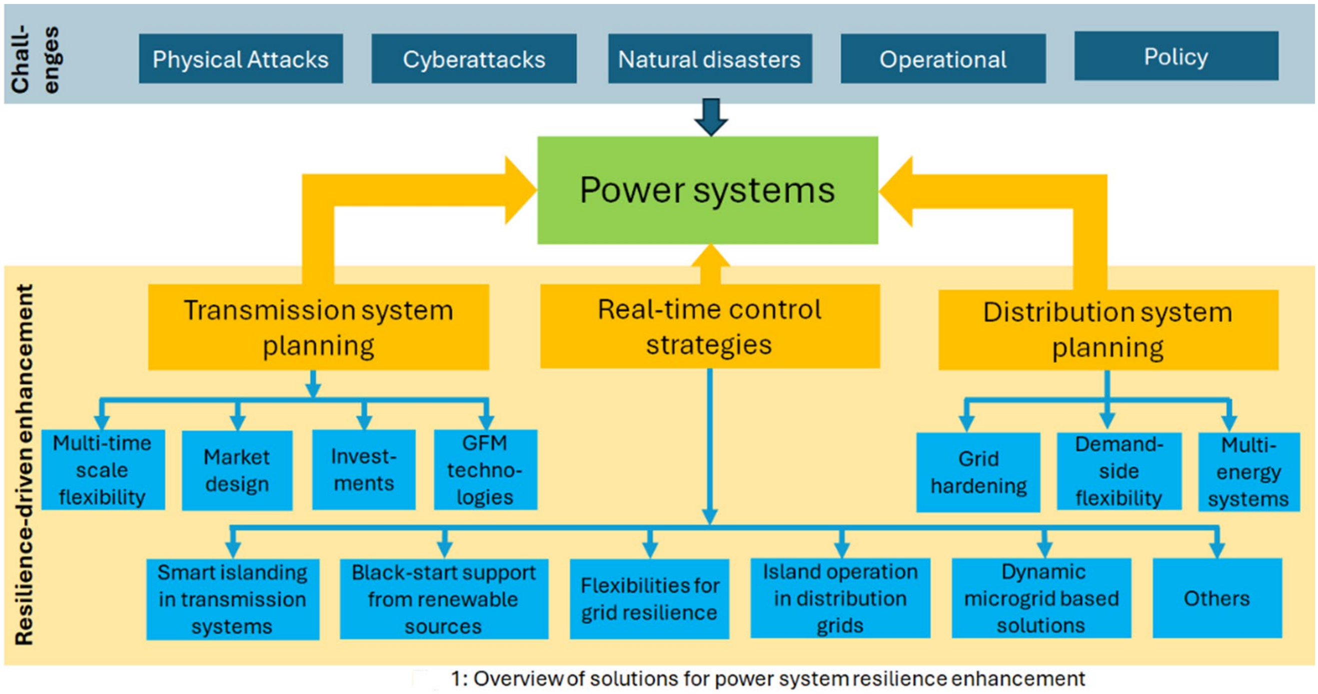

Fig. 1 Overview of solutions for power system resilience enhancement

(ii) support of for islanding operation when disconnected from grids; (iii) support during a transmission system split.

Island Operation in Distribution Grids

At Chalmers University of Technology in Sweden, initiatives have been taken towards this direction to develop and demonstrate innovative solutions to enhance the resilience and security of supply of future power systems using the bottom-up approach, focusing on securing the resilient energy supply of local energy systems of various forms (e.g., energy communities, energy islands, etc.) and enhancing their capabilities to support up-stream grids in normal and critical (e.g., large power outages/blackouts) conditions. The solutions will be demonstrated in the RESIST project [47] at Chalmers Wind Turbine test site (hosting a wind turbine, solar PVs and BESS) on Björkö island in Gothenburg, Sweden.

Dynamic Microgrid based Solutions

Micrgrids are potential solutions for increasing resilience in distribution grids due to their ability to support islanding operations during grid disturbances [48, 49] [50]. has presented a comprehensive review of microgrids' strategies enhancing resilience, including, e.g., (i) Transformation of conventional power networks into microgrids; (ii) Dynamic microgrid formation followed by a catastrophic event (e.g., reconfiguration of existing microgrids); (iii) Networked microgrid formation (i.e., geographically closely located microgrids can be networked to support each other during major disruptions); (iv) Multi-energy microgrids and energy hubs (e.g., increased resilience in electricity, heating, gas networks by the ability to support each other during a major disturbance).

Discussions and Recommendations

Discussions on Challenges and Solutions

Figure 1 summarizes the resilience challenges discussed in Section II, the resilience-driven planning in Section III and real-time control strategies for resilience enhancement in Section IV. Please note that the solutions proposed are many, this paper only focuses on those related to planning and real-time control. Solutions to addressing cyber security are not in the scope of this paper either. As illustrated in Fig. 1, for resilience enhancement, it is imperative to have an integrated solution addressing the power system as a whole, i.e., from generation to transmission, distribution and local systems and resources. Furthermore, it is necessary to employ planning actions in transmission and distribution systems, as well as real-time controls at all levels. It is also important to involve stakeholders of the whole value chain of the power systems as well as other coupled networks such as heating, gas, transport, etc., to ensure that the solutions are technically, economically and socially efficient. The subsections below will present key recommendations related to the planning and regulatory aspects as well as key research directions for enhancing power system resilience

Planning and Regulatory Recommendations

Requirements on Resilience The energy systems are still vulnerable to weather-induced events, various types of attacks, especially physical attacks. The grid resilience should be considered as a strong requirement from the authorities for the grid operators to ensure their grids' resilience to be able to continue to support the social activities as well as national securities even during the extreme weather events or grid disruption.

Incentivize Resilience Investments As stated in [29], the regulatory framework for system operators, screening criteria for private investments and resilience funding must **incentivize climate adaptation** such as physical system hardening, improvements in system operation, recovery planning, capacity building, and smart grid technologies, such as smart meters, remote control, and advanced system automation. These adaptation measures should use sound cost-benefit analysis and a consistent impact assessment framework. These will ensure that customers can rely on a decarbonized power system capable of dealing with the effects of the climate change.

Societal and End-User Involvement and Acceptance The current planning models for the grid infrastructure need to factor in resilience constraints and costs. It is important to get the end-users and various stakeholders involved in the process to ensure that the investment would reach a balance between the cost of providing resilience and the willingness or acceptance to pay for resilience (e.g., avoiding long-duration outages) from stakeholders.

Suggestions for Future Research

Development of Resilience Metrics and Resilience-Readiness Assessment Framework As discussed earlier, there have not been a commonly agreed resilience metrics. It would be desirable to propose a set of metrics, e.g., performance-based indicators (PBIs) for assessments of grid resilience against different types of threats, including, e.g., (i) natural disasters and pandemic events; (ii) human-made physical- and cyber-attack events; (iii) system design, aging, and human error. PBIs are useful when evaluating certain resilience measures' effectiveness. These metrics can be used as inputs, e.g., (i) in long-term resilience-driven planning because they measure the potential benefits and costs associated with proposed resilience improvements and investments; (ii) resilience-driven real-time monitoring and control strategies. It is also desirable to develop a framework to analyze the "Resilience-readiness" of existing grids with regards to a grid's ability to predict, adapt, and respond to all hazards and threats. This framework would help the grid operators (DSOs and TSOs) to determine the answer to such questions as, e.g., "how resilient is my grid?", and "what are the measures for resilience improvements, and how to get there?".

Development of Methods To Integrate Resilience into the Long-Term Planning of the Power Systems A new planning model is needed to support the distribution grid operators to plan for their grids for new areas, reinforcement of existing grids, or simply perform investment analysis for new elements in their networks, to enhance grid's resilience. The goals of such planning are to strengthen the grid, i.e., "system hardening", to ensure that the grid or part of the grid will survive after sudden and large disturbances, for examples, part of the local grids can still operate with its own resources (i.e., island operation) after being disconnected from the main grids.

Development of a Co-Simulation of Interdependent Systems As suggested in [51], some of the challenges with the modeling of an interdependent cyber-physical system can be analyzed using co-simulation tools. It is desirable to develop a co-simulation platform for transmission and distribution grids hosting DERs. Using this platform, it is possible to generate various disturbance scenarios and run multiple dynamic simulations based on scenarios generated by the power systems. The simulation platform can be used for e.g., resilience-driven grid planning, real-time monitoring and assessment of resilience for resilience enhancement.

Demonstrations of Resilience Solutions Many solutions proposed in the literature are based on model development and testing using simulations. It is important to evaluate the resilience solutions using real-life demonstrations by e.g., integrating solutions into a control platform of a real test site, performing different test scenarios and evaluating the results. For this, as mentioned earlier, Chalmers University of Technology has plans to demonstrate island operations to increase resilience using a real-life setup hosting a wind turbine, solar panels and BESS.

Conclusions

This paper presented a systematic review of power system resilience focusing on definition, metrics, assessment methods and measures for enhancing resilience. The key findings for the paper are that there have not been a commonly agreed definition and methods to assess power system resilience and that they are dependent on the main drivers of the organizations who defined it. It would be important to align the definition as well as the assessment methods which can lead to a common framework for addressing resilience, when it comes to the planning and investments in solutions for resilience. The review also highlighted that it is essential that the grid operators have coordinated solutions addressing the power system resilience from generation to transmission, distribution and local systems and distributed energy resources. Key suggestions for resilience enhancement for regulatory authorities include, e.g., requirements on resilience by grid operators and incentive mechanisms for resilience investments. It is also important to involve stakeholders of the whole value chain of the power systems as well as other coupled networks such as heating, gas, transport, etc., in developing solutions to ensure that outcomes are technically, economically and socially efficient. Based on identified research gaps from the review, suggestions for future research could include, e.g., development of resilience metrics and resilience-readiness assessment framework, development of methods to integrate resilience into the long-term planning of the power systems, development of a co-simulation of interdependent systems, and most importantly, real-life demonstrations and validations of resilience solutions.

Author Contributions L.A.T. initiated the paper and ideas, drafted the overall content, collected the literature, wrote Abstract, Sections I, IV, V, IV and overall reviewed and edited the paper. I. B. drafted the overall content, collected the literature, wrote the Sections II, III, prepared Figure 1, organized references, overall reviewed and edited the paper. D.S. contributed to the paper content development and reviewed the paper.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/ (accessed on 17-07-2025).
2. Power IEEE, Society E. Resilience Framework, Methods, and Metrics for the Electricity Sector, Technical Report PES-TR83, October 2020.
3. Werneskog J, Barr J. Resilient och trygg elförsörjning, Power-Circle, 2022: https://powercircle.org/FINAL_resilient-och-trygg-elf%C3%B6rs%C3%B6rjning.pdf.
4. CIGRE. Power System Resilience, 2019: https://www.cigre.org/article/GB/news/the_latest_news/defining-power-system-resilience, accessed on 31-05-2025.
5. https://protectourpower.org/blog/electric-grid-resilience-ferc-definition (accessed on 31-05-2025).
6. Taft JD. Electric Grid Resilience and Reliability for Grid Architecture, PNNL, 2017.
7. Vision ENTSO-E. A Power System for a Carbon Neutral Europe, 2022.
8. https://smart-networks-energy-transition.ec.europa.eu/system/files/2022-06/MJ0722296ENN.en__0.pdf (accessed 31-05-2025).
9. Denkmann L, Cowan A. Federal investigators charge two Puyallup men for Christmas substation attacks. https://www.kuow.org/stories/federal-investigators-charge-two-puyallup-men-for-christmas-substation-attacks (accessed 31-05-2025).
10. https://www.bbc.com/news/articles/c4gel3g84q0o (accessed on 31-05-2025).
11. Stanković AM et al. Sept., Methods for Analysis and Quantification of Power System Resilience, in IEEE Transactions on Power Systems. 2023;38(5):4774–4787.
12. https://www.eurelectric.org/in-detail/energy-resilience/ (accessed on 31-05-2025).
13. Shehod A. Ukraine power grid cyberattack and US susceptibility: Cybersecurity implications of smart grid advancements in the US, Massachusetts Inst. Technol., Cambridge, MA, USA, Tech. Rep. 22, 2016.
14. Liu Z, Wang L. A Distributionally Robust Defender-Attacker-Defender Model for Resilience Enhancement of Power Systems Against Malicious Cyberattacks, in IEEE Transactions on Power Systems. 2023;38(6):4986–4997.
15. Liao C et al. Sept., A Resilience Evaluation Method Considering Power Source Ability and Network Topology of Power Systems, in IEEE Systems Journal. 2023;17(3):3527–3538.
16. Wang J, Pinson P, Chatzivasileiadis S, Panteli M, Strbac G, Terzija V. On machine Learning-Based techniques for future sustainable and resilient energy systems. IEEE Trans Sustain Energy. 2023;14(2):1230–43.
17. Barrett EL, et al. A Risk-Based framework for power system modeling to improve resilience to extreme events. IEEE Open Access J Power Energy. 2023;10:25–35.

18. Xiang Y, Wang T, Wang Z. Framework for preventive control of power systems to defend against extreme events. CSEE J Power Energy Syst. 2024;10(2):856–70.
19. Giachetti RE, Van Bossuyt DL. Military energy resilience models and climate: do our models adequately consider climate risks?? In. IEEE Open J Syst Eng. 2023;1:153–63.
20. Shi W, Liang H, Bittner M. Decision Support for Smart Distribution System Against Natural Disasters During Health Pandemics Considering Resilience, in IEEE Access. 2024;12:66335–66351.
21. Veit DJ, Mazzuchi TA, Sarkani S. Measuring and Architecting System Resilience Through Trade Study Analysis, in IEEE Systems Journal. 2023;17(1):1181–1192.
22. Natural Environmental Research Council. https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-5.pdf (accessed 30-05-2025).
23. ENTSO-E. Position paper on the European commission's proposal for a. Cyber Resilience Act; 2023.
24. Wang Y, Yang Y, Xu Q. Integrated model for resilience evaluation of Power-Gas systems under windstorms. CSEE J Power Energy Syst. 2024;10(4):1427–40.
25. Zhu Y, Xiao Y, Wang X, Chen C, Lu Z, Wang X. Enhancing distribution system resilience with Peer-to-Peer transactions. IEEE Trans Power Syst. 2025;40(1):907–19.
26. Shadaei M, Khazaei J. Dynamic Resilience Evaluation of DC MGs: Integrating Real-Time Metrics With Lyapunov-Based Stability Assessment, in IEEE Transactions on Transportation Electrification. 2025;11(1):4619–4633.
27. Oh B-C, Son Y-G, Zhao D, Singh C, Kim S-Y. A Bi-Level approach for networked microgrid planning considering multiple contingencies and resilience. IEEE Trans Power Syst. 2024;39(4):5620–30.
28. Li T, Han X, Sun H, Wu W, Zhang D. A Multi-Agent distributed operation solution to electricity and natural gas distribution systems for enhancing resilience. IEEE Trans Smart Grid. 2024;15(2):1525–43.
29. https://resilience.eurelectric.org/ (accessed 31-05-2025).
30. Position Paper EDSO. Climate Resilience Metrics for Electricity Grids, 2024.
31. Anderson K, Hotchkiss E, Murphy C. Valuing resilience in electricity systems, NREL, 2019 https://research-hub.nrel.gov/en/publications/valuing-resilience-in-electricity-systems (accessed 31-05-2025).
32. Sabouhi H, Doroudi A, Fotuhi-Firuzabad M, Bashiri M. Electrical power system resilience assessment: A comprehensive approach. IEEE Syst J. 2020;14(2):2643–52.
33. Wintzek P, Ali SA, Zdrallek M, Monscheidt J, Gemsjäger B, Slupinski A. Development of Planning and Operation Guidelines for Strategic Grid Planning of Urban Low-Voltage Grids with a New Supply Task, Electricity 2021;2:614–652.
34. Siemens. White paper - New planning principles for urban power grids: Strategies for the future, 2022.
35. https://lequotidien.lu/a-la-une/beckerich-lance-la-premiere-communaute-energetique-communale-du-luxembourg/ (accessed 31-05-2025).
36. E.DSO Technology Guidelines Local Energy Optimisation in Electricity Grids, 2025.
37. Yuvaraj T, Devabalaji KR, Suresh TD, Prabaharan N, Ueda S, Senjyu T. Enhancing Indian practical distribution system resilience through microgrid formation and integration of distributed energy resources considering battery electric vehicle, in IEEE access. 2023;11:133521–39.
38. Panteli M, Trakas DN, Mancarella P, Hatziargyriou ND. Boosting the power grid resilience to extreme weather events using defensive islanding. IEEE Trans Smart Grid. 2016;7(6):2913–22.
39. Li Y, Wu S. Controlled Islanding for a Hybrid AC/DC Grid With VSC-HVDC Using Semi-Supervised Spectral Clustering, in IEEE Access. 2019;7:10478–10490.
40. Quirós-Tortós J, Sánchez-García R, Brodzki J, Bialek J, Terzija V. Constrained spectral clustering-based methodology for intentional controlled islanding of large-scale power systems. IET Gener Transm Distrib. 2015;9(1):31–42.
41. Ding L, Gonzalez-Longatt FM, Wall P, Terzija V. Two-step spectral clustering controlled islanding algorithm. IEEE Trans Power Syst. 2013;28(1):75–84.
42. Li J, Liu C-C. Power system reconfiguration based on multilevel graph partitioning, 2009 IEEE Bucharest PowerTech, Bucharest, Romania, 2009.
43. https://www.svk.se/press-och-nyheter/nyheter/allmanna-nyheter/2023/hojda-anslag-ger-battre-beredskap-for-hela-elsektorn/ (accessed 31-05-2025).
44. Zhongmei Pan N, Jenkins J, Wu. Black start from renewable energy resources: review and a case study of great Britain. Renew Sustain Energy Rev, 209, 2025.
45. Laboratory PNN. Electric Grid Blackstart: Trends, Challenges, and Opportunities, 2022.
46. https://www.fen.ethz.ch/activities/system-operation/sccer-furies-dynamics.html (accessed 31-05-2025).
47. RESIST-. Energy islanding as a service for resilient renewable based energy systems (https://research.chalmers.se/en/project/12307) (accessed 16-07-2025).
48. An Y, Liu D, Chen B, Wang J. Enhancing the distribution grid resilience using cyber-physical oriented islanding strategy. IET Gener Transm Distrib. 2020;14:2026–33. https://doi.org/10.1049/iet-gtd.2019.0184.
49. Illia M, Diahovchenko G, Kandaperumal AK, Srivastava. Enabling resiliency using microgrids with dynamic boundaries. Electr Power Syst Res, 221, 2023.
50. Akhtar Hussain V-H, Bui H-M, Kim. Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience. Appl Energy, 240, 2019.
51. Kandaperumal G, Srivastava AK. Resilience of the electric distribution systems: concepts, classification, assessment, challenges, and research needs. IET Smart Grid. 2020;3:133–43.