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Review

Power system resilience and strategies for a sustainable infrastructure: A review

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ABSTRACT

The increasing occurrence of severe vulnerabilities, such as natural catastrophes and man-made attacks, has resulted in a corresponding rise in power outages on a global scale. Given the growing recognition of such exceptional occurrences, there is a pressing need to examine the matters pertaining to resilience and the mitigation of risks. This study presents a comprehensive overview of the current state-of-the-art in power system resiliency, as well as an exploration of the measures required to ensure a sustainable environment.These instances of measures include resilience by enabling localized generation and distribution of electricity,diversification of energy resources, withstanding of severe weather conditions, cyberattacks and enabling communities to proactively address the consequences of power outages. There are multiple approaches to bolstering resiliency, which aim to facilitate recovery from unforeseen circumstances and promote stability in the face of uncertain events. These measures also serve to mitigate the impact of unexpected incidents such as power outages. Integrating unpredictable renewable energy sources like solar and wind power into energy networks is difficult, especially in terms of resilience. Renewable energy output fluctuates owing to weather and time of day, requiring sophisticated grid management, energy storage, and demand-response mechanisms to maintain system balance and resilience. This study elucidates the enhanced principles of power system dependability and resilience, in addition to several ways for establishing a sustainable power ecosystem. It examines the complex dynamics of risk assessment, including equipment failures, natural disasters, and human errors, to determine their likelihood and implications. Moreover, the study thoroughly examines the critical moments that occur after accidents, emphasizing the need of prompt reaction and recovery measures in reducing downtime and restoring regular operations to impacted power networks. This involves determining the fundamental reasons behind the incidents, such as whether they arise from equipment malfunctions, human mistakes, external influences like natural calamities, or cyber assaults. In addition, the report examines the efficacy of current response protocols and emergency procedures in reducing the impact of accidents and restoring regular operations to impacted electrical systems.

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1. Introduction

Power system resilience pertains to the capacity of an electrical power system to endure and recuperate from various disruptions and

Nomenclature

RESs	Renewable energy sources
DG	Distributed generation
DOE	Department of Energy
MAS	Multi Agent System
PEV	Plug in- Electric vehicle
PHEV	Plug in- Hybrid electric vehicle
PRA	Probabilistic Risk assessment
DoS	Denial of Service
SCADA	Supervisory Control and Data Acquisition
DERs	Distributed Energy Resources
HILP	High Impact Low Probability
AHP	Analytic Hierarchy Process
EMS	Energy Management System
POSOCO	Power System Operation Cooperation Limited

disturbances, encompassing but not limited to natural calamities, equipment malfunctions, cyber intrusions, or unanticipated incidents [1]. Throughout these adversities, the power system must consistently deliver a reliable and uninterrupted electricity supply to its consumers [2]. Incorporating resilience into power system planning and operation is paramount [3], as it serves to guarantee the continuous provision of electricity [4] even under unfavourable circumstances.

Throughout history, there has been a significant transformation in the trajectory of events during periods characterised by catastrophic natural disasters [5]. Examples include volcanic eruptions devastating ancient civilizations like Pompeii and tropical storms causing significant damage to coastal regions. Uncertain and severe occurrences such as hurricanes [6], tornadoes, subsequent flooding, tsunamis, earthquakes [7], wildfires, and ice storms have a disruptive impact on the resilient infrastructure of the electrical system [8]. Researchers have been motivated to investigate resilient and sustainable power systems due to the presence of incidents, such as extreme geomagnetic disturbances (GMDs) [9], physical attacks, cyber-attacks, coordinated cyber [10] or regulated attacks, electromagnetic-based pulse (EMP), higher-altitude EMP (HEMP), and intentional electromagnetic-based interference (IEMI) attacks [11]. The digitization of society, along with changing consumer expectations, fuel limitations for power generation, and the influence of weather on energy production, have all generated a pressing need for improved resiliency [12].

As technology has improved, people have become more dependent on it, often without giving enough thought to the bad things that could happen. Consequently, the frequency of natural disasters such as earthquakes, severe floods, powerful cyclones, and tropical storms has surpassed anticipated levels. All of these factors have a significant detrimental impact on the electrical system, ranging from increased occurrences of blackouts to the destruction of critical infrastructure such as transmission [8] lines, power plants, and substations. Events of this nature have the potential to instil fear in individuals, paralyse populations, and devastate various systems such as electricity generation, transmission, and distribution, as well as interconnected systems like natural gas pipelines, fuel transportation, and telecommunications. In order to mitigate these unfavourable circumstances, it is imperative to modify the operational and regulatory course of action. Enhancing the resilience of the electricity system [13] can be achieved by proactive measures undertaken prior to, during, and after to the occurrence of a disaster.

In the context of a power system, the concept of resiliency encompasses the ability to enhance the system's robustness in the face of adverse circumstances and to promptly recover from significant, infrequent incidents. Power system outages [14,15] have diverse financial consequences on the community, affecting not just residential areas but also small enterprises, including huge organizations. The increasing prevalence of digital technologies in society, such as the widespread use of smart grids, electric vehicles, and renewable energy sources, has emphasized the pressing need to strengthen the resilience of electricity systems. Resiliency can be seen as the inherent ability of a power system to effectively respond and adapt to dynamic situations encountered throughout the transmission of electricity, while ensuring the provision of safe, reliable, and affordable energy, as well as demonstrating environmental responsibility.This study presents an analysis of novel technologies, techniques, and tools that can effectively tackle the issue of resilience in the pursuit of restoring sustainability. The enhancement of resiliency in power systems is predicated upon three key elements: damage avoidance, system recovery, and survivability.

This paper is structured as follows: Section 2 represents the key aspects of power system resilience.Section 3 reviews the strategy for power system resilience.Section4 provides detailed explanation for sustainability of power system,while Section 5 discusses the conclusion and future work.

2. Key aspects of power system resilience

Power system resilience [Fig. 1] encompasses a comprehensive integration of technological, operational, and organizational strategies aimed at fortifying the electrical grid's ability to endure, adjust to, and recuperate from diverse disturbances or disruptions. Power system resilience, as shown in Fig. 1, involves the comprehensive incorporation of technological, operational, and organizational methods that are carefully crafted to enhance the electrical grid's ability to endure, adjust to, and recover from various disturbances or disruptions. This comprehensive approach recognizes the complex and diverse nature of the difficulties faced by modern power systems, which include extreme weather occurrences, equipment failures, cyber-attacks, and cascading outages. Technological techniques involve implementing advancements in grid infrastructure, such as smart grid technologies, enhanced monitoring and control systems, and grid-scale energy storage. These advancements are intended to improve the flexibility, reliability, and response capabilities of the system. Operational strategies aim to maximize the efficiency of grid operations and maintenance practices by utilizing real-time monitoring and situational awareness systems. These strategies also involve building strong emergency response methods to reduce downtime and service interruptions. Organizational tactics involve promoting collaboration and coordination among many stakeholders, such as utilities, regulators, government agencies, and the

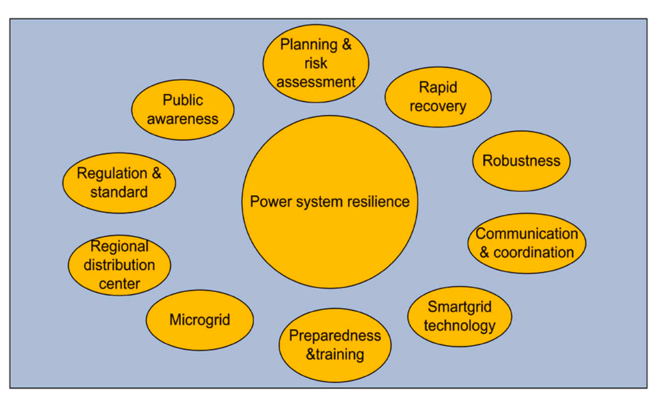

Fig. 1. Key aspects of power system resilience.

public. This is done to improve the sharing of information, allocation of resources, and decision-making processes in times of crisis. By incorporating these three fundamental aspects of resilience, the power system can enhance its ability to tolerate disruptions, adjust to evolving circumstances, and promptly recover from unfavorable incidents, thereby guaranteeing the uninterrupted provision of dependable and protected electricity to consumers.

2.1. Impact of disasters on Power system

The main area of study has primarily been centered on improving the reliability of the power system, with subsequent efforts aimed at strengthening the quality and resilience of the network [17]. Disasters [Fig. 2] have a diverse range of manifestations and are classified into distinct categories according to their characteristics, origins, and consequences. These categorizations aid emergency responders, policymakers, and researchers in gaining a more comprehensive understanding of and effectively addressing the distinct problems presented by various categories of catastrophes. The following are several prevalent classifications of disasters.

This phenomenon can be attributed to the occurrence of a majority of blackouts and power failures during natural catastrophes.

The above mentioned are the impacts [Table 1 & Table 2] on the power system by natural disasters but the grid [18] is quite resilient if the occurrence of the incidence is known beforehand.

2.2. Vulnerability in power system

The primary objective of power generating is to uphold equilibrium between the demand and supply of electricity. However, disruptions can occur during the processes of generation, transmission, and distribution, posing challenges in maintaining equilibrium. The power system [19] is comprised of a physical grid, as well as software-based components such as networking, communication, sensors, and databases. Vulnerability [Table 3] Incidence of severe Blackouts throughout the world can be categorized into three distinct classifications: physical vulnerability, cyber vulnerability, and cyber-physical vulnerability [20,21].The latter encompasses vulnerabilities [Fig. 3] within cyber-physical systems, such as control systems [22] and estimating systems.

Physical vulnerability [23] can be defined as the inherent proneness of a system, structure, or asset to experience damage, disruption, or harm when subjected to external threats, dangers, or stressors. The aforementioned concept has frequent application across diverse disciplines such as engineering, disaster management [24], and security [25]. The conduction of a physical vulnerability assessment method and indices [26,27] is necessary in order to comprehend and address the risks linked to natural disasters, technology accidents, and other unfavorable occurrences.

The term "cyber vulnerability" pertains to deficiencies or imperfections in a computer system, network, software, or hardware that can be manipulated by malicious individuals to get unauthorized entry, pilfer information, disrupt activities, or otherwise jeopardize the security [35] and reliability of digital resources. Cyber vulnerabilities may arise due

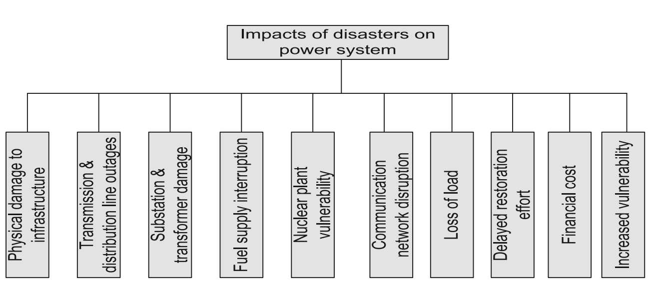

Fig. 2. Impacts of disasters on the power system.

Table 1
Cause of blackouts.

Cause of blackout	Percentage
Equipment Failure (Internal Cause)	47.86 %
Natural Disasters	30.71 %
Malfunctions	10.10 %
Vandalism	5.71 %
Supply shortage	4.29 %
Cyber attack	1.43 %

Table 2
Incidence of severe Blackouts throughout the world.

Incidence of severe Blackouts throughout the world			
Country	year	No of affected	duration
Newzealand	1998	70,000	4 weeks
Brazil	1999	97,000,000	5 hour
India	2001	226,000,000	12 hour
USA & Canada	2003	50,000,000	4 days
Italy	2003	56,000,000	18 hour
Spain	2004	2000,000	10days(5 black outs)
Indonesia	2005	100,000,000	7 hour
SouthWest Europe	2006	15,000,000	2 hour
Brazil+Paraguay	2009	87,000,000	7 hour
Brazil	2011	53,000,000	16 hour
India	2012	600 Million	1 day
Bangladesh	2014	150 Million	10 hour
Pakistan	2015	140 million	1 week
Turkey	2015	70 million	10 days
Puerto Rico	2017	1.5 million	7 month
Venezuela	2019	30 million	10 days
Argentina	2019	48 million	10 hour
JAVA(Indonesia)	2019	120 million	2 days
Srilanka	2020	21 million	1 day
Pakistan	2021	200 million	1 day
Bangladesh	2022	140 million	1 day
Pakistan	2023	230 million	1 day

Table 3
Estimation methods for physical vulnerability.

Method	Reference
Fragility Curve Estimation for infrastructure	[15,27,84,87,95,100,104]
Fragility of overhead lines as a function of wind speed	[43,85,86,135,137,142]
Curve – fitting technique which helps in structural damages	[45,86]
Underground lines' fragility curve	[84,87,91]

to a range of circumstances, encompassing software defects, misconfigurations, insufficient security measures, and design faults. The identification and mitigation of these vulnerabilities are of utmost importance in ensuring the integrity of cyber security [25] measures. Cyber vulnerability [36] can be categorized into four distinct types: reconnaissance, denial of service (DOS), command injection, and measurement injection. Each of these factors has the potential to inflict significant harm on the system. The various categories of cyber vulnerabilities are depicted in Fig. 3 and Fig. 4. In order to mitigate cyber vulnerabilities, it is imperative to assess and design control topologies for systems such as supervisory control [37] and data acquisition (SCADA) and distributed energy resource (DER) [38] based on the resilience of the system.

Cyber-physical vulnerability pertains to flaws or vulnerabilities in systems that combine digital (cyber) and physical elements, resulting in distinct issues in the areas of cyber security and safeguarding critical infrastructure. The risks emerge from the interconnectivity of cyber systems, encompassing software, networks, and data, with tangible elements such as sensors, actuators, and industrial machinery. Cyber-physical systems, which are commonly found in important sectors like

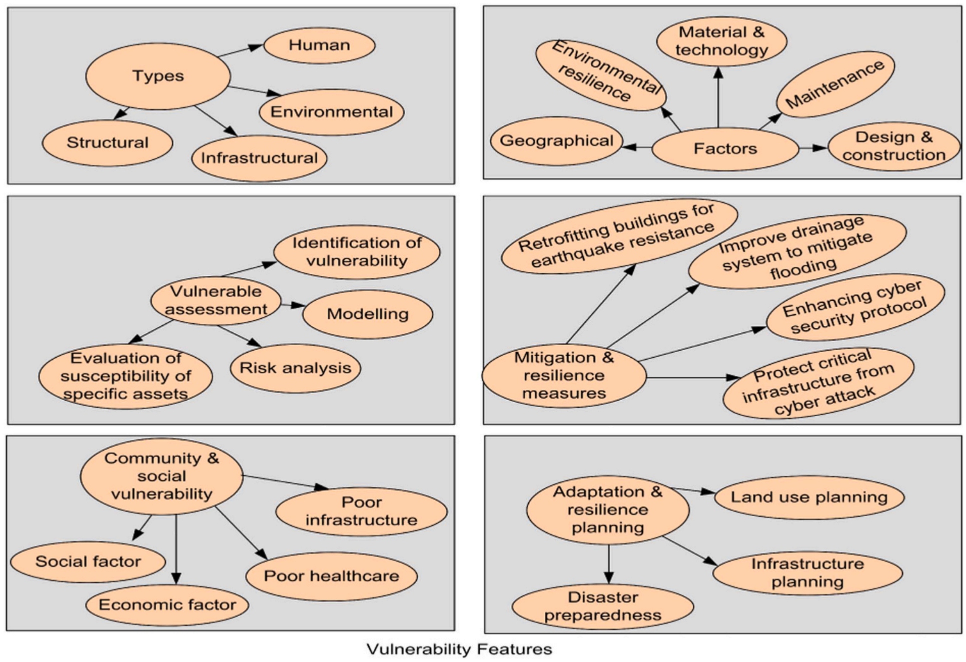

Fig. 3. Vulnerability and its associated features.

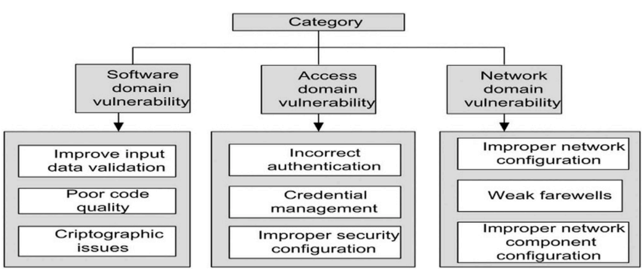

Fig. 4. Cyber vulnerabilities.

energy, transportation, and manufacturing, can be vulnerable to cyber assaults that take advantage of their integration to produce physical effects, such as equipment failures, interruptions in processes, or safety risks. To tackle cyber-physical vulnerabilities, it is necessary to adopt comprehensive approaches that take into account both cyber and physical elements. This includes implementing strong cyber security measures, ensuring secure software and network structures, developing resilience strategies, and adopting proactive risk management practices. By addressing cyber-physical vulnerabilities, businesses may protect critical infrastructure assets, assure uninterrupted operations, and uphold the safety and security of vital societal functions.

vulnerability assessment methods and indices -The vulnerability matrix, alternatively referred to as a risk assessment matrix, serves as a systematic and structured instrument for evaluating and prioritizing vulnerabilities or hazards. The utilization of this approach is prevalent in the fields of risk management, disaster preparedness, and security planning [28]. The matrix facilitates the classification of vulnerabilities [29] for organizations or individuals, taking into account their potential impact and likelihood. This enables more informed decision-making in terms of risk mitigation and resource allocation. Typically, there are two main dimensions in a vulnerability [30] matrix. The first one is Impact (severity), which evaluates the potential repercussions or severity of vulnerability should it be exploited or should a negative occurrence take place. Impact is sometimes divided into many categories, including low, moderate, high, and crucial. Another one is likelihood (probability), which assesses the possibility or probability of an unfavorable event transpiring or a vulnerability [31] being exploited. Additionally, there are different levels of likelihood, such as low, moderate, high, and certain.

The relative changes in performance measures before and after the occurrence of C_{N-k}can be used to calculate a vulnerability index [32]. The network vulnerability $\nu(C_{N-k})$ connected to a chosen contingency C_{N-k} is provided by

$$\nu(C_{N-k}) = \frac{|M - M(C_{N-k})|}{M}$$

where M is the value of the measure for the undamaged network and $M(C_{N-k})$ is a vulnerability [33] metric following contingency C_{N-k}.

The system performance index is a metric that can be utilized to assess the comparative magnitude of a contingency. The predominant method for evaluating system performance indices involves quantifying the extent to which system variables, including as line flows, bus voltages, and bus power injections, deviate from their rated values. The indices used to quantify issues pertaining to loading and voltage limit violations.

The active power performance index is denoted by (PI_ρ) and its purpose is to quantify the extent of line overloads(34) and is assigned.

$$PI_\rho = \sum_{i=1}^{N_1} \left(\frac{W}{2n}\right)\left(\frac{P_1}{P_1^{\max}}\right)^{2n}$$

Where P_1 is the power flow in line l

$P_1^{\max}$ Indicates the MW capacity limit of line l.

N_1 is the number of overloaded line in the system.

W is the real power weighting factor

Reactive power performance index

$$PI_V = \sum_{i=1}^{N_B} \left(\frac{W}{2n}\right)\left(\frac{|V_i| - |V_i^{SP}|}{P_1^{\max}}\right)^{2n}$$

Where V_i indicates the voltage magnitude corresponding to Bus i

V_i^{SP} Indicates specified voltage corresponding to bus i.

n Indicates the positive number and its value is 1.

2.3. System risk assessment and resilience

Prior to delving into the concept of resilience, it is imperative to develop an understanding of risk [39] and risk assessment, as they serve as the foundation for any proactive measures made to mitigate unfavorable occurrences. Risk refers to the probability or likelihood of an event occurring. Risk assessment and resilience applications are essential for assuring the strength and dependability of power systems. Through a methodical assessment of potential dangers and their corresponding levels of risk, operators of power systems can discover weaknesses and take proactive steps to minimize them. This entails the examination of multiple issues, including equipment malfunctions, natural calamities, cyber vulnerabilities, and operational mistakes. Resilience applications primarily aim to improve the power systems' capacity to endure and promptly recover from disruptive events. This encompasses the execution of redundancy measures, the establishment of contingency plans, and the integration of advanced monitoring and control systems. By combining risk assessment and resilience measures, power systems can adjust to fluctuating circumstances, reduce periods of inactivity, and uphold dependable service provision, even when confronted with unexpected obstacles.

The risk assessment component, as outlined in the pressure and release model, is depicted in Fig. 5. The aforementioned graphic provides a clear depiction of the correlation between the aftermath or consequences of a disaster or attack and the likelihood and severity of the occurrence. The system's vulnerability to attack or lack of protection, as well as its ability to comprehend and respond to the consequences, demonstrates the level of resilience exhibited by the system. The concept of resilience in a physical entity refers to its capacity to anticipate, withstand, comprehend, react to, adjust to, and recover from a disruption or disturbance. Fig. 5 provides a comprehensive depiction of the risk and its different attributes in related to power system resilience.

A resilient micro grid [Fig. 6] has the capacity to conduct a complete risk assessment encompassing a range of hazards, failures, and incidents. This document delineates the fundamental security and safety criteria associated with these particular demand scenarios. In addition, it continuously produces real-time mappings of the Internet Public Library (IPL) on various web platforms that are specifically focused on character healing. Risk assessment plays a pivotal function in augmenting profitability and return on investment (ROI) inside Micro grid networks. Furthermore, it functions to alleviate any hazards linked to the provision of energy, so guaranteeing minimal interruptions.

Hazard as well as risk analysis [39] based techniques in the MGs are quite challenging-The hazardous level is calculated from the said formula

$$(H_L) = S_i \times C_i = (P_i + F_i + A_i) \times C_i$$

S_i Stands for consequence of severity of this Hazard. Here C_i has been the class hazardous event, P_i refers probability, F_i refers frequency and A_i indicates the capability for avoiding failure. The complex nature and dynamic operating environment of Microgrids (MGs) present significant problems for hazard and risk analysis approaches. The calculation of the hazardous level entails a complex procedure that necessitates meticulous evaluation of multiple aspects, such as the dependability of components, possible failure modes, ambient conditions, and operational parameters. Furthermore, the interdependent structure of MGs presents intricacies, as malfunctions or interruptions in one component of the system might spread to other regions, intensifying the total level of risk. In addition, the incorporation of renewable energy sources and smart grid technologies adds complexity to the study of hazards and risks. These components generate new uncertainties and dependencies inside the system. Despite the difficulties faced, it is crucial to have precise evaluation of dangers and uncertainties in order to guarantee the durability and dependability of MGs. This allows operators to put into action efficient steps to reduce the impact of any interruptions and protect important infrastructure. Therefore, although the task of analyzing hazards and risks in MGs may be difficult, it is crucial for improving the system's ability to recover and safeguarding against unexpected incidents.

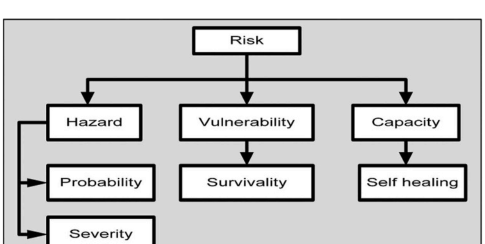

Fig. 5. Risk and its different components.

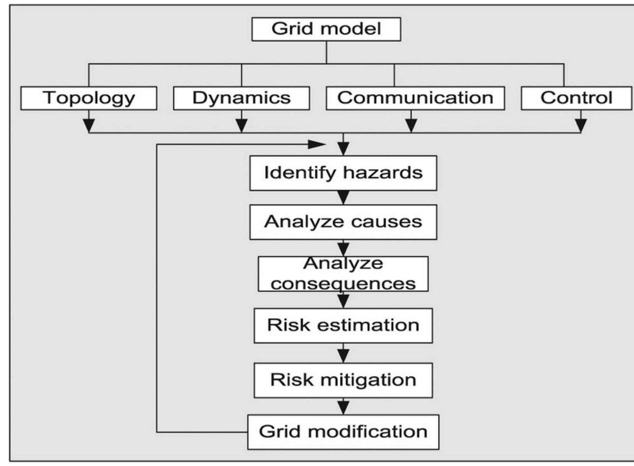

Fig. 6. Flow chart of a Resilient Micro grid model.

2.4. Reliability of a power system

Power system dependability and power system resilience are interconnected; however they possess distinct conceptual differences, as illustrated in Table 4. Upon examining the underlying principles, it becomes evident that resilience is associated with low-probability, high-impact events, whereas reliability typically aligns with high-probability, low-impact events. According to the North American Electric dependability Corporation (NERC), dependability can be defined as the ability to meet the power demands of household customers even in the event of unexpected equipment failures or other factors that may reduce the availability of electricity [46].

Fig. 7 illustrates the aforementioned system approach in a graphical format, depicting the progression from a system under assault. It also includes a comparative analysis of traditional operating modes, current operating mode, and the desired optimal [42] operating mode. The current operating mode clearly exhibits superior performance compared to the traditional system, particularly in terms of its ability to self-heal

Table 4
Reliability vs Resilience.

Reliability	Resilience
Deals with high probability and low impact events.	Deals with low probability and high impact events.
Standard measures are present.	Standard measures are still being formulated.
Depends on resource adequacy and security.	Depends on survivability and self-healing.
Metrics are not cause-specific.	Metrics are cause-specific.

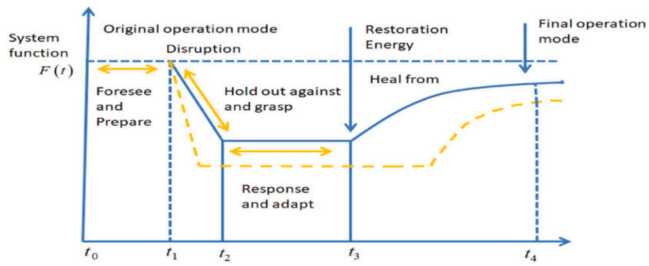

Fig. 7. Graphical representation of line of action of a system during disaster.

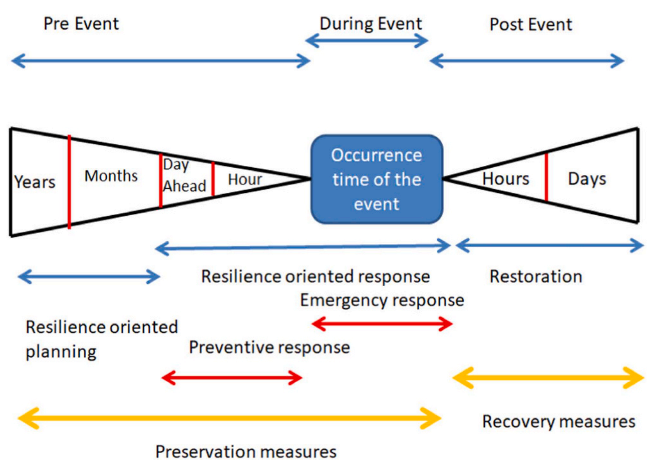

Fig. 8. Measures of resilience in factors of instance of occurrence.

[43] and restore the original state following a disaster. The targeted system exhibits a time-dependent curve that represents the ideal behavior of a system function, wherein no alterations are observed during and subsequent to an undesired attack on power system equipment. Furthermore, the occurrence of a blackout [44] is completely eliminated. The pursuit of an optimal system [45] is commendable; yet, it is crucial to minimize the time intervals between successive attack stages in order to mitigate their impact.

2.5. Regulation and standard of resiliency

In the realm of power systems, specifically within the domain of electrical grids, the preservation of an uninterrupted and dependable provision of electricity is of paramount importance. This objective remains crucial, even when confronted with potential disturbances and calamities. In order to enhance the resilience of electricity systems, a range of laws and standards have been devised and put into effect. Regulations and standards pertaining to this matter may vary among countries.

The International Electro technical Commission (IEC) is responsible for the publication of international standards pertaining to the dependability and resilience of power systems. The scope of these standards encompasses a diverse array of subjects, encompassing grid control [47], protection, and communication protocols that collectively enhance the resilience of the grid. This can be effectively utilized to enhance the resilience of power utilities and grid operators. The primary objective of the National Electric Reliability Council (NERC) is to establish and enforce standards for Critical Infrastructure Protection (CIP) [48] with a specific emphasis on safeguarding the cyber security of power systems. In order to safeguard critical infrastructure from cyber threats and bolster the resilience of the grid against cyber-attacks, particular cyber security rules and standards are enforced. The primary focus of the IEC 61850 standard pertains to the communication networks and systems utilized in power utility [49] automation. The enhancement(38) of communication infrastructure inside power systems facilitates the optimization of grid operation, leading to increased efficiency and reliability. The oversight of the reliability of the bulk power system in the United States is entrusted to the Federal Energy Regulatory Commission (FERC). The Federal Energy Regulatory Commission (FERC) has implemented a set of regulations and standards [50] aimed at safeguarding the resilience and dependability of the electric grid. These measures encompass several aspects such as grid planning [51], operation, and cyber security, thereby ensuring the robustness of the system. Grid operators and utilities frequently have the responsibility of creating and managing emergency preparedness and response plans. The aforementioned plans delineate the strategies for responding to diverse grid disturbances and calamities with the aim of minimizing operational downtime and expediting power restoration. The establishment of a standardized framework for the interconnection of distributed energy resources [52] (DERs), such as solar panels and wind turbines, with the power grid is essential to ensure the secure and robust integration of these resources into the existing power system. The establishment of standards pertaining to the design, operation, and connectivity of micro grids [40] serves to guarantee the robustness [53] of smaller, localized power systems that possess the capability to function autonomously or in conjunction with the main power grid [54].

2.6. Metrics and Resilience Evaluation Method

Discussing the establishment of standard measures for resilience is not deemed relevant, as currently no such metrics have been developed or introduced [55,56]. However, periodic progress can be observed in the measurements put forth by many authors. The measurements can be classified into two distinct groups, namely metrics based on qualities and metrics [57] based on system performance. Metrics derived from attributes provide insights into the elements that contribute to the varying levels of resilience in a power system, such as robustness [58], adaptability, resourcefulness, and self-healing [59] capabilities. On the other hand, metrics derived from system performance offer an assessment of the actual resilience exhibited by the system.

The following [Table 5] shows several system parameters for resilience metrics that have been suggested by different resilience based literatures.

Resilience measures [60] are typically classified into various qualities and performance-based matrices. Attributes-based metrics provide insights that can impact the resilience of a system when compared to its current state. The measurement of system properties such as robustness,

Table 5
System Parameters proposed by several literatures.

System Parameters	References
*resourcefulness	[58,62]
*rapid recovery	[62]
*robustness	[151]
*adaptability	[2,63,77]
*load shedding investment costs	[29,39,67,73,104]
*saving costs of restoration	[125]
*algebraic connectivity	[85,92]
*between ness centrality	
adaptability percentage	[40]
*flexibility	[63,71]
*outage cost recovery	[12]
outage recovery capacity	
*Resistance	[64]
*Recovery	[18]
*Resilience	[60]
*speed in which the system responds	
*how efficient the recovery is	[19,33,133,142, 155]
*how economic the recovery is	
*Resilience metric related to availability of system equipment	[18,20]

adaptability, resourcefulness, and recoverability is facilitated by attribute-based metrics. Furthermore, performance-based metrics are utilized to assess the resilience of the system [61]. Additional performance-based measures have been provided to analyze quantitative data associated with infrastructure outputs, identify disruptions, and establish metrics for measuring infrastructure resilience.

The development of resilience measures can be facilitated by examining the various traits and attributes of power system resilience, including resourcefulness, robustness [62], rapid recovery, and adaptability. The literature has identified five resilience metrics with distinct attributes. These metrics include: (i) the investment cost for load shedding, which measures resourcefulness; (ii) the cost associated with restoration savings, which pertains to rapid recovery; (iii) algebraic connectivity, which relates to robustness; (iv) betweenness centrality, also associated with robustness; and (v) adaptability percentage, which captures adaptability. Various weights are allocated to each parameter in order to calibrate all the resilience measurements. In a further study, the authors propose three measures that encompass several aspects of resilience. These metrics [63] include: (i) flexibility metrics, which measure the proportion of load successfully served during each recovery iteration relative to the overall system demand; (ii) outage cost recovery metrics and (iii) outage recovery capacity metrics. In their study, the authors have selected three metrics, namely Resistance, Recovery, and the Resilience metrics, to effectively assess the level of resilience [64].

The resistance meter is a measure that quantifies the relationship between the overall power demand with system loads and the summation of active powers delivered to non-interrupted customers, taking into account the load priority factor. The recovery meter is a measure that quantifies the relationship between the anticipated energy provided and the cumulative energy requirement for the disrupted load during a given timeframe. The resilience indicator represents the proportion of anticipated energy delivered during the duration of the research period, encompassing both loads restored due to the establishment of micro grids and loads associated with non-faulted feeders, relative to the overall energy demand. In order to evaluate the resilience of a system following catastrophic events, resilience metric has been presented in reference. This metric takes into consideration the speed of the system's response, the efficiency of the recovery process, and the economic [65] aspects of the recovery. The authors in references and have proposed a resilience metric that quantifies the ratio between the recovered loads and the actual loads on both the AC and DC sides of micro grids [66]. This statistic guarantees the ability of the most essential loads to remain operational, as stated in references and additionally, the measurement is conducted using a numerical scale ranging from zero to one, with zero indicating the lowest level of resilience and one indicating the maximum level. The authors in reference have presented a resilience metric that is grounded in the social welfare of both the power grid and water systems. This resilience metric is formulated as the aggregate of three key components: the robustness of the system, the recoverability of the system within a predetermined timeframe, and the speed at which the system can recover. The authors of reference have proposed a conceptual resilience curve for the purpose of defining and quantifying resilience in power systems. The figure presented in Fig. 7 demonstrates the relationship between the level of resilience [67]and the occurrence of a disaster event, highlighting its time-dependent nature. A set of metrics has been proposed in previous studies that are derived from the resilience curve. The metrics in question are commonly referred to as FLEP, which is an acronym representing the following aspects: the rate at which resilience decreases during phase 1 (progression of disturbance), the extent of degradation in the post-disturbance state during phase 2 (post-disturbance degradation), and the speed at which the network recovers during phase 3(restoration). Additionally, the resilience curve has been utilized in a previous study to construct a resilience metric [55] that takes into account the provision of crucial load during the restorative and post-restorative phases. The evaluation of this metric is carried out in the following manner.

$$R = \int_{t_r}^{t_r+T^0} F(t)dt$$

The symbol F(t) represents the system performance function. The symbol represents the initiation of the restoration phase, while represents the combined duration of the restoration and post-restoration periods. The performance of the system is characterized by the aggregate power delivered to the critical loads [68], contingent upon their respective priorities. Various metrics [56] have been suggested to quantify the resilience of a power system, wherein resilience is characterized as the ratio of the area under the actual performance curve to the area under the intended performance curve. The conventional approach has typically assumed a constant end performance curve, disregarding the potential variations in the actual performance curve over time due to system restoration attempts and severe disaster events. In this proposal, a resilience measure is introduced that is based on the maximum decline in system performance and the resulting losses. This metric is expressed through a specific formula or equation.

$$R = 100\left(1 - \frac{L_{Mm}}{L_{max}}\right)$$

$$R_e = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r}$$

The variable "L_{Mm}" represents the quantification of the highest level of decline in system performance, whereas "L_{max} " is the operator's incurred detriment resulting from the disconnection of all loads and distributed generators (DGs) [69,70]. A resilience metric can be derived based on the duration and profile of the event, incorporating the failure profile (F), recovery profile (R), incident time T_i, and failure duration T_f. A resilience metric based on the Cobb-Douglas production function can be formulated by incorporating variables such as anticipation, adaptation, perception, and response.

$$CR = A^{\rho} + AD^{\beta} + P^{\gamma} + RD^{\varphi}$$

where CR is the collective resilience and A, AD, P, and RD, represent, respectively, anticipate, adapt, perceive, and respond. The exponents (ρ, β, γ, and φ) represent the weights of relative importance of the ability where $\rho+\beta+\gamma+\phi = 1$.

C. Code based matrices- A proposed metric based on code is suggested to examine both the extent and duration of the power outage. The calculation of unscaled resilience is followed by a scaling procedure to transform metric values onto a nine-point scale.

$$m' = c(\alpha + \exp(f))(1 + f)$$

$$f = \frac{\text{load unaffected by PDS events(KW)}}{\text{Total load of PDS(KW)}}$$

In order for a system to exhibit resilience, it is imperative that it fulfills certain criteria, namely: applications in network flexibility, enterprise focus on utility [71] services, operational value proposition, active security strategy, preference for interdependent networks, and tight network coupling. In addition, as seen in [Fig. 9], it is important to conduct system identification and vulnerability analysis at each stage [32], followed by the implementation of resilience operations. These operations encompass the assessment of the power system's recovery capacity and absorbing capability.

The concept of Recovery Potential refers to the inherent capacity of a system to undergo healing and restoration following the onset of a

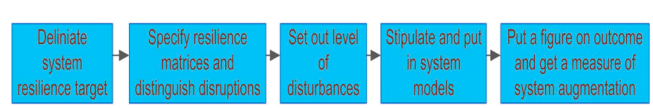

Fig. 9. Approach for system resilience.

natural disaster. The primary obstacle faced by a power system grid is the restoration [72] of its initial state following the repercussions of a catastrophic event. The topic of vulnerability [32,73] analysis is extensively examined in section I and section II. These sections encompass the essential measures implemented prior to, during, and following a disaster event, with the aim of enhancing the resilience [74] of the power system [Fig. 10].

2.7. Resilience Enhancement Method

For enhancement [75,76] [Fig. 12] of power system and to make it more resilient, comparative studies have been done and is shown in Table 6. While observing and going through the methods, they are again divided into four categories like

a]Problem category,
b]Hierarchy,
c]Model,
d]Stage as shown in [Fig. 11].

Within the problem category, one may identify many evaluation approaches for resilience [Fig. 12]. The process of planning [Fig. 11] is undertaken to facilitate improvement, and afterwards implemented as operational activities. The term "hierarchy" [76] pertains to the sequential arrangement of processes involved in the delivery of energy to end-customers, encompassing generation, transmission, and distribution [77,79,80]. The term "model" encompasses the intricate model, operational power flow [29] model, and multi-agent model that are afterwards employed to implement the proposed strategies aimed at enhancing system resilience. As previously mentioned in section I, the term "stage" pertains to the several phases of resilience that occur prior to, during, and subsequent to the onset of a disaster or disruption. A comprehensive examination of optimal topology [78,79] reconfiguration and islanding, as well as optimal energy [80,84] management system (EMS) and resource allocation, is presented.

In “model” stage some algorithms are adopted for easy restoration [81] after disturbances [Fig. 12]. The list of these algorithms for application in grid for enhancement [75] ([86](87)of system resilience is given in [Table 6].

3. Strategy for power system resilience

Creating a resilient power system strategy necessitates a thorough and all-encompassing approach, taking into account diverse facets of the electricity infrastructure. Conducting a comprehensive risk assessment is of utmost importance in order to identify potential risks and vulnerabilities. The aforementioned factors encompass a range of potential interruptions, such as natural disasters, cyber threats, equipment failures, and other similar occurrences. It is imperative to comprehend the potential ramifications of these threats on the electrical system. Further there is a pressing need to establish a more varied energy mix in order to mitigate reliance on a singular energy source. The use of renewable energy sources, such as solar and wind, serves to augment the overall adaptability and resilience of the power system. The implementation of micro grids is a viable approach to establish localized energy systems that possess the capability to function alone or interconnect with the primary grid. Micro grids bolster resilience by affording supplementary electrical power during periods of service disruption and by offering support to essential infrastructures. In order to effectively implement a comprehensive strategy, it is imperative to incorporate energy storage equipment, such as batteries, for the purpose of storing surplus energy during regular operations and subsequently releasing it during periods of heightened demand or in the event of generation disturbances.

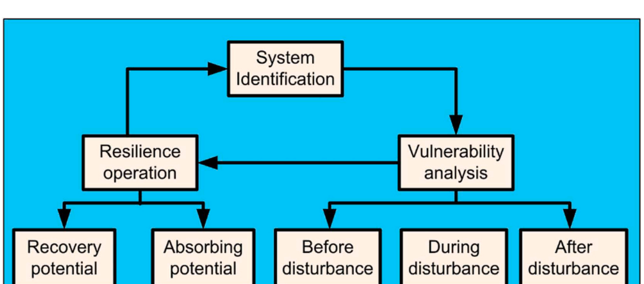

Fig. 10. Ideal resilience framework [104].

Table 6
List of Algorithms for resilience enhancement.

Reference	Proposed algorithm
[76]	Artificial intelligence
[77]	Nonlinear adaptive robust optimization
[73,104,125,132,153]	A Resilience – oriented methodology based on the restoration and load group
[82]	Novel genetic
[87]	Computational optimization
[90]	Deep reinforcement optimization
[78]	Numerical Simulations
[136]	Hierarchical control
[137]	Sequential proactive
[25,122,154]	A two layer decentralized control method
[52]	A modified Viterbi algorithm

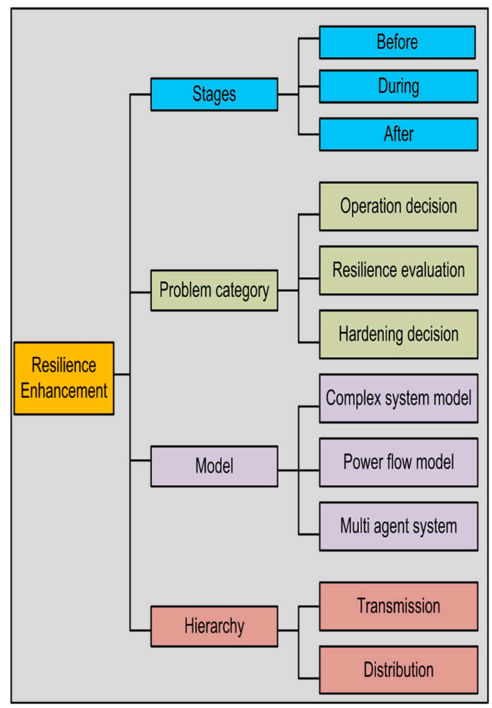

Fig. 11. Resilience enhancement stages.

The use of smart grid technology for the purposes of real-time monitoring, control, and automation is important. This facilitates expedited identification and prompt reaction to disturbances, hence enhancing the overall dependability and robustness [151] of the power system. Furthermore, energy storage systems play a crucial role in bolstering the stability of power grids and facilitating rapid responses to fluctuations in energy supply and demand. It is imperative to provide redundancy within the essential elements of the power system, including transmission lines and substations. Furthermore, it is advisable to allocate resources towards the enhancement of infrastructure hardening measures in order to enhance the resilience of critical components against adverse weather conditions, physical assaults, and other plausible hazards. It is imperative to deploy resilient cyber security protocols

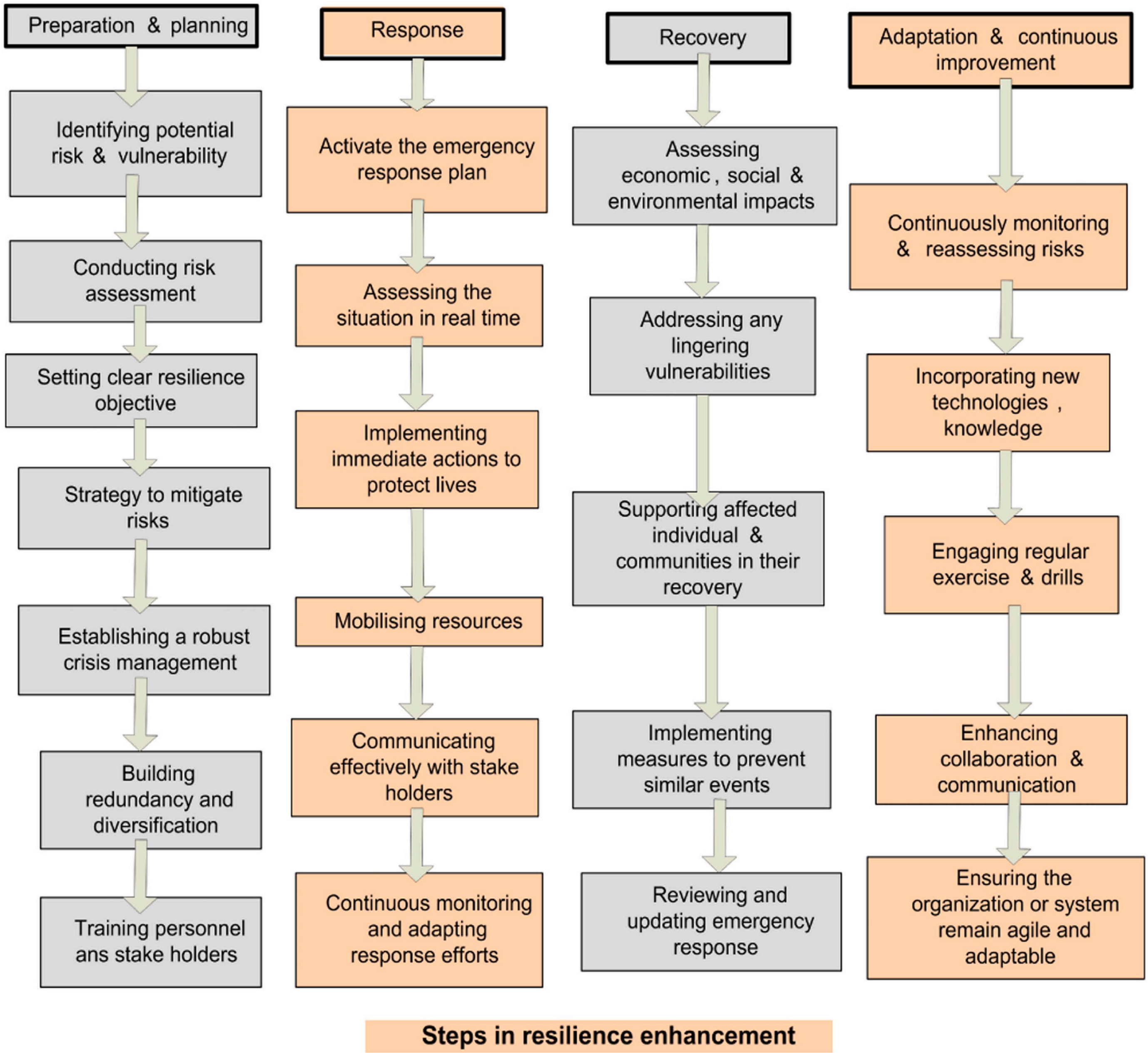

Fig. 12. Different steps in resilience enhancement.

in order to safeguard control systems, communication networks, and other essential infrastructure against potential cyber risks. This encompasses routine evaluations of cyber security measures, comprehensive employee education initiatives, and the adoption of cutting-edge security solutions. It is imperative to establish and consistently revise all-encompassing emergency preparedness and response strategies. This includes the provision of personnel training, the execution of drills, and the establishment of unambiguous communication and coordination protocols with pertinent parties. It is imperative to establish and consistently revise all-encompassing emergency preparedness and response strategies. This includes the provision of personnel training, the implementation of drills, and the establishment of unambiguous communication and coordination protocols with pertinent parties.

This analysis aims to identify several potential threats [82] and hazards that have the capacity to disrupt the electrical system [83]. These include but are not limited to natural disasters such as hurricanes [6] and earthquakes, cyber-attacks, equipment failures, and human errors. There is an urgent requirement to perform a thorough vulnerability assessment in order to gain insight into the specific areas. To guarantee adherence to pertinent legislation and standards concerning power system resilience. It is imperative to remain informed about the dynamic [5] nature of legislation and adapt strategy accordingly.

It is also recommended to allocate resources towards enhancing infrastructure in order to enhance [84] the resilience of the electricity system. The proposed measures encompass the modernization of outdated equipment, the reinforcement of substations and transmission lines, and the integration of grid automation technology. The examination pertains to the progression of micro grids [85] or distributed energy resources (DERs) [86] as potential solutions for furnishing supplementary power during instances of service interruptions. The implementation of smart grid [32] technology can be employed to augment grid visibility and control. This capability facilitates the continuous monitoring and prompt response to disruptions in the electrical system.

The integration of sophisticated sensors, advanced communication networks, and grid analytics plays a crucial role in enhancing the efficiency of grid operations and facilitating the timely detection of failures. The use of a diverse range of power generation sources is crucial in order to mitigate the dependence on a singular energy source [87]. The integration of renewable energy [88,89] sources and energy storage into the grid can be seen as a potential solution. One approach to enhancing grid reliability is incorporating redundancy through the establishment of alternate pathways for power transmission and distribution. The objective is to formulate and execute resilient cyber security strategies aimed at safeguarding the power system from potential cyber threats. The aforementioned measures encompass firewalls, intrusion detection [90] systems, and employee training pertaining to best practices in cyber security.

Organizations should establish and consistently revise comprehensive emergency response plans that encompass a range of situations, including but not limited to severe weather disasters and cyber breaches. To ensure a coordinated reaction, it is imperative to build a well-defined incident command structure and regularly engage in drills and exercises. It is imperative to keep strategic reserves of essential equipment and supplies, such as transformers [91–94] and replacement parts, in order to facilitate prompt restoration [95] in the case of equipment breakdowns. It is imperative to provide sufficient fuel reserves to support backup power generation. The objective is to disseminate knowledge to the general population regarding the appropriate measures to undertake in anticipation of and during power outages and emergency situations. This inquiry pertains to the provision of information regarding emergency contacts, safety protocols, and energy conservation practices during periods of power outages [96].

To promote collaboration, it is essential to establish effective partnerships with government agencies, emergency responders, and neighboring utilities, thereby facilitating a synchronized response to regional emergencies. Disseminate essential information and valuable resources to pertinent stakeholders. The implementation of monitoring systems is crucial for the real-time tracking of the health and performance of the power system. Regular evaluations and after-action reviews should be conducted to assess the efficacy of resilience methods and suggest potential areas for enhancement [97]. Advocate for the allocation of resources towards research and development endeavors aimed at promoting the progress of technologies and tactics that bolster the resilience of power systems. It is imperative to remain well-informed regarding the emergence of potential risks and the corresponding solutions. Formulate comprehensive strategies for building enduring resilience that take into account forthcoming obstacles, such as climate change, evolving energy demands [98], and technology progress. In order to foster resilience at the grassroots level, it is imperative to actively participate in and establish connections with local communities. It is imperative to foster the proactive engagement [49] of communities in the formulation of emergency preparedness strategies, including the establishment of community-based micro grids [99–101] or alternative power sources [102]. It is imperative to appropriately devote adequate financial resources towards resilience efforts, while also ensuring the availability of financing for essential improvements and maintenance.

Fig. 13 illustrates the several components of planning and design, response, and recovery or self-healing [40], all of which are founded on the concept of resilience. Preservation measures encompass the domains of planning, design, and response. Typically, the processes of planning and design are characterized by their time-intensive nature. This process may need a significant amount of time, potentially spanning several months or even years. However, the restoration [41] process, which falls under the category of recovery procedures, must be completed within a short timeframe of hours or days.

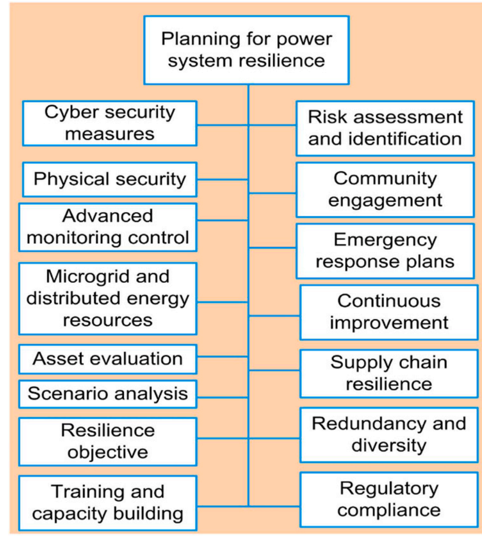

Fig. 13. Planning for power system resilience.

Table 7
Planning for power system resilience.

Planning for Power System Resilience		
Level	Approach	Reference
Distribution Level	Hardware based	[21–27,28]
	Software based	[24,30,34,36, 38,47,49,92]
	Combining both hardware and software	[24–27]
	Stochastic based	[31]
	Robust optimization based	[12,16]
Transmission Level	Reinforcement of the transmission system with strengthening the existing equipment	[27,35]
	Development of transmission facilities with addition of equipment and devices	[22,33,34]
	Combined approaches	[22,33–35]
	Stochastic based	[34]
	Robust optimization based	[12,16]

3.1. *Preparedness and training*

The establishment of power system resilience necessitates the inclusion of preparedness and training as essential elements. Sufficient preparation and continuous training are essential in enabling power system operators [103], maintenance staff, emergency responders, and other pertinent stakeholders to efficiently address and recuperate from disruptions and emergencies. The achievement of power system resilience necessitates the implementation of a proactive and all-encompassing strategy towards preparedness and training. Power utilities can improve their capacity to respond efficiently to disturbances and maintain the dependable provision of electricity to their consumers, even under unfavorable circumstances, by allocating resources to these domains and consistently evaluating and revising emergency plans and training initiatives [104] [Fig. 14].

4. Sustainability of the power system

The term "sustainability" is commonly employed and subject to several interpretations. In the majority of instances, there is a focus on the importance of protecting, enhancing, and balancing the triple-bottom-line (TBL) components of the Environment, Economy, and Society. The triple-bottom-line (TBL) idea encompasses a comprehensive approach to sustainability, integrating three interrelated

elements: the environment, economy, and society. Every element has a vital function in defining strategies for sustainable development and

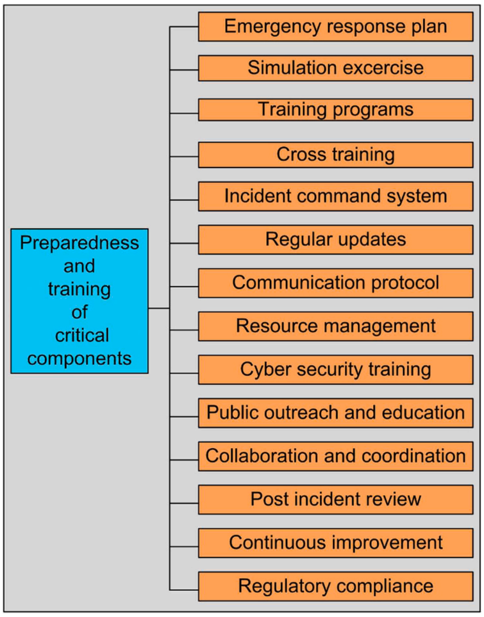

Fig. 14. Different components of preparedness and training.

promoting resilience in the face of global challenges. The environmental part of the Triple Bottom Line (TBL) focuses on the protection and restoration of natural ecosystems, the conservation of biodiversity, and the reduction of environmental degradation. This entails the reduction of resource depletion, the mitigation of pollution and greenhouse gas emissions, and the advocacy for sustainable land use practices. Additionally, the economic aspect emphasizes the significance of promoting economic expansion and affluence while guaranteeing fair allocation of resources and opportunities. Sustainable economic practices encompass the promotion of circular economies, investment in renewable energy and green technology, and the cultivation of innovation and entrepreneurship that are in line with environmental and social goals. Finally, the social aspect prioritizes the welfare, fairness, and empowerment of communities, encompassing the availability of education, healthcare, and social services, while also advocating for diversity, inclusivity, and social equality. Sustainable development strategies aim to tackle social disparities, empower vulnerable communities, and advocate for the preservation of cultural diversity and legacy. The TBL framework offers a holistic and balanced approach to decision-making by incorporating three dimensions of sustainability. It aims to optimize results for people, planet, and prosperity in the present and for future generations.

The field of sustainability research, as depicted in Fig. 15(a and b), is closely connected to the comprehensive examination of resilience and vulnerability [36] within a given context. Furthermore, the field of sustainability has experienced significant growth as a subject of research, particularly in its application towards the development of sustainable cities and vital infrastructure. The fundamental components of sustainable development are commonly referred to as the three P's: People, Planet, and Profit. These three aspects are represented by the drivers of social, environmental, and economic factors, as depicted in Fig. 15(a) and Fig. 15(b).

The socio-economic state of a certain location plays a crucial role in the development of a resilient infrastructure [Fig. 16]. Moreover, the significance of technology diminishes when it fails to capture the interest of investors or users. Due to this factor, pilot initiatives experience significant failure. Furthermore, these challenges might be attributed to a lack of economic and technological awareness among the players. Furthermore, socioeconomic interaction pertains to the behavioral patterns exhibited by individuals in both social and economic contexts. Vulnerable socio-economic conditions can arise from several factors such as poverty, handicap, age, gender, religion, and other related aspects. Socioeconomic resilience refers to the capacity of several

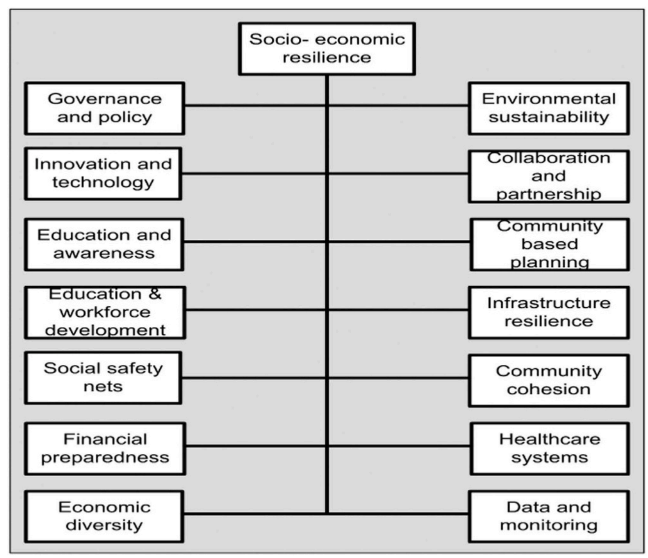

Fig. 16. Factors related to socio economic resilience.

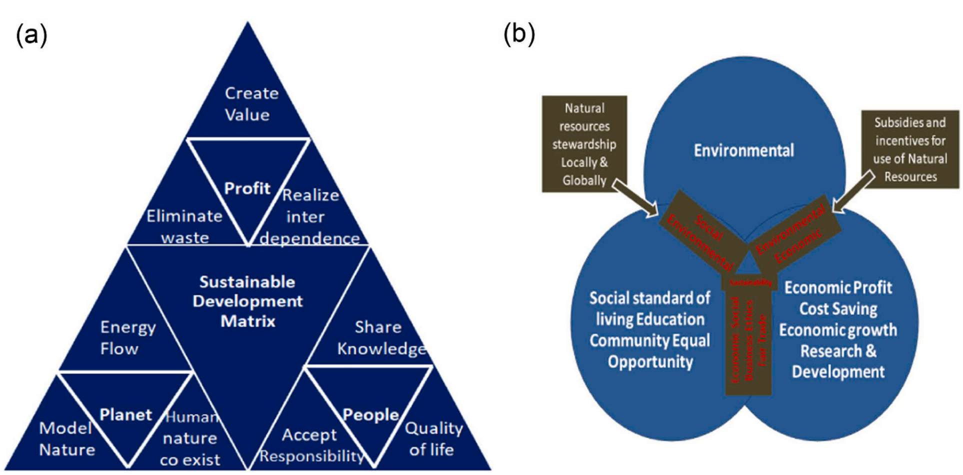

Fig. 15. (a). Sustainable development matrix triangle Fig. 15(b). Three spheres of sustainability [Adopted from 2002 University of Michigan Sustainability Assessment].

socioeconomic factors to mitigate the adverse effects of losses on individuals' overall welfare and their ability to successfully recuperate. Non-governmental organizations (NGOs) primarily prioritize the development of social and economic capital by conducting thorough risk analysis [31] and resilience assessments in order to construct resilience activities. The concept of socioeconomic resilience [105] pertains to the evaluation of an individual or community's capacity to endure and recover from two distinct forms of adversity, namely the loss of financial resources and the decline in overall quality of life [106].

Within the power system framework, the concepts of socioeconomic resilience and vulnerability are closely connected to the dependability and availability of energy provision, which can have substantial effects on communities and economies. An instance of socioeconomic resilience might be observed in the scenario of microgrid deployments in rural or isolated regions. Microgrids, frequently fueled by sustainable energy sources like solar or wind, offer dependable electricity to communities without access to traditional power infrastructure or located in neglected areas. Microgrids can promote economic activity, bolster local companies, boost healthcare and education facilities, and improve general quality of life by increasing energy access. This, in turn, helps to strengthen socioeconomic resilience.

On the other hand, socioeconomic vulnerability can be demonstrated by the impacts of power outages in cities or places with high population density. Significant disturbances to the electricity infrastructure, whether caused by extreme weather conditions, equipment malfunctions, or cyber assaults, can have extensive ramifications on enterprises, industries, and families. Extended power outages can lead to financial setbacks for businesses, disruptions to essential services like healthcare facilities or public transportation, and heightened vulnerability for marginalized communities that may not have backup power options or other forms of assistance. These disruptions can worsen pre-existing socioeconomic inequalities and present considerable obstacles for recovery and resilience initiatives.

These examples demonstrate the complex connection between the power system and socioeconomic processes, emphasizing the significance of constructing robust energy infrastructure that can endure interruptions while also meeting the requirements and susceptibilities of various populations. By incorporating socioeconomic factors into energy planning and policy-making, stakeholders can strive to develop power systems that are more inclusive, equitable, and robust, thereby benefiting all individuals in society.

Based on the available evidence, it can be deduced that

$$\text{Risk} = f\,(\text{Hazard}, \text{Exposure}, \text{Vulnerability}, \text{Capacity}).$$

According to the World Bank (2014)

$$\text{Socio} - \text{economicresilience} = \frac{\text{Asset loss}}{\text{Welfare loss}}$$

The factors that affect poverty are closely connected to the sustainability of the power system. Poverty frequently coincides with restricted availability of dependable and reasonably priced electricity, as disadvantaged communities may lack the necessary infrastructure and financial means to connect to the power grid or afford energy services. Energy poverty not only sustains socioeconomic inequalities but also weakens the resilience and sustainability of the power system. In the absence of inclusive energy access, marginalized communities are at a higher risk of experiencing the negative consequences of energy crises, such as blackouts or lack of fuel. These circumstances can worsen poverty and impede economic progress. To establish a sustainable power system that promotes fair development and improves the well-being of all communities, it is crucial to tackle poverty-related issues, including enhancing energy availability, affordability, and resilience.

There are several factors that influence the prevalence of poverty within a population.These are related to (a) geographical location (b) Greater negative impacts in terms of health, income, and access to basic services (c) Difficulty in replacing lost assets.The process of assessment involves the identification of vulnerable [107] groups, as well as an examination of their capacities and requirements. The nature of the phenomenon under investigation allows for the utilization of both qualitative and quantitative research methods. The components [Table 8] that have been examined are:

The methodologies employed to evaluate social resilience utilize sub-dimensions. The key elements under consideration include social structure, social support, safety and welfare, equity, and local culture. The methodologies employed to evaluate economic resilience make use of sub-dimensions. The three key aspects under consideration are structure, security [35], and dynamism. An effective instrument engages in iterative procedures that encompass scenario-based strategic planning and the active involvement of stakeholders in the design process.

When evaluating social and economic resilience in the context of the power system, certain approaches provide valuable information on the ability of communities and economies to endure and recover from shocks. Social resilience evaluations frequently entail community-based assessments, utilizing methods such as surveys, interviews, and interactive approaches to measure perceptions, requirements, and susceptibilities associated with energy access and dependability. Alternatively, economic resilience evaluations can employ economic impact analyses to measure the consequences of power system interruptions on local economies, such as employment, income, and company activity. Cost-benefit studies can assess the economic consequences of various power system investments or policies, providing a structure to prioritize steps that enhance resilience. By utilizing these approaches, those with a vested interest can acquire a thorough comprehension of the societal and financial forces that influence the ability to recover from challenges within the energy system. This knowledge can then be used to guide specific actions and policy choices aimed at constructing more robust and resilient societies and economies.

In order to effectively develop the ability to foresee, absorb, recover from, and adapt to various systemic risks, it is imperative to accept the inherent uncertainty that underlies these challenges. Certain risks can be effectively mitigated by the implementation of proactive measures such as the establishment of precautionary buffers, the use of monetary and fiscal policies, as well as the implementation of government support programs. The acknowledgement of profound uncertainties necessitates the recognition that the economic system is fundamentally supported by the social system, and thus, the latter must possess the institutional capability to effectively address these uncertainties.

The contributions of communities [Table 9] to resilience are multi-faceted and contingent upon specific contexts. Indigenous knowledge, sustainable practices, and the adoption of risk reduction strategies are crucial in fostering resilience. Actions play a pivotal role in the promotion of social-economic resilience [Table 10]. The provision of fundamental services and social safety nets advocate (a)for the implementation of policies aimed at facilitating affordable and secure housing options. (b) increased involvement of several stakeholders [108].

Communities are essential in enhancing resilience within the electricity system through a range of examples and initiatives. A viable strategy is the implementation of community-based renewable energy initiatives, wherein inhabitants of a particular area pool their resources

Table 8
Different components of Resilience.

Components of social resilience	Components of economic resilience:
Awareness of households wrt risk	Ability to resist potential damage in households, vulnerability of income
Knowledge about resources, organizations, identifying vulnerable groups	Capability to compensate damage
Attitude of communities towards engaging in initiatives	Ability to recover occupational and income conditions post-disaster
Skills related to first aid, evacuation planning, search and rescue	
Social capital based on interrelation of community members, trust, consensus and collective action	

Table 9
Tools for community level resilience assessment.

Tools	Risk focussed	Region	Scale	Qual/Quant
CoBRA	Drought	Horn of Africa	Community, Household	Both(formative)
USAID	Poverty	Global	Community	Both (summative)
Hyogo	Natural risks	Global	City &state	Both(formative)
CDRI	Multiple	South Asia	City	Both (summative)
CRDSA	Multiple	Saudi Arabia	Community	Both (summative)

Table 10
Action plan for Socio economic resilience [109].

Local Government	Media	Community	NGO's,Civil Society
Build, understanding on hazard, climate change	Raise awareness among the vulnerable population With respect to the entitlements of individuals. Opportunities for sustainable means of living	Provide authentic information to assessors	Collect relevant contextual information regarding the factors upon which the livelihoods of the target group are contingent.
This report aims to consolidate data pertaining to hazards, predicted repercussions, and geographical context.	Advocate for safety standards at workplace	Adhere to the precautions, evacuation plans	This analysis aims to evaluate the degree to which the community [110] and livelihood are susceptible to various threats.
	Advocate for the implementation of mechanisms that facilitate the widespread dissemination of weather forecasts and timely information regarding potential hazards.	Participate in DRR related trainings, workshops	This study employs a participative technique to obtain knowledge and subsequently analyze capacities.
		Utilize indigenous knowledge	It is imperative to provide training to officials in order to effectively cater to the requirements of marginalized populations.

to finance and oversee the operation of renewable energy infrastructure, such as solar panels or wind turbines. These projects not only improve energy security and decrease reliance on centralized power systems, but also promote community solidarity and stimulate economic growth. Another approach involves community-led energy efficiency efforts, in which neighbors work together to decrease energy usage by implementing measures such as home weatherization, appliance improvements, and behavior modification campaigns. Communities can enhance their resilience to energy shortages and price volatility, as well as mitigate greenhouse gas emissions, by enhancing energy efficiency. Moreover, community emergency preparedness and response programs enable communities to respond efficiently to power outages and other energy-related events by providing training, communication networks, and mutual aid agreements. Communities can make a substantial contribution to improving the resilience of the power system and ensuring that all members have access to reliable and sustainable energy by utilizing their local expertise, resources, and working together.

4.1. Sustainable Infrastructure

The establishment of sustainable infrastructure [111] is necessary in order to effectively tackle environmental concerns, promote economic growth, and enhance the overall quality of life for present and future generations. The primary objective of sustainable infrastructure is to mitigate its ecological footprint, bolster its capacity to withstand adverse conditions, and foster societal and economic prosperity. The following are essential strategies for the development and execution of sustainable infrastructure projects.(Figs. 17 and 18).

Micro grids possess inherent resilience as a result of their operational capabilities, such as the capacity to detach from the main grid during contingencies and afterwards reconnect once the contingencies have been resolved. Following the occurrence of an islanding [112] incident, it is customary for the backup generators to assume control [113] and sustain the power supply to the load. In the past, onsite generating at load centers has commonly relied on diesel generators, micro turbines, and heat and power combination plants. Nevertheless, the functionality of these systems is contingent upon the presence of fuel on the premises, a factor that may prove inadequate in ensuring the prolonged continuity of operations. Furthermore, the impact of natural disasters on the availability of essential infrastructure, such as pipelines and transportation systems, is a significant factor in determining the level of resilience within a community or region [110]. In instances of this nature, the implementation of a sustainable micro grid that incorporates a varied assortment of renewable energy sources is crucial for enhancing resiliency [164]. It is also of vital importance to integrate smart grid with novel heating, ventilation and air-conditioning (HVAC) systems in built environment towards low/zero carbon targets [165]. A sustainable micro grid possesses the capability to endure a prolonged power loss by incorporating sufficient energy storage to fulfill the demand during nighttime hours and maintain system stability. Resilience and sustainability, although having separate meanings, are interconnected and are commonly seen as mutually supportive in the endeavor to establish strong and long-lasting systems [114].

4.2. Sustainability through Power system Resilience

Sustainability, as the third component of the triad, refers to the capacity to fulfill current power demands while ensuring that the ability of future generations to satisfy their own energy requirements remains intact. Sustainability [115] enables firms to implement tangible measures aimed at benefiting individuals, the environment, and financial

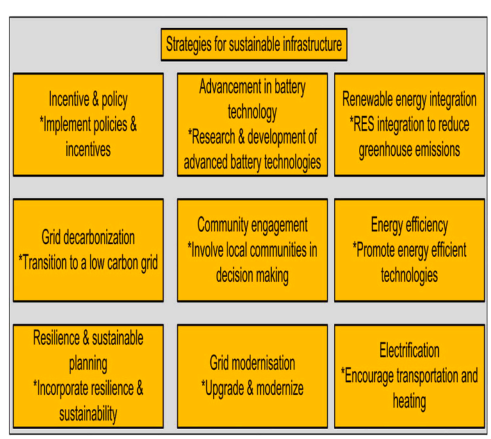

Fig. 17. Different strategies for Sustainable infrastructure.

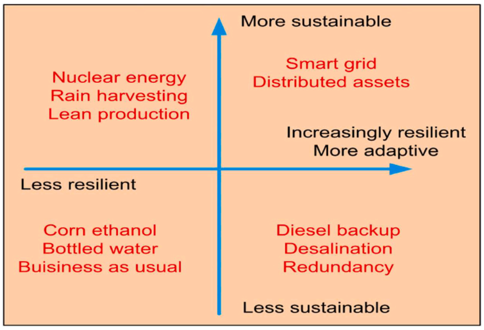

Fig. 18. Relationship between Resilience and Sustainability [154].

gains. Renewable power sources that are carbon-neutral offer significant environmental benefits. However, it is important to acknowledge that these sources also have certain drawbacks in terms of their resilience [116], as discussed before. In addition, the task of effectively managing the network in the near-to-intermediate future has emerged as a real-time endeavor involving the delicate equilibrium between renewable energy sources and conventional ones. While these efforts are focused on achieving solutions that result in net-zero carbon targets, it is important to acknowledge that this is just one component of the broader sustainability framework. Commencing the process of decarbonization is commendable; yet, it must to be regarded as merely the initial step in a broader endeavor.

A resilient power system [117–120] is essential for ensuring sustainability, as it must possess the capacity to withstand unforeseen circumstances such as equipment failures, unpredictable weather patterns, natural calamities, and energy deficits. Furthermore, it is imperative to maintain the continuity and reliability of client service [121] even in the event of any unforeseen incidents. The attainment of sustainability necessitates modifications in both the provision and utilisation of electricity.Furthermore, it is essentisl for a power system to possess environmental friendliness in order to facilitate the establishment of a sustainable society. Hence, the primary obstacles in attaining sustainability lie in mitigating climate change and addressing environmental issues. In comparison to other sources of pollution, such as automotive emissions, power plants offer a greater degree of monitoring feasibility for greenhouse gas emissions.

4.2.1. Sustainable Micro grids

Micro grids exhibit inherent resilience [122] due to their capacity to operate autonomously during emergencies and afterwards reintegrate into the larger power grid once the incident has passed. Moreover, it is expected that the backup generators will assume control [111,123] and continue to provide power to the load following an occurrence of islanding [110,113]. In the past, the generation of electricity at load centers has been achieved through the utilization of diesel generators, micro turbines, and combined heat and power plants. Nevertheless, the functionality of these systems relies on the availability of on-site fuel, which may prove inadequate in the event of a prolonged power disruption [124]. Furthermore, the impact of a natural disaster on essential infrastructure, like pipelines and transportation systems, plays a pivotal role in determining resilience [125].

In order to enhance resilience, it is imperative to implement a sustainable micro grid that incorporates a diverse range of renewable energy sources. A sustainable micro grid [101] can effectively navigate a prolonged outage by incorporating sufficient storage capacity to fulfill emergency demand and maintain stability.The affordability of grid supply is mostly attributed to the lack of grid parity in the majority of nations, as renewable energy sources have not yet achieved cost competitiveness. Hence, it is imperative to be adequately prepared to bear the expenses associated with the production of renewable energy and its storage, which can be considered as a form of investment in resilience. Furthermore, the level of resilience is subjective and exhibits variability among distinct consumer demographics and sectors within the industry. A residential consumer may opt to forgo payment for resilience measures and opt to endure electrical deprivation during an outage. The services and production sectors necessitate a considerable degree of resilience [126] due to the potential for substantial losses resulting from disruptions. The conventional cost-benefit analysis also yields a higher net present cost (NPC) for the project, hence discouraging investments in sustainable micro grids [51]. Hence, doing a thorough assessment of resilience and accurately determining the potential for revenue generation would serve as incentives for investing in sustainable micro grids. Furthermore, optimizing the source and storage sizing by considering factors such as load profile [127], critical loads [128], and the anticipated timing and duration of power outages [107,129] can result in a reduction of the net present cost (NPC).

Moreover, the degree of resilience [130] is subjective and exhibits variation across many sectors and customers. Residential customers have the option to endure a power loss rather than incurring costs associated with ensuring resilience [131]. In contrast, the service [99] and manufacturing industries necessitate a significant degree of adaptability due to the potential for substantial financial setbacks resulting from disruptions.In the course of grid operations, conventional generators reliant on fossil fuels experience significant periods of underutilization during their operational lifespan(112). Throughout its lifespan, this entity has minimal utility [71,132], serving mostly as a temporary backup for a limited duration. Nevertheless, a sustainable micro grid that is connected to the grid has the ability to engage in several activities, so generating revenue by leveraging smart grid [133–135] technologies. Efficient management [132–136] of on-site manufacturing can potentially lead to the reduction of electricity expenses. Microcontrollers possess the capability to engage in energy arbitration, effectively managing resources by considering the temporal utilization of the network's tariff signal. Under such circumstances, the utilization of on-site energy storage [137] assumes a significant role as it enables the generation of electricity [138] during periods of high demand. In the context of a liberalized market organization, the potential for profit maximization can be enhanced through active participation in the market. Furthermore, alongside the capacity market, a robust micro grid [139] equipped with rapid reaction storage [140] has the potential to engage in the supplementary service market. In addition, electric cars have the potential to enhance flexibility without necessitating any initial expenditure. The assertion is substantiated by the primary motive behind the acquisition of electric vehicles. A significant quantity of electric vehicles has the capability to integrate with the micro grid and offer their services during periods of inactivity. Nevertheless, a precise evaluation of the spatial and temporal dispersion of electric vehicles [141] can have an impact [106] on the costs associated with sustainability. Thus, the device's sole purpose during its operational lifespan is to serve as a source of backup power for a limited duration.

The notion of power system resilience [142,143] and measures for a sustainable infrastructure are in accordance with multiple Sustainable Development Goals (SDGs) [144–149] established by the United Nations. The aforementioned objectives encompass the imperative for the establishment of infrastructure that is both sustainable and robust, the provision of energy accessibility, the safeguarding of the environment, and the promotion of economic advancement. The integration of power system resilience [145,150,153–156] and sustainable infrastructure initiatives plays a crucial role in the attainment of many Sustainable Development Goals (SDGs) [156–163].

These methods effectively facilitate the provision of accessible and affordable clean energy, foster economic growth, and reduce the adverse effects of climate change. The implementation of these solutions in power systems on a global scale is imperative in order to foster a more sustainable and resilient future [151,152].

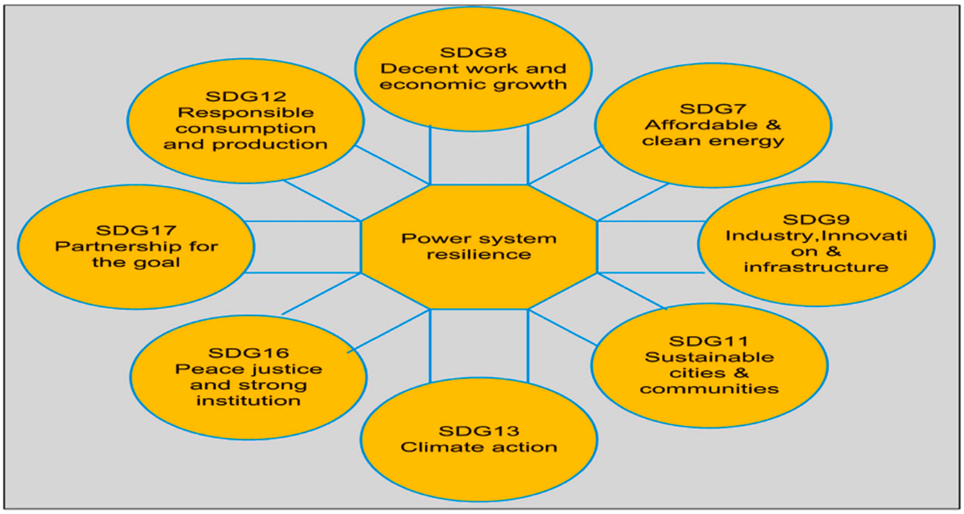

Fig. 19. power system resilience and measures for multiple sustainable goals.

5. Conclusion

Given the increasing magnitude of risks posed by both natural and human-induced hazards, the need for power system resilience has emerged as a crucial need in guaranteeing the uninterrupted provision of energy. It is imperative to proactively address physical, cyber, and communications vulnerabilities in a comprehensive manner to maintain the resilience of power system.

The primary objective of this study is to establish a comprehensive and quantitative methodology for identifying potential risks, assessing the vulnerabilities associated with these risks, and implementing appropriate mitigation measures to ensure the reliable and resilient operation of the power system. Implementing microgrid systems is an example of a specific measure that can greatly improve the resilience of the electricity supply. Microgrids are decentralized energy systems that can function autonomously or in conjunction with the primary power grid, making use of dispersed energy resources including solar panels, wind turbines, and battery storage. Microgrids enhance the resilience of the power system by reducing dependence on centralized infrastructure through the use of diverse energy sources and decentralized generation and distribution. This enables the system to better withstand disturbances like extreme weather events or cyber-attacks. In addition, microgrids can offer vital services in times of catastrophes, such as hospitals, emergency shelters, and communication networks, guaranteeing uninterrupted power supply to crucial facilities when the primary grid is damaged. Moreover, microgrids have the capacity to facilitate the sharing of energy and the ability to operate independently, enabling communities to sustain power supply even in the absence of connection to the primary grid. In general, the introduction of microgrid systems improves the ability of the power system to withstand and recover from disruptions by enhancing dependability, decreasing susceptibility to outages, and enhancing flexibility and agility in responding to disturbances.

Power systems are susceptible to several physical dangers, including but not limited to natural calamities, climate fluctuations, and deliberate acts of aggression by humans. The potential risks associated with cyber-attacks encompass a wide spectrum, ranging from unintentional isolation of an islanded system to the activation of out-of-phase reclosing in a micro grid, ultimately leading to detrimental effects on the rotating machinery. The operation of power network can be threatened by many occurrences, such as interruptions in the supply of natural gas and/or water, due to the significant interdependence of Critical Infrastructure systems. The paper also presents a discussion on the sustainability Critical Infrastructure systems and their influence on the modeling of resilience in power system. Integrating sustainability principles into power system resilience measures is important for constructing a resilient and adaptable energy infrastructure. To build a power system that can withstand shocks and disruptions and improve environmental and social well-being, stakeholders can incorporate sustainability principles like renewable energy integration, energy efficiency, and environmental stewardship into resilience planning and implementation. In addition to reducing fossil fuel use and greenhouse gas emissions, investing in renewable energy sources like solar, wind, and hydropower diversifies the energy mix and reduces fuel price volatility, improving energy security and resilience. Promote energy efficiency methods like demand-side management, smart grid technology, and building retrofits to minimize energy consumption and operational costs and improve the system's ability to react to shifting demand patterns and supply disruptions. Including ecosystem preservation, biodiversity conservation, and climate adaptation in resilience strategies makes the power system adaptable to environmental threats and promotes ecosystem health and sustainability. Resilience techniques and sustainability principles can make the power system more robust, efficient, and environmentally sustainable, providing reliable and equitable clean energy access for future generations.

The present study introduces a quantitative approach to threat modeling for the purpose of calculating the risk factor. Quantifying the likelihood and impact of threats and disruptions provides a systematic framework for power system resilience assessment. Mathematical models, probabilistic analysis, and data-driven methods help stakeholders identify vulnerabilities, prioritize remediation, and optimize resource allocation to improve system resilience. Threat modeling can estimate the likelihood of extreme weather occurrences, cyberattacks, equipment failures, and supply chain disruptions and accompanying power outages, economic losses, and social implications. Quantifying these risks helps decision-makers invest in infrastructure hardening, redundancy, and emergency planning to reduce interruptions. Stakeholders can simulate threat scenarios and evaluate resilience strategies' risk mitigation and system reliability using the quantitative approach. Quantitative threat modeling in resilience assessments helps the power system anticipate, plan for, and respond to a variety of threats, assuring service continuity and reducing societal and economic disturbances.

This research examines a range of mitigation measures that have been suggested for the several phases of disaster recovery, including pre-disaster, during-disaster, and post-disaster modes. The mitigating tactics that have been suggested encompass system hardening techniques as well as steps to enhance operational effectiveness. Mitigation solutions are categorized to facilitate the improvement of several characteristics of the power network, such as robustness, redundancy, resourcefulness, response, and recovery. Future research efforts will encompass the formulation and establishment of measures that may effectively measure the resilience of power system in the face of diverse threats. Future power system resilience research will focus on several critical areas to improve energy infrastructure reliability, adaptability, and sustainability. Developing powerful predictive analytics and machine learning algorithms for risk assessment and disruption early warning systems is a priority. These systems can uncover new risks and weaknesses by analyzing massive volumes of data from sensors, weather forecasts, and grid operations, enabling proactive mitigation. Grid-scale energy storage, demand response, and distributed energy resources will also be studied to improve system flexibility and resilience. These technologies can help power grid operators manage supply and demand, minimize reliance on centralized equipment, and improve emergency response. Future research will integrate renewable energy sources and microgrid systems into the power grid, allowing communities to generate and store electricity and sustain key services during outages. Future research in these areas will enable more efficient, dependable, and sustainable energy infrastructure that can resist shocks and satisfy society's changing needs, improving power system resilience.

Through the process of quantifying the resilience of various methods, future decision-makers will gain the ability to evaluate the economic viability of the technology. These cost-benefit assessments will provide assistance in the formulation of policies and practices that may effectively guide the development and implementation of power system.

CRediT authorship contribution statement

Satabdi Bastia: Conceptualization, Writing – original draft. **Asit Mohanty:** Conceptualization, Investigation, Methodology, Validation, Writing – original draft. **Manzoore Elahi M. Soudagar:** Conceptualization, Writing – original draft. **Sarthak Dash:** Investigation, Writing – original draft. **Erdem Cuce:** Conceptualization, Writing – original draft, Funding acquisition. **Agileswari A/P Ramasamy:** Conceptualization, Supervision, Validation, Writing – original draft. **T. M. Yunus Khan:** Conceptualization, Writing – original draft, Funding acquisition. **Renuga A/P Verayiah:** Conceptualization, Formal analysis, Supervision, Writing – original draft.

Declaration of Competing Interest

We declare that this review article "Power System Resilience and Strategies for a Sustainable Infrastructure: A Review"is genuine and it is neither copied nor taken from any source.This work is not funded from any source. We declare that we have followed all the ethical ways during processing of our work. Finally we declare that there is no conflict of interest between any of the authors.

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