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# Meta-analysis of the strategies for self-healing and resilience in power systems

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ABSTRACT

This paper presents a survey of the literature on the strategies to enhance the resilience of power systems while shedding lights on the research gaps. Using a deductive methodology on the literature covering the resilience of power systems, we reviewed more than two hundred peer-reviewed articles spanning the 2010–2019 decade. We find that there is vacuum on the level of integration that considers the interdependence of local or decentralized decision making in an adaptive power system. This gap is widened by the absence of policies to enhance resilience in power networks. While there is significant coverage and convergence of research on algorithms for solving the multi-objective problem in optimization routines, there are still uncharted territories on how to incorporate system degradation while designing these self-restoration systems. We posit that a shift to a smarter, cleaner and more resilient power network requires sustained investments rather than disaster-induced responses.

## 1. Introduction

It is generally acknowledged that one of the greatest challenges facing the society of the 21st century is related to sustainable and low-carbon use of energy [1] because many sectors of the economy are dependent on reliable and resilient energy supply. In fact, the unprecedented demand for electricity is accompanied by concerns for climate change leading to why many countries are turning to cleaner and more efficient technologies for producing power. Likewise, there has also been a paradigm shift in the way consumption is managed and power is distributed across the grid. Combined, these two factors have burdened conventional radial power grids with unfamiliar issues such as the uncertainty around overloaded generators and stretched transmission lines and weakened distribution systems susceptible to extreme failures or even total blackouts.

To provide a concrete example, recently, the demand for electricity for heat in the state of Texas soared due to unexpected low temperatures leading to the spontaneous shutting down of several power plants [2]. The soaring demand plunged the frequency of supply significantly below 60 Hz, and that eventually led to cascading blackouts. Historically, preparing a system for component failure included increasing redundant components and alternative options for replacing faulted sections. While mostly effective, such methods have been proven to be less cost-efficient in the long run and unproven against more recent types of faults introduced by renewable energy. This calls for a change in the way power grids are designed to handle not only the stochastic nature of renewable energy sources, but also the faults and cascading failures. In the past decade, researchers in the energy sector have focused on developing adaptive protection schemes and flexible network topology to increase the resilience of power grids while also attaining optimized power generation.

Capable of locating and analyzing faults and then executing appropriate corrective action, "self-healing systems" have been proposed and even implemented in parts of the world. These systems use intelligent fault identification modules, smart metering units, synchrophasor measurements, communications infrastructure, and re-configurable network topology to achieve self-healing functions. Undoubtedly, new technology requires concurrent policy development and governmental support for any change to be made to the public-sector utilities. Globally, at both the national and local levels, policymakers have developed new pilot programs to make the shift to smart power infrastructure possible.

The thesis of this paper is to examine the literature on the status of self-healing in power systems in recognition of the detrimental impacts of man-made or natural disasters on critical infrastructure systems. The objective is to emphasize the knowledge gaps while simultaneously exploring investment and policy frameworks for self-healing systems. In this paper, an extended exploration is conducted on the more recent and relevant literature on power network resilience strategies covering the decade, 2010–2019. The focus over this time interval is underscored by the uptick in the frequency for network restoration and system re-

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silience. This review is informed by the correlated response in the research arena on models and approaches to better catalyze the recovery of socioeconomic systems – that depend on electricity supply – of communities in the advent of a disaster. The COVID-19 pandemic has also reinforced the need for change by highlighting the importance of flexibility for resilient energy systems especially with policy recommendations aimed at improving flexibility in energy systems [3,4]. The interdependence of the sectors of the economy particularly the dependence of food and water systems on energy requires instituting the right sets of policies to promote an array of technology options to meet the resilience at the nexus of these systems for sustainable development [5–8].

In summary, this paper adds value through the following contributions. First, it offers a comprehensive and an updated review of literature on self-healing systems that includes components, modern approaches, and currently developed and pending policy incentives. The research offers an all-encompassing view of the entire scope of self-healing systems that, to the best of our knowledge, has not been covered with emphasis on the drawbacks or shortcomings of certain approaches especially when considered with all aspects of restoration schemes in power systems. Second, this review introduces response to power system disruptions from the lens of self-healing, and offers a look-up reference for emerging scholars in this research space. The value lies in offering a single source of information with suggestions for future research agendas in this domain. Third, the bibliometric analysis in this review identifies research trends with a data-driven view of the global collaborations between authors and their geographical distributions in this arena. Fourth, the coverage of market-driven policy initiatives adds value to the technological evaluations – as aspect that we have not seen in the extant literature. This review sheds lights on policy frameworks that will incentivize non-governmental actors, such as the private sector and utilities, to make investments into electricity network resilience and disaster risk-mitigation and preparedness. Fifth, and most importantly, this review draws attention to the gaps in research such as quantifying the value of self-healing systems.

The rest of this paper is organized as presented in Fig. 1 as follows. Section 2 provides the methodology used in the paper and some basic descriptive analysis of the surveyed literature. Section 3 presents the concept of self-healing and the inspiration drawn from self-healing processes such as morphogenesis in plants and other natural systems. Section 4 presents the configurations of self-healing in power systems while Section 5 discusses the different types of approaches for power system enhancements. Section 6 discusses public policies for power system infrastructure resilience. Section 7 focuses on disaster-induced risk mitigation. Section 8 highlights the major challenges in self-healing systems. Section 9 discusses the significant observations of the meta-analysis, and Section 10 concludes.

## 2. Methodology

To obtain the required networks for bibliometric analysis, the procedure similar to [9] described in Fig. 2 is followed. The literature examined were drawn from databases such as Google Scholar, Web of Science, Scopus and PubMed with papers from the last decade, *i.e.,* 2010–2019. The search criteria centers around self-healing systems including specific keywords to limit the scope of the meta-analysis. The resulting database returns were downloaded with their titles, authors, publishing years, affiliations, keywords, abstract, country and the full citation for each document.

Next, the database is imported to VOSViewer, a software capable of visualizing bibliometric networks and co-citation maps [10]. It is necessary to refine the database to curtail repeated or similar words and to obtain an accurate visualization as described in Stage 2 of Fig. 2. In addition, constraints for minimum occurrences or minimum citations are applied to limit items included in the network. Adjusting parameters such as scaling and size variation for adequate visualization precedes the final step on obtaining the network in Fig. 3. This keyword network especially helps in recognizing links between keywords that are related to the topic with minimum occurrence of at least twenty. The nodes are represented by the keywords and their sizes are based on their counts. The lines represent the connection between any two nodes. It is also important to note that the color of the nodes indicates the mean year of occurrence or publication of that node according to the color scale at the bottom of the figure.

Evidently, smart grid, distributed generation, and microgrid are the top keywords or phrases with the highest occurrence. The main takeaway from this network is the increased research interest in microgrids in recent years, and the move towards renewable energy sources. It is also critical to note that while resilience has received increasing attention in recent years, there is still a dearth of research focus on the topic.

## 3. Self-healing

Approaches in recent literature often highlight, amongst others, increases in redundant capacities [11–17]; non-centralized generating assets [18–26] or mobile power generators [21,27] as a hedge against systemic failure; operational considerations through radial and meshed topology [28]; mitigating real time market disruptions [29]; or the use of non-cooperative [30] or cooperative [31] game-theory on distributed energy resources. While methodologies have offered considerable improvement in the system's robustness and resilience, they consequently are often prohibitive when life-cycle costs are considered [32]. The management of spare capacity which only comes into use under low-probability high-consequence (LPHC) events like hurricanes or other disasters also warrant upkeep expenses to guarantee their availability when the need arises. The value proposition of the given methodology over many of these approaches is the inherent self-organization and self-healing which serves as a prerequisite for the inclusion of any of these approaches. Furthermore even when such need arises, it will be within the bounds of an optimal deployment scheme.

A major limitation of these approaches is the outright absence of the consideration for system degradation. The level of system performance prior to a disaster dictates the severity of the outcomes. It is aptly noted that a deteriorated system may still be functional; however, such a system will have a very limited resistance to shock-induced failure. Thus, the inclusion of the system's deterioration as a metric of internal stimuli in the self-healing process is critical not only to understanding the system's vulnerability, but also in proffering the necessary restoration investments prior to an outright breakdown or failure, disaster-induced or not. Lastly, the awareness that even without these interdependent systems, the degradation in their performance over time requires characterizing the changes in the evolution of their performance levels in order to develop an effective restoration investment strategy. Historically, the perception of engineering design is based on optimizing a preselected physical characteristic of a system to meet specific functions with the objective of minimizing cost or maximizing performance [33]. However, the increasing need to balance safety and cost, and the increasing interdependence call for a change in the management of these systems. Table 1 below provides a summary of self-healing processes in nature as premises for inspiration on how power systems could adapt.

For example, plant morphology shows that plant growth widely reflects ambient environmental conditions through their dynamic vascular system. The branches act as agents that collectively decide on the distribution of resources (water and minerals) leading to a relatively optimized access to more favorable regions of the environment. The amount of a resource, such as sunlight reaching leaves, determines the thickness or growth of a connection. This acts as a model for self-healing power systems. The need for self-healing in materials is of huge interest as there is an increase in the lifetime of the material, reduction in replacement costs and improved product safety. The idea behind analyzing the healing behavior seen in living nature is to extend these ideas to address the fatigue problems in synthetic materials and open new avenues of insight and research. We posit here that self-healing

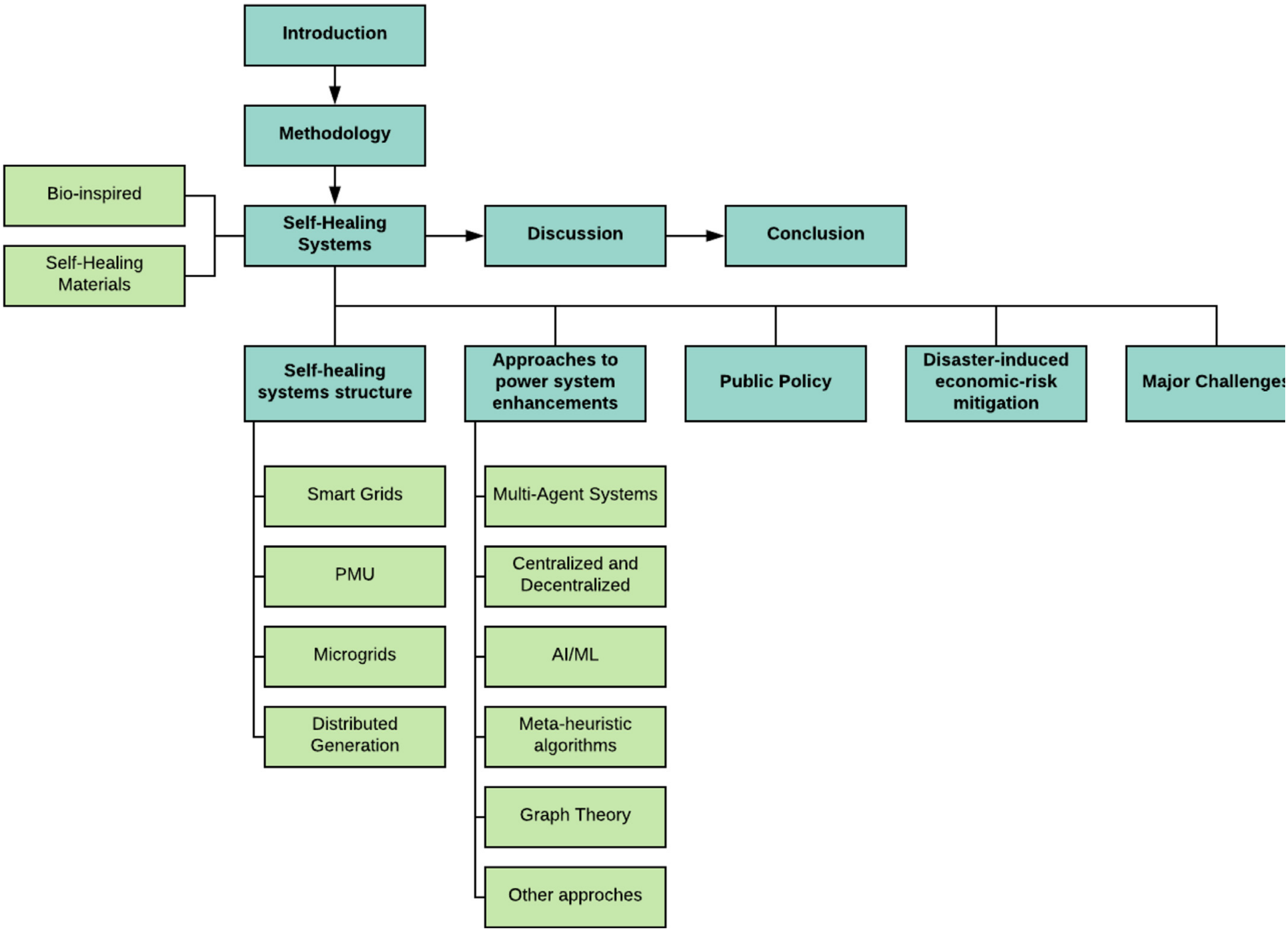


**Fig. 1.** Framework of the meta-analysis on adaptive power systems.

**Table 1**
Summary of the premises of self-healing in power systems.

| Premise | Objective | Contribution |
|---|---|---|
| *Self-healing inspired by nature* [34–47] | To identify processes in nature that power systems could adopt for self-healing. | 1. Utilizing the concept of morphogenesis, i.e., the death of a cell creates stimuli to the neighboring cells which, in-turn make adaptations that lead to corrective outcomes. 2. Modelling branches as individual agents that collectively decide on distribution of limited resources to all their nodes. 3. The Vascular Morphogenesis Controller (VMC) relocates nodes shows adaptation to environmentalgradients and recovery after structural damages. |
| *Self-healing materials*[48–52] | To adapt healing processes to synthetic materials and open new avenues of research and insight. | 1. New materials have been designed and prepared with intrinsic autonomic self-healing. 2. Thermodynamic requirements and chemical reactions that lead to self-healing nature have been assessed. |

approach is most relevant in the disturbance progress, post-event and restoration phases of system resilience. Table 2 summarizes some of the materials that are appropriate for self-healing schemes in power system components.

**Deduction 1** (Research Gap)**.** Approaches for self-identification of failures in power systems or auto-restoration schemes after certain types of failures have been developed. While these schemes add value through their inherent self-healing properties, such properties are limited by their optimal deployment strategies. Further, the inclusion of system deterioration as a metric to understand the systems vulnerabilities is a critical task in planning the restoration scheme. Moreover, with the increase in interdependencies within systems, these approaches cannot be designed through conventional engineering design methodologies of pre-selecting variables and maximizing performance while lowering costs. There are significant gaps on replicating biological processes, *e.g.*, morphogenesis, to adapting the power grid in the event of a failure and, consequently, keeping costs in check. There is a vacuum in the level of integration required in a complex adaptive system with interdependence, local or decentralized decision making with the influence of underlying policies.

## 4. Power systems configurations for self-healing

With the large scale penetration of renewable energy sources combined with power grids capable of isolating themselves in microgrids, the scale and complexity of distribution networks make it difficult to design and plan the network. Fault location, Isolation, and Service restoration (FLISR), according to [53–56], establishes the platform for reliable

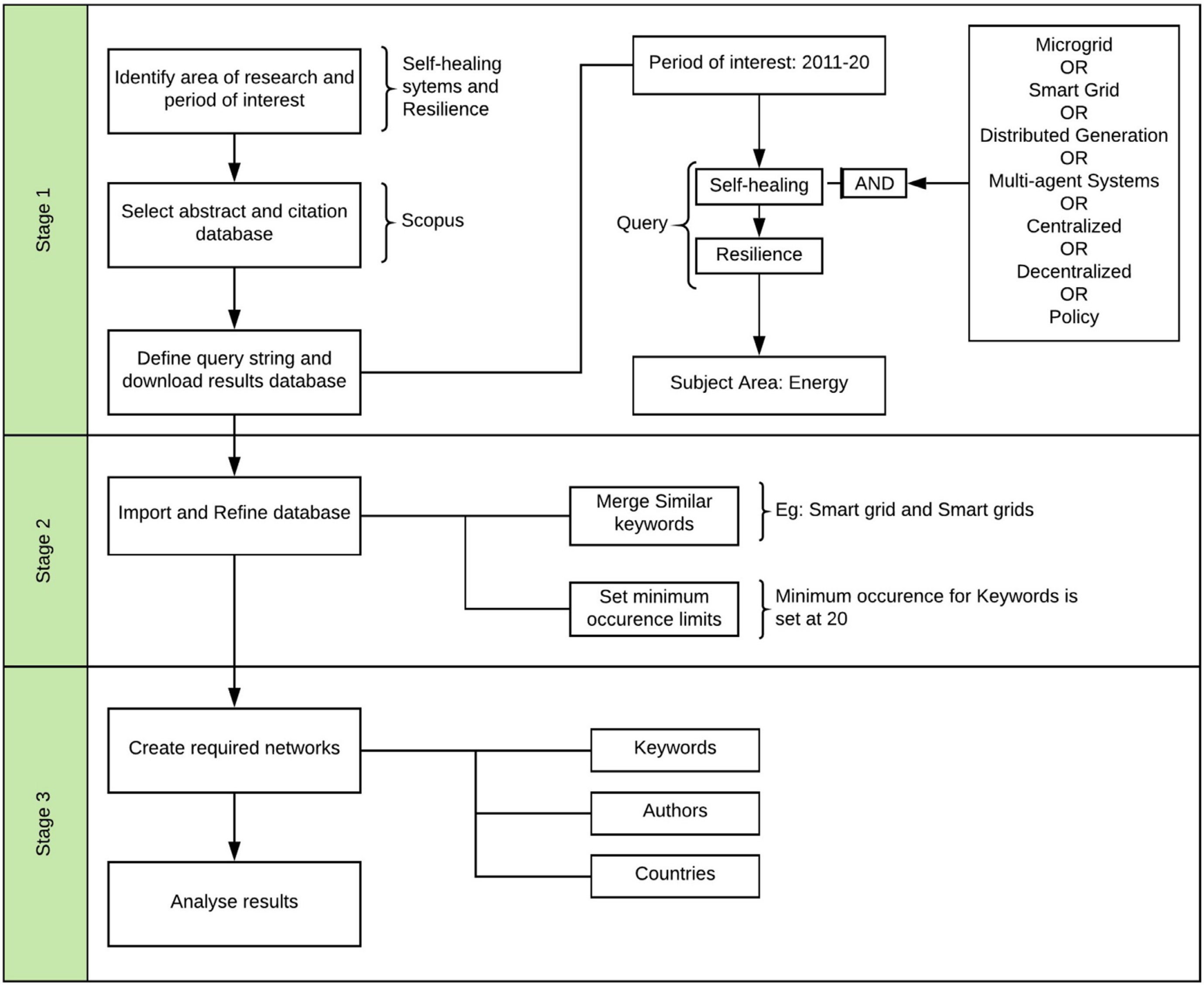


**Fig. 2.** Procedure for conducting the meta-analysis and obtaining the bibliometric networks.

**Table 2**
Materials for self-healing in power systems.

| Materials | **Mechanism of self-healing** |
|---|---|
| Polymers: hard elastic polypropylene (HPP) [49,51,52] | HPP, just as other viscoelastic polymers, was observed to consist of a stacked lamellar morphology, perpendicular to the axis of polymer extrusion, that was capable of healing interlamellar micro voids formed following stretching (in the perpendicular direction). |
| Ceramics: Barium Titanate Glass, Ceramic Thin Films [50]. | Microencapsulation approach is the embedding of a microencapsulated liquid healing agent and solid catalytic chemical materials within a polymer matrix; such that upon damage-induced cracking in the matrix, microcapsules release their encapsulated liquid healing agent into the crack planes. |
| Concretes: fiber reinforced concrete [49,52]. | Extrinsically self-healing materials were developed in which fibers, employed for reinforcing the material, were filled with a self-repair fluid. These composite materials would autonomously heal (i.e., damage would break the fibers releasing the healing fluid, which would fill microscopic cracks). |
| Polymer composites [52] | Cracking leads to mechanical degradation of fiber-reinforced polymer composites; in microelectronic polymeric components it can also lead to electrical failure. Here, structural polymeric material have the ability to autonomically heal cracks. The material incorporates a microencapsulated healing agent that is released upon crack intrusion. Polymerization of the healing agent is then triggered by contact with an embedded catalyst, bonding the crack faces. |

and secure distribution of energy, and when performed autonomously, become the base framework for self-healing and resilient systems. In particular, these systems can be centralized or decentralized based on various factors such as the scale and complexity of the network, penetration of renewable energy, presence of variable demand and demand response programs.

To recognize a self-healing power distribution system is a complex task, for it requires a systematic analysis of technologies, and, as shown in [57], a three dimensional framework containing a technology dimension, temporal dimension, and a functional dimension. Designing a self-healing control system also involves identifying the possible states of the power system to appropriately define the constraints. These states as

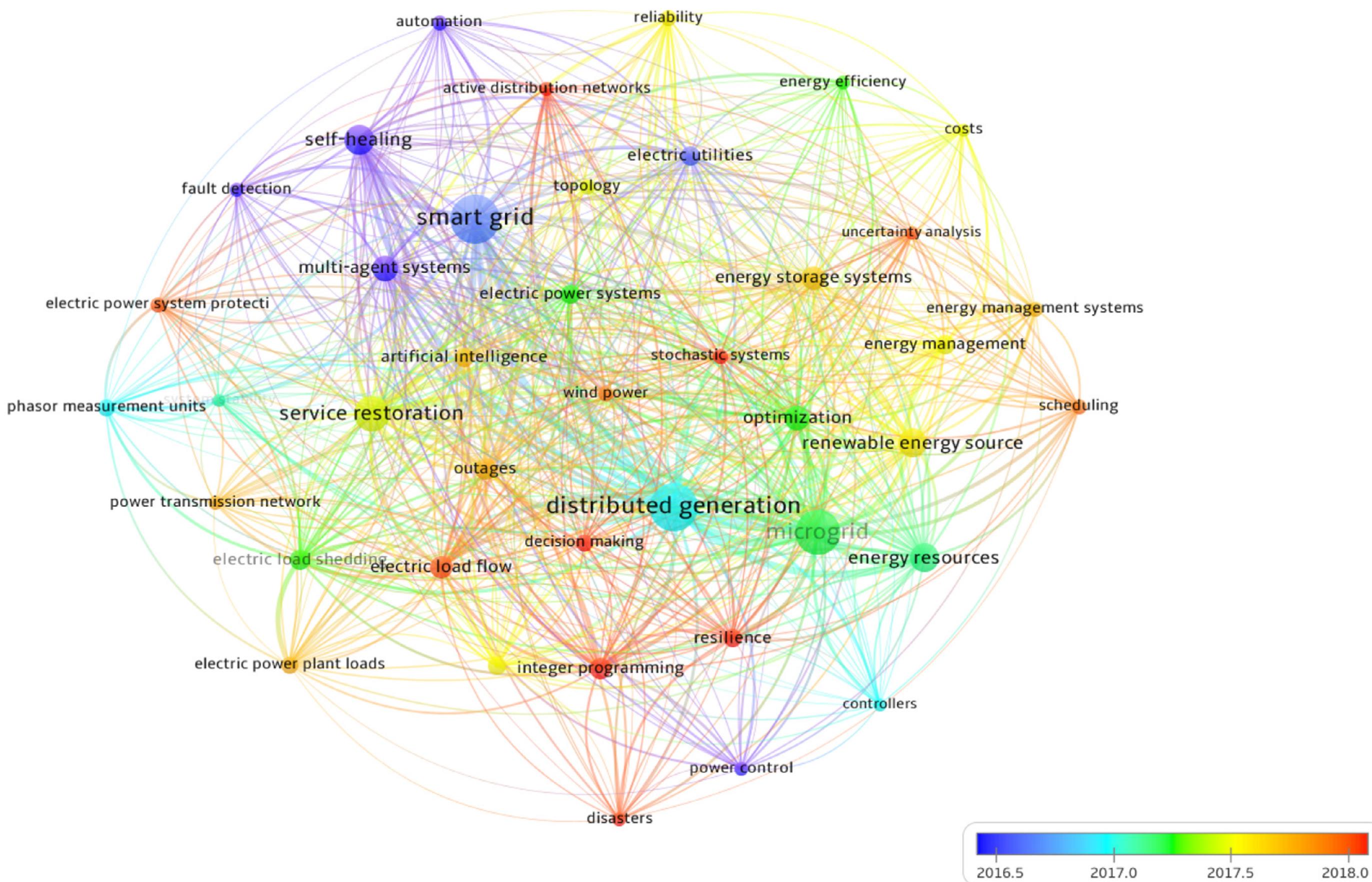


**Fig. 3.** Bibliometric network of keywords.

described in [58] are optimizing, normal, fragile, fault and breakdown state where a self-healing system will work towards ultimately reaching the optimizing state in normal operation or normal state in emergency operation.

Zidan et al. [53] suggests upgrading existing conventional power grid components to implement FLISR capabilities, further employing adequate intelligence through modern technologies to support self-healing functions such as data acquisition, decision control, power flow optimization and fault detection. Such a complex system upgrade needs the ability to monitor and diagnose the network through digital signal processing in intelligent sensors connected via a wireless network with enough speed and bandwidth to support big data transmission to ultimately create an interconnected power and communications structure of systems. These advanced systems are categorized into primary system, secondary system, information and communication technologies and control systems [59–62]. The primary and secondary systems, also known as the base power systems [63], make the actual power network, from generation to switches to variable loads and energy storage systems. The information and communications systems, or support systems, cover the entire grid to provide two-way communication between each component and its controller for monitoring, fault detection and control commands. The control or application systems are responsible for processing real-time data, diagnose faults, execute corrective action, and obtain feedback through response loops to achieve self-healing [64].

Another approach at defining the self-healing framework is creating a hierarchical layered system architecture where each layer has its designated level of control and functions with bi-directional flow between each subsequent layer through wired/wireless connections. One example is Strategic Power Infrastructure Defense (SPID) system, with a deliberative layer (highest level), a coordination layer, and a reactive layer (lowest level). The deliberative layer is responsible for a wide area control and handles the largest amount of information whereas the reactive layer collects real time inputs with a narrowly focused control [65].

In its final report on smart grids [66], the U.S. Electric Power Research Institute detailed the approach to estimate the benefits of a smart grid project, and broadened the definition as implementation of technologies, devices, and controls to optimize the efficient, reliable and safe delivery of electricity. The European Commission further added integration of renewable sources, and a flexible service-oriented grid to its definition [67,68]. Establishing a wide area measurement system (WAMS) using synchrophasor measurements from Phasor Measurement Units (PMU) that are strategically placed along the transmission network is one way to reduce the risk of cascading failures down the line. This helps smart power grids with high penetration of renewable energy sources in tracking real-time dynamics by monitoring the current and voltage phasors. Self-sufficiency implies integrating distributed energy resources (DER), energy storage systems (ESS), and controllable loads, which can be designed to act as a single controllable entity. The adaptable and flexible structure of microgrids brings further benefits, such as less pollution, reliability, and increase in power transmission efficiency for consumers, utilities, and countries. Table 3 summarizes the objective, methodology and contribution of each of the components of a self-healing system while listing the list of references for each.

**Deduction 2** (Elements of a self-healing network)**.** Integrating the aforementioned components could lead to an ideal self-healing grid consisting of the following: real-time monitoring; distributed adaptive energy management system and control; information and communications network; and flexible power grid structure capable of reconfiguration. A key distinction between self-healing networks and traditional power

**Table 3**
Summary of the locus of self-healing in power systems.

| Locus | Objective | Methodology | Contribution |
|---|---|---|---|
| *Smart Grids* [59,60,66–72,73,74–79–81–83,84,85–93] | To improve the grid by deploying intelligent metering, protection and communication tools to become more resilient, sustainable for customer interaction while integrating renewable energy and grid flexibility. | 1. Design a grid with subsystems: Power, Communication and Information. 2. Establish a real-time, bi-directional communication flow between components with data processing. 3. Integrate renewable energy in the network. | 1. Smart grids optimize power generation and network typology, fault detection and provide service restoration strategy. 2. The data is autonomously used across the grid-wide computing network from downstream customer devices to substations in order to drive fault diagnoses and implement proactive and restorative adjustments at the grid level required. |
| *PMU* [60,62,63,79,82,94] | To establish a wide area measurement system (WAMS) using synchrophasor measurements from Phasor Measurement Units (PMU) that are strategically placed along the transmission network. | 1. Establish network and identify strategic locations for PMUs to cover the network by the WAMS. 2. Calibrate the PMUs for specific network. 3. Analyse feedback from the WAMS to verify corrective actions. | 1. PMUs help smart power grids with high penetration of renewable energy in tracking real-time dynamics by monitoring the current and voltage phasors 2. Calculation of swing angles for stability determination; providing coordination between local controllers; generation loss prediction by measuring real-time frequency deviation. |
| *Micrograms* [9,62,69,71,83,95–128] | To establish self-sufficient microgrid that includes energy storage systems and controllable loads as a single entity capable of bi-directional power flow. | 1. Design a grid with distributed control and smart agents capable of isolation if failure occurs. 2. Self-sufficicy of each unit with independent energy management system. 3. Utilize optimization modules to solve the stochastic problem that accounts for the uncertainty in power generation and scheduling. | 1. Microgrids provide the ability to isolate faults, eliminating the need for redundant assets and complicated preventive measures. 2. Offer a platform for future research in advanced power systems due to their flexibility and ability. 3. Open up opportunities for bi-directional communications with the main grid and other microgrids to facilitate power distribution and load calculations. |
| *Distributed Generation* [53,62,73,77,83,86,87,117,129–135–139] | To provide local and on-site power generation using small-scale devices such as diesel generators or renewable energy source-based generators (RES-based) | 1. Identify strategic locations geographically to establish distributed generation.2. Install them according to the weather pattern and demands of the specific location. 3. Evaluate the need for dispatch such as micro-turbines or energy storage systems. | 1. They support self-healing functions by delivering island operations to avoid cascading failures and minimizing losses to the non-affected parts of the grid.2. They participate in power selling to the main grid. 3. Tackles the issue of uncertain power generation by RES-based generators. 4. Reduction of feeder power losses; flatter voltage profile; peak demand shaving. |

grids is the two-way power and information flow due in emerging microgrids with advanced data acquisition components. Microgrids can also be in island mode to provide isolation to a faulted area and ensure uninterrupted power supply to the highest number of consumers. Papers have proposed power-sharing and negotiations between the networked microgrids and the main grid; however, there is a dearth of research in prioritizing critical load. Some authors have also discussed the customer-side participation in power distribution. Real time monitoring is enhanced by a wide area measurement system and the optimal placement of PMUs at strategic points.

## 5. Approaches to power system enhancements

Self-healing systems popularly have at least two modes of operation, normal mode where the objective is to deliver power in the most efficient manner keeping costs low, and self-healing mode where a fault or multiple faults have been detected and the objective is to execute appropriate corrective action and ensure power supply to the maximum number of customers. Systems, typically, are also designed to locate said faults and identify the type and potential damage that can be caused by them. All these requirements make the power optimization problem a multi-objective non linear function and there are classes of approaches proposed by researchers to tackle a part of or all of the requirements described.

Multi-agent systems (MAS) deploy several intelligent agents with the ability to communicate with each other to reach a global set of goals by each completing their local tasks subject to system-wide and local constraints on decision variables [83]. These systems are designed such that each agent has its specialized role and it can either communicate with another layer or report to a higher agent depending on the topology of the network. They are strategically placed at locations in the network and follow predefined communication protocols.

Centralized approaches traditionally require a main controller responsible for data analysis, fault detection, optimization and commands for service restoration. While ideal for finding the best global solution, a central solution is slow in computation, has a high inertia in terms of reconfiguration, and due to a central control, has a single point of complete failure [53]. Decentralized approaches are contingent on distributed control and depend on peer-to-peer communications between local monitoring devices such as IEDs. Bi-directional power flow and large complicated network topologies are ideal for application of a decentralized control strategy, where data is processed locally instead of a single SCADA-like controlling agent [53].

Fault diagnosis in distribution grids due to little understanding of operation rules, losses in conventional data collection, integration of DGs and introduction of smart meters such as PMUs, is difficult to realize with the existing data. Thus, this calls for various machine-learning based programs (artificial intelligence) that can identify patterns and go through training modules to form rules and understanding of the new architectures being explored in the current phase of research on self-healing grids.

Meta-heuristic algorithms are designed to solve multi-objective optimization problems using a set of rules or strategies to develop a heuristic algorithm. With the induction of expert knowledge, heuristic algorithms are proven to be faster in computation as they limit the search to desired area [58]. While powerful, most of the meta-heuristic algorithms

**Table 4**
Snapshot of approaches to power system enhancements.

| Approach | Objective | Methodology | Contribution |
|---|---|---|---|
| *Multi-Agent Systems* [83,100,131,140,141–150] | To deploy intelligent agents with the ability to communicate with each other as they complete their tasks subject to system-wide and local constraints on decision variables. | 1. Establish an autonomous network at local levels.2. Communicate and report to a higher agent based on network topology.3. Consider multiple faults at different locations and capture inter-agent interactions. | 1. Multi agent systems provide a platform for future development for full autonomy in the power grid. 2. Multi agents systems incorporate peer-to-peer connections with interchangable roles.3. Hedges against failures of power systems by offering the highest level of resilience. |
| *Centralized/ Decentralized Approach* [53,88,114,119,151–158] | To model a fault restoration system with either a centralized control subsystem responsible for data analysis, fault detection, restoration and optimization, or a distributed control scheme with subsystems capable of local control and peer-to-peer communication. | 1. Deploy supervisory control and data acquisition (SCADA) and a distribution management system (DMS) to extend control over the entire grid in a centralized approach.2. Set-up local monitoring devices at a microgrid stage and a second layer of devices to communicate with the entire network in a decentralized approach. | 1. Centralized approach is ideal for finding the best global solution with a robust security system and a relatively simple set of communication protocols.2. Decentralized approach offers a low cost ratio, reliability by eliminating a single point of failure, lower inertia for reconfiguration, and an ideal environment for penetration of distributed generation. |
| *AI/Machine Learning* [82,139,159–162] | To incorporate various machine-learning based programs that can identify patterns and go through training modules to form rules and understanding of the new architectures being explored in the current phase of research on self-healing grids. | 1. Design artificial intelligence algorithm based on machine learning, evolutionary learning, support vector methods or artificial neural networks. 2. Use a training data set with scenarios or a simulated environment for supervised learning of the artificial intelligence system. | 1. AI systems overcome the difficulty in realising fault diagnosis in distribution grids integration of DGs and introduction of smart meters caused by losses in data collection and little understanding of operation rules. 2. These systems constantly learn and correct prior probabilities of events in their calculation to better optimize power distribution. |
| *Meta-heuristic Algorithms* [58,86,112,129,163–165] | To apply meta-heuristic algorithms designed to solve multi-objective optimization problems using a set of rules based on expert knowledge for faster computation. | 1. Choose a meta-heuristic algorithm based on the various existing algorithms in the current field or research. 2. Modify these algorithms by incorporating expert knowledge to optimize their performance for power systems | By limiting the desired search area through expert knowledge and incoporating robust logic for multi-objective problems, meta-heuristic algorithms offer a more efficient way to reach an accurate solution. |
| *Graph Theory* [74,166,167] | To model the network topology using mathematical structures with edges and vertices. | 1. Map the current network topology with an appropriate graph theory based algorithm. 2. Utilize the mathematical structure to find the optimal configuration for a network that incorporates microgrids | 1. These approaches have the benefit of being able to leverage the knowledge from existing research done on graph theory. 2. These approaches provide a systematic way of tracking the changes in network configurations whilst calculating the performance of each of them. |

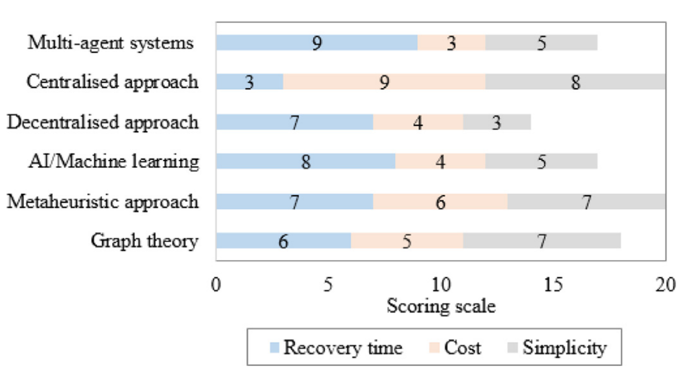


**Fig. 4.** Assessment of the approaches.

by themselves suffer inherent drawbacks such as poor or premature convergence or local trapping, as pointed out in [129].

Alternatively, power grids are often mapped as graphs, which are mathematical structures with vertices and edges, used to model relationships between two adjacent objects in a network topology, utilizing graph theory. Table 4 provides a summary of the objective, methodology and contribution of each of the approaches for power system enhancements.

Fig. 4 represents a performance evaluation matrix of the different approaches. The three metrics these approaches are scored on are (i) recovery time after a fault, (ii) cost of installation and maintenance, and (iii) simplicity of set up. The scores are decided by the consolidated analysis of the papers included in the review. A scale of 1–10, 10 being the highest an approach can score and 1 being the lowest, is used. It is important to note that these scores are qualitative comparative analysis of the individual approaches based on the authors evaluation of the analysis in the referenced papers.

**Other Approaches:** There are a few approaches that do not directly fall under the categories discussed above. One such strategy is put forward in [168] for self-healing of smart grids with individual optimization modules for generation - providing optimal generator start up sequence, transmission - identifying mentioned paths and energizing the transmission network and distribution - obtaining load pickup sequence. Yang et al. [169] solve the MINLP optimization problem using the Benders Decomposition algorithm to divide the problem into an ILP master problem and a LP sub-problem which is further solved by primal-dual interior point problem.

A new perspective is offered to limit the fault current with the help of a super-conducting fault current controller using the intrinsic properties of a superconductor [170]. The paper identifies the need to keep the fault current under control to protect the connected devices and enable corresponding control structures to carry out required restoration schemes. LoPorto [171] designs an automatic sectionalizing and restoration (ASR) scheme for Pepco Holdings Inc using distributed automation. The alarm management system proposed in [172] recognizes the issue of prioritizing alarms for individual events occurring during a self-healing cycle and creates an efficient framework for dealing with low level event patterns using complex event processing.

In addition, some fundamental criteria for power reestablishment after a fault are considered based on factors such as priority customer service, energy supplied, technical loses, voltage and loading limits with scales for each criterion and defined trade-offs. Trade-offs represent how much one criterion is more significant than another implemented through the analytical hierarchy process (AHP). A pairwise comparison between criteria can be obtained through a global value function and a mathematical multi-criterion evaluation can be used to determine the optimal restoration decision based on the scenario [166].

**Deduction 3** (Opportunities to address cascading failures)**.** Multi-agent systems overcome the issues individually faced by centralized or distributed systems, such as single point of failure, by placing an intelligent agent with specified roles and autonomy. However, the literature on the analysis and modeling of the communication between these agents is scarce. AI/ML based approaches are broadly used for fault identification in conjunction with IEDs and PMUs, essentially to bridge the gap left by lack of data pertaining to smart power system faults. Despite the preponderance of research on the development of meta-heuristic algorithms for solving the multi-objective problem in optimization or selection of appropriate corrective action, the gap still remains in incorporating system degradation while designing these approaches. A holistic self-healing scheme deploying a multi-agent system with AI-based fault detection and use of an improved meta-heuristic algorithm for the optimization problem can be designed to enhance self-healing.

## 6. Public polices for infrastructure resilience

Khodaei [173] defines resiliency as the ability of power systems to withstand low-probability high impact incidents in an efficient manner while ensuring the least interruptions in supply and quick service restoration. Self-healing systems are designed to ensure each aspect of this process is a resilient power grid. Further, a resilient smart grid or microgrid sectionalizes affected components of the grid to aid efficient restoration [83]. This necessitates long-term planning and cross departmental coordination, to facilitate design, planning and implementation of smart grid systems for power management and control [111]. The extant literature shows that the metrics for resilience varies widely including cost [174–179], recovery duration [177,179–183], operational resilience [18,184], distribution level quantification of resilience [185,186], and flexibility and adaptability [15].

It is imperative to note that the problem of enhancing infrastructure resilience is less about a lack of smart technology, but rather more about a lack of smart policy [187]. The urgency to have policymakers, such as Public Service Commissions, institute enactments to incentivize the private sector and the utility industry to make dynamic resilience-enhancing investments is critical prior to a disaster because such investments are dire in a disaster's aftermath. The absence of such policy prescriptions has been shown to discourage investment, and this investment hesitance is supported by prospect theory – private investors or industry-level decision makers have less incentives and wherewithal to make resilience investments subsequent to a disaster [188].

Consequently, resilience in any system does not result from sporadic or intermittent efforts but rather requires sustained investments [189]. Implementation of smart grid technologies is needed at a regional level in local development projects [190]. After every new disaster, the society is constantly reminded that there is an insufficiency of support for capacity building. Even though it has already been nearly eight years since a magnitude-9 earthquake unleashed a savage tsunami in northeastern Japan, the disaster's consequences are still evident today. For example, as of 2017, approximately a third of the 150,000 evacuees who lost their homes still live in temporary housing. While it's no surprise that the effects of the world's costliest disaster still linger, it's relevant to note that policymakers in Japan have upgraded the country's tsunami warning system [191].

However, there is no known effort to improve the resilience of the power system aside from earthquake engineers offering ways to build structures that are more resistant to quakes and tsunamis. On the one hand, rebuilding for resistance to quakes and tsunamis is vital, but it ignores the nuclear power plant issues that accompanied and exacerbated the disaster. On the other hand, shutting down the nuclear facilities requires building electricity technology portfolios that offer a higher level of resilience. In a similar vein, Hurricane Irma's impact on Florida in 2017 shed light on how rural communities served by municipally-owned utilities had prolonged power outages, further underlying the need for more knowledge on policy prescriptions for power restoration as a function of the socioeconomic vulnerabilities of communities [192,193].

The absence of robust policies to incentivize industry or private sector investment evidently impacts the risk management by decision makers at the firm level on their procedures and preparedness [194,195]. In terms of modeling specifics, agent-based simulation models- with the use of GIS data for spatial input information- have been developed for evacuation [196] and route assignment [197], [198], urban infrastructure resilience [189,199,200], and electricity network fortification [18,182,201–204], amongst others. However, very few of these models have considered the mechanism of retrofitting the system under study with adaptive investments or proffer potential policy alternatives as expected in the management of these complex interdependent systems [205]. The justification is further strengthened by the emergence of public-private partnerships in domains such as clean electricity initiatives. This is evident in how local governments and the private sector are already exploring means of working collaboratively to advance energy efficiency. For instance, (i) Kansas City, Missouri, is supporting Property Assessed Clean Energy (PACE) financing programs that are accelerating electric energy investments by residents and commercial building corporations [206]; (ii) there are on-going lessons gained from investor-owned utility Duke Energy's collaborations with city governments across North Carolina [207]; (iii) Tata power company and the Government of Delhi created a pilot project for preliminary study of advanced metering by installing smart meters at 500 residences in the city [208] and (iv) a five-year development plan has been established in China for compliance of energy related policies and strategies [209].

**Deduction 4** (The role of public-private partnerships)**.** System resilience implies enduring failure events by ensuring least interruption and most efficient restoration. By extension, the extant literature indicates that enhancing resilience is an issue requiring modernizing of conventional energy technologies and policies. Thus, there is a gap in understanding the incentives for the implementation of smart power systems for the private sector. This discourages investment in new, untested, technology in the energy sector. There is a lack of public policy to support retrofitting the current grid with intelligent systems that could offer smart power control systems. Research indicates that a shift to smarter, cleaner energy management would require sustained investments and governmental support rather than event-driven or sporadic attention. There are promising instances where public-private partnership has reinforced the potential of deploying smart self-healing systems in different parts of the world.

## 7. Disaster-induced economic-risk mitigation

One of the recent contributions to literature that argues coherently for an integrated approach to disaster resilience highlights the strategies for co-existing amongst natural hazards with the aid of an economic resilience index [210]. The fragility, survivability and recovery of a power grid in during such natural disasters can be measured using four resilience indices, derived using Monte Carlo Simulation methods [211]. However, narrowing the requisite approach into an index may provide a starting point for a more thorough discourse due to the complexity of interdependent systems. Because of the widespread diffusion of functional networks exposes the system to multi-source vulnerabilities and large-scale disruptions [175,212,213], the emerging field of resilience quantification requires metrics including absorptive, adaptive, and restorative capacities [176,214–216].

In fact, the dimensions of resilience have been placed into six different categories aptly tagged, "WEIGHT" [183]. Therefore, many studies that have explored methods to (i) improve economic resilience either with the aid of input-output or computable general equilibrium (CGE) models [181,188,217–222], or from the lens of microeconomics [188,216,223–227], or (ii) prioritize investments in resilience with the aid of multi-criteria decision analysis [228–231], or with models of sequential decision making [232] have all provided relatively useful guidance and outcomes. However, the absence of a dynamic and adaptive mechanism to reinforce the resilience-enhancing investments into the interconnected economic systems [177] translate much of the outcomes into isolated analysis on recovery or preparedness missing the resilience dimensions and categories. Thus, the extant literature captured by the approaches above and the complex adaptive system of systems approach are analogous to the results from a sensitivity analysis (single variable in isolation as seen in extant literature) *versus* a scenario analysis (multiple variables representing a combination of outcomes).

A few researchers have approached this investigation from the lens of a complex adaptive system theory [213,233], but at the exclusion of the policy or investment implications. To advance our knowledge over and above these studies would be an elaborate process that encompasses a truly complex systematic methodology with significant emphasis on the underlying electricity infrastructure. This would be in a process that offers guidance for dynamic inter-temporal investment allocation. One of the marginal shortcomings of some of the existing approaches is their focus on the intricate dependencies between the non-electric sectors of the economy at the expense of the electricity network. However, it is evident that failures to this critical enterprise system as already witnessed by recent disasters, such as Hurricanes Harvey, Irma, and Maria, mandates modeling dedication and extra attention without losing sight of the dependent economic sectors.

Natural disasters have the potential to cause serious damage to energy supply through single point fault or cascading failures leading to a full scale blackout, which in turn affects other interdependent systems such as industries, transportation and communications infrastructure [178,234,235]. The 8.8 Richter scale earthquake in 2010 in Chile that rocked the energy supply for a vast area [236] is another example demonstrating the importance of tackling such cascading failures at the earliest trigger. Identifying most probable failure modes, i.e. discovering weak links and generators working under the capacity [237]; capturing the progression of cascading faults using stochastic Markov model to derive transition probabilities [238]; studying line failures utilizing linear power-flow models [239]; analyzing inter-dependency between power and communication network through power-flow equations [240]; and geographically tracking line outages to prevent cascading failures [241] are a few approaches to be examined to tackle cascading failures in disaster-stricken electrical systems. Specifically, Abbey et al. [179] point out the scenario where fossil fuel transportation to island grids post-disaster is hindered, making the isolated electrical system unreliable and thus proposing the need for divesting into distributed generation to relieve the load from fossil fuel based generation [242,243].

## 8. Major challenges

The advent of smart power grids, complex power control modules, and increased penetration of distributed energy resources bring along a series of challenges which can individually derail the hopes to complete the implementation of such projects and hinder their ability to benefit the existing power infrastructure. Moreover, these challenges are multifaceted and range from technical to political to social sources as described in Table 5.

The negative perception amongst stakeholders [73], hesitance towards participation by customers [92], and fear of failure are some of the social challenges that need to be tackled while introducing a novel project to the society. Zidan et al. [53] mention the realistic short-term scenario where FDIR actions are performed through human operation and the concerns that it involves, such as unreliable performance and increased time delays. They also go on to elucidate the significance of smart grid development to be a gradual and planned process, integrating policy changes for each stage of the process. Pilot projects with advanced metering, increased communications components, and control components will have high initial costs, with negligible validation [64,73].

Various technical challenges are recognized by authors either specific to their approach or generally applicable to all self-healing systems. At the forefront of these is the introduction of uncertainty in incorporating renewable energy sources and the additional computation that goes behind adequately predicting their supply [53,60,81,133,244]. Also, with varying load and microgrid structure, bi-directional power flow necessitates monitoring of power flow direction and development of new components that can handle the dynamic structure. Distributed generation and microgrids bring along a host of new issues like no inertial support during transient events and voltage instabilities due to islanded microgrids [82]. Performance evaluation of self-healing systems will require the need to establish a new initial baseline of existing components and measurements of impact for each new component against the baseline [64]. Tight coupling amongst components of a smart rid also increases the risk of cascading failures leading to a full scale blackout [133,245]. Courtesy of increased dependency on cyber networks and crucial role played by data, there is an increased threat of a cyber attack and invasion of privacy in introducing self-healing systems [73,246]. A few examples of cyber attacks in SCADA are mentioned in [76], such as SQL injection attacks, denial of service attacks, identity spoofing, eavesdropping or replay attack and spyware.

## 9. Discussion

Research has been conducted on various approaches undertaking the task of identifying failures or restoring the power system after a certain type of failure which increase the system's robustness and resilience. Although, while these schemes add value through their inherent self-healing properties, such properties are limited by their optimal deployment strategies. Further, inclusion of system deterioration as a metric to understand the systems vulnerabilities is a critical task in planning the restoration scheme. Moreover, with the increase in interdependence within systems, these approaches cannot just be designed through conventional engineering design methodologies of pre-selecting variables and maximizing performance while lowering costs. A scarce amount of research solves such problem by replicating biological processes in plants, morphogenesis for example, to structure the response of a power grid in the event of a failure, ultimately reducing system redundancies and consequently keeping the cost constraints in check. To note, the level of integration in a complex adaptive system with a focus on interdependence, local or decentralized decision making, and managing the policies and markets, are yet to be examined.

Fig. 5 shows how each of the sections in the paper influence the others. At the centre is the concept of self-healing systems, and the diagram largely reflects how the each of these sections have a contribution in defining it. The arrows depict direction of influence and the relations shown are based on the extensive research conducted in the paper.

The incorporation of a components discussed in Section 5 would form an ideal self-healing grid, with real time monitoring, central or distributed adaptive energy management system and control, information and communications network and flexible power grid structure capable of reconfiguration. The most fundamental distinction between self-healing grids and traditional power grids is the introduction of two-way power and information flow due to the introduction of microgrids and advanced data acquisition components. Microgrids also introduce islanding capabilities in a grid, to isolate the faulted area and ensure uninterrupted power supply to highest number of customers. Papers have proposed power-sharing and negotiations between networked microgrids and the main grid, enabled by DGs capable of generating extra

**Table 5**
Synthesis of challenges and gaps.

| Type of challenge | Impact of research gap |
|---|---|
| *Technical Challenge:* System interdependence | Restoration schemes are being designed through conventional methodologies without taking the interdependencies of the system into consideration. This highlights the gaps on replicating self-healing in biological processes. |
| *Technical Challenge:* Implementation | Efforts to achieve coupling between grid components also increase the risk of cascading failures leading to a full-scale blackout. This shows the gaps in AI/Machine learning designs. |
| *Social Challenge* | This manifests in the negative perception amongst stakeholders and hesitance towards participation by customers to emerging technologies. The gaps are inherent in the limited understanding of the incentives for private sector investments. |
| *Political Challenge* | There is significant reluctance for investments in new carbon-free technology in the energy sector also worsened by the absence or inconsistency in policy interventions for pre-disaster recovery plans. The gap here is knowing the impact of policies on decentralized or local decision making. |

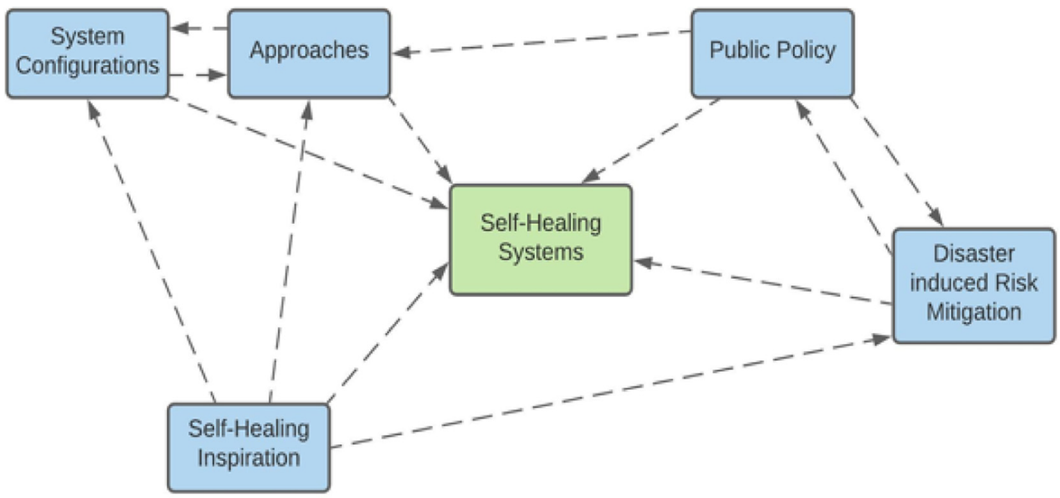


**Fig. 5.** Integration of the review elements.

power; however, there is lack of research in prioritizing critical load. Self-healing schemes incorporating DGs need to account for the fault-current increase they cause and the continued supply to faulted region post islanding operation, rather than the obvious influx of uncertainty in the power flow equations. Some authors have also discussed the customer-side participation in power distribution. The real time monitoring is enhanced by establishing a wide area measurement system and optimal placement of PMUs at strategic points.

Multi-agent systems overcome the issues individually faced by centralized and distributed approaches, like single point of failure or inability to find the best global solution, by placing intelligent agent with option of specified roles at the local level with a pre-defined level of autonomy. Literature on the analysis and modeling of the communication between these agents is scarce. AI/ML based approaches are broadly used for fault identification in conjunction with IEDs and PMUs, essentially to bridge the gap left by lack of data pertaining to smart power system faults. These schemes use teaching modules to train the controller to detect either faults or fault signatures in advance to facilitate faster corrective action.

There is a substantial amount of research on development of meta-heuristic algorithms for solving the multi-objective problem for optimization or selection of appropriate corrective action, leveraging their benefit expert knowledge to reduce search area for the optimal solution. As mentioned earlier, there is a vast gap in the research towards incorporating system degradation while designing these approaches and most of the papers design or validate their designs based on single faults or predetermine number of faults. Despite research efforts aimed at addressing cascading failures, the society still experiences extreme events such as complete blackouts that are prolonged and expensive. A holistic self-healing scheme deploying a multi-agent system with AI based fault detection and use of an improved meta-heuristic algorithm for the optimization problem can be designed to handle the entire process of power system self-healing and restoration.

System resilience is aptly defined as its ability to endure failure events, while ensuring least interruption and most efficient restoration practices. However research has indicated that enhancing resilience is an issue that requires the modernizing of conventional energy policies as well. Most importantly, there is a gap in policy to incentivize the development and implementation of smart power systems for private sector companies, further discouraging any investment in new untested technology in the energy sector. There is a lack of public policy for the management of retrofitting intelligent systems on the current grid, which would offer the most immediate solution to implement smart power control systems. It is appropriately indicated in research that a shift to smarter, cleaner energy management would require a sustained investments and governmental support rather than event driven and sporadic surges of interest [247,248]. There are though a few instances where a public-private partnership has reinforced the potential of deploying smart self-healing systems in different parts of the world.

The left panel of Fig. 6 is a heat map illustrating the cumulative development and the right panel shows the year-wise trends of research in the four facets of power system enhancements using adaptive systems as extracted from the reviewed papers. They reveal the lack of approaches that translate self-healing schemes to enhancement or quantification of system resilience. Evidently, a lot has been done on system reliability as well as fault detection and the effects of disasters. We observe the increasing trend of interest in self-healing systems in the first half of the decade with improvement in system reliability. The heat map results in a few key open-ended questions that the research community should aim to answer: To what quantifiable extent do self-healing schemes relay to improvements in system resilience? How do the developments in studying failures and disasters correlate with improvements in resilience? How are system reliability and system resilience associated?

| Cumulative | Self-healing | Failures, disasters, cascading | Resilience, resurrection | Reliability |
|---|---|---|---|---|
| 2010 | 8 | 10 | 8 | 9 |
| 2011 | 24 | 27 | 17 | 31 |
| 2012 | 44 | 44 | 23 | 48 |
| 2013 | 62 | 54 | 28 | 66 |
| 2014 | 90 | 78 | 33 | 102 |
| 2015 | 108 | 92 | 43 | 117 |
| 2016 | 135 | 118 | 57 | 148 |
| 2017 | 152 | 137 | 64 | 175 |
| 2018 | 174 | 156 | 84 | 204 |
| 2019 | 185 | 166 | 91 | 212 |

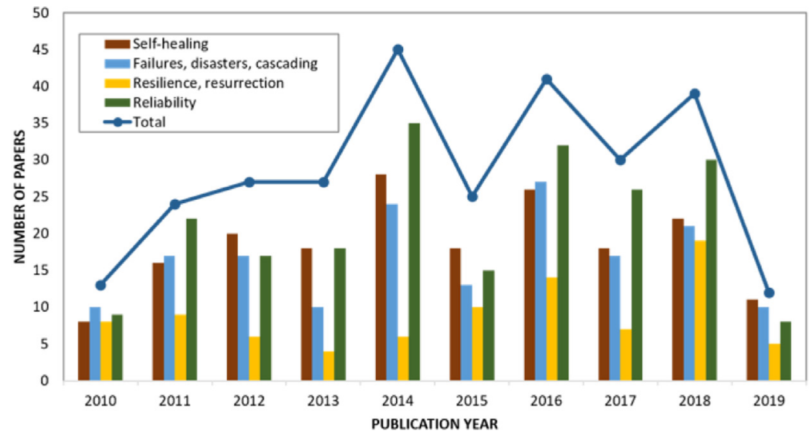


**Fig. 6.** Research areas by cumulative development (left panel) and by yearly trends (right panel).

This review essentially points out the absence of definitive answers to these questions, and suggests a direction for future work in the field of self-healing in power systems.

## 10. Conclusion

The evidence of gaps in research is significant in the context of self-healing or self-restoration schemes in power systems. This paper highlights crucial considerations for such self-healing systems with identified opportunities to limit the inherent cascading failures in the advent of a disruption. The influence of public-private partnerships are prerequisites for investment allocation. In summary, this paper offers value by shedding lights on four thematic extractions from the literature.

First, it provides a policy framework that will incentivize non-governmental actors such as the private sector and utilities to make investments into electricity network resilience and disaster risk-mitigation and preparedness. Second, the meta-analysis offers an integrated modeling environment that will make the investments above to be adaptive and across the economic sectors. This will prevent the often-isolated approaches that have marginally improved decision making because the proposed models, due to their integration, will encompass a truly complex system of systems methodology. Third, the prescription for detailing a proposed multidisciplinary or hybrid modeling approach includes the inherent self-healing that subsumes the development and application of the integrated models. This holds the potential to radically improve system performance and enhance resilience especially when the state of infrastructural decay is used as a metric of environmental/operational stimuli in the self-healing process or as a measure of the system's vulnerability. The fourth highlight is that it is imperative to offer a recovery or restoration timeline that is optimal. Such recovery timelines would have a drastic reduction in economic losses in a process that involves the stability of the power network, and will be consistent with outcomes due to sustained investments.

There were challenges while curating the sources for this study. The first challenge was eliminating the bias in selecting the relevant journal papers. Initially, papers related to cascading and disasters were majorly downloaded prior to collating papers related to bio-inspired or self-healing in power networks. Second, certain papers are more tightly related as they were generated by from a correlation of references, looking into the "related articles" and carefully studying them. This was done to make the approach more systematic. The search was also performed in a manner to help prevent the search engine from producing outcomes relevant to previously accessed material, and limit the influence of other factors. Lastly, papers recently published, 2010–2019, were selected in comparison to more dated literature in order to make sure the study is based on emerging trends.

## Declaration of Competing Interest

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

## CRediT authorship contribution statement

**Ekundayo Shittu:** Conceptualization, Methodology, Data curation, Resources, Funding acquisition, Visualization, Writing - original draft, Writing - review & editing, Supervision. **Abhijai Tibrewala:** Data curation, Visualization, Writing - original draft. **Swetha Kalla:** Writing - original draft. **Xiaonan Wang:** Writing - review & editing.

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## References

[1] Yan J. Energy systems in transition: challenges and opportunities. Adv Appl Energy 2020.
[2] Traywick C, Chediak M, Malik NS, Saul J. The two hours that nearly destroyed texas's electric grid. Bloomberg Green 2021. Https://www.bloomberg.com/news/features/2021-02-20/texas-blackout-how-the-electrical-grid-failed.
[3] Heffron RJ, Körner M-F, Schöpf M, Wagner J, Weibelzahl M. The role of flexibility in the light of the COVID-19 pandemic and beyond: contributing to a sustainable and resilient energy future in europe. Renewable Sustainable Energy Rev 2021;140:110743.
[4] Jiang P, Van Fan Y, Klemeš JJ. Impacts of COVID-19 on energy demand and consumption: challenges, lessons and emerging opportunities. Appl Energy 2021:116441.
[5] Feng B, van Dam KH, Guo M, Shah N, Passmore S, Wang X. Planning of food-energy-water-waste (FEW2) nexus for sustainable development. BMC Chem Eng 2020;2(1):1–19.
[6] Wang X, van Dam KH, Triantafyllidis C, Koppelaar RH, Shah N. Energy-water nexus design and operation towards the sustainable development goals. Comput Chem Eng 2019;124:162–71.
[7] Wang X, Guo M, Koppelaar RH, van Dam KH, Triantafyllidis CP, Shah N. A nexus approach for sustainable urban energy-water-waste systems planning and operation. EnvironSci. Technol 2018;52(5):3257–66.
[8] Bieber N, Ker JH, Wang X, Triantafyllidis C, van Dam KH, Koppelaar RH, Shah N. Sustainable planning of the energy-water-food nexus using decision making tools. Energy Policy 2018;113:584–607.
[9] Barra P, Coury DV, Fernandes R. A survey on adaptive protection of microgrids and distribution systems with distributed generators. Renewable Sustainable Energy Rev 2020;118:109524.
[10] Van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. Scientometrics 2010;84(2):523–38.
[11] Brown MA. Building resilient communities before and after the hurricanes. In: Transforming disaster response. Routledge; 2018. p. 128–63.

[12] Inserra D, Bogie J, Katz D, Furth S, Burke M, Tubb K, et al. After the storms: lessons from hurricane response and recovery in 2017. Heritage Foundation; 2018.
[13] Bukhsh WA, Bell K, Bedford T. Risk and reliability assessment of future power systems. In: European safety and reliability conference 2016; 2016.
[14] Gardner MT, Cheng Y, May R, Beard C, Sterbenz J, Medhi D. Creating network resilience against disasters using service level agreements. In: 2016 12th International conference on the design of reliable communication networks (DRCN). IEEE; 2016. p. 62–70.
[15] Nowell B, Bodkin CP, Bayoumi D. Redundancy as a strategy in disaster response systems: a pathway to resilience or a recipe for disaster? J Conting Crisis Manage 2017;25(3):123–35.
[16] Che L, Shahidehpour M. Adaptive formation of microgrids with mobile emergency resources for critical service restoration in extreme conditions. IEEE Trans Power Syst 2018;34(1):742–53.
[17] Gholami A, Aminifar F, Shahidehpour M. Front lines against the darkness: enhancing the resilience of the electricity grid through microgrid facilities. IEEE Electrif Mag 2016;4(1):18–24.
[18] Wang Y, Chen C, Wang J, Baldick R. Research on resilience of power systems under natural disasters–a review. IEEE Trans Power Syst 2015;31(2):1604–13.
[19] Yuan W, Wang J, Qiu F, Chen C, Kang C, Zeng B. Robust optimization-based resilient distribution network planning against natural disasters. IEEE Trans Smart Grid 2016;7(6):2817–26.
[20] Chen C, Wang J, Qiu F, Zhao D. Resilient distribution system by microgrids formation after natural disasters. IEEE Trans Smart Grid 2015;7(2):958–66.
[21] Kim J, Dvorkin Y. Enhancing distribution system resilience with mobile energy storage and microgrids. IEEE Trans Smart Grid 2018;10(5):4996–5006.
[22] Ding T, Lin Y, Li G, Bie Z. A new model for resilient distribution systems by microgrids formation. IEEE Trans Power Syst 2017;32(5):4145–7.
[23] Gao H, Chen Y, Xu Y, Liu C-C. Resilience-oriented critical load restoration using microgrids in distribution systems. IEEE Trans Smart Grid 2016;7(6):2837–48.
[24] Li B, Roche R, Miraoui A. A temporal-spatial natural disaster model for power system resilience improvement using DG and lines hardening. In: 2017 IEEE Manchester PowerTech. IEEE; 2017. p. 1–6.
[25] Eskandarpour R, Edwards G, Khodaei A. Resilience-constrained unit commitment considering the impact of microgrids. In: 2016 North American power symposium(NAPS). IEEE; 2016. p. 1–5.
[26] Maharjan S, Zhang Y, Gjessing S, Ulleberg O, Eliassen F. Providing microgrid resilience during emergencies using distributed energy resources. In: 2015 IEEE globecom workshops (GC Wkshps). IEEE; 2015. p. 1–6.
[27] Lei S, Wang J, Chen C, Hou Y. Mobile emergency generator pre-positioning and real-time allocation for resilient response to natural disasters. IEEE Trans Smart Grid 2016;9(3):2030–41.
[28] Sedzro KSA, Lamadrid AJ, Zuluaga LF. Allocation of resources using a microgrid formation approach for resilient electric grids. IEEE Trans Power Syst 2017;33(3):2633–43.
[29] Wood P, Shiltz D, Nudell TR, Hussain A, Annaswamy AM. A framework for evaluating the resilience of dynamic real-time market mechanisms. IEEE Trans Smart Grid 2016;7(6):2904–12.
[30] Chen J, Zhu Q. A game-theoretic framework for resilient and distributed generation control of renewable energies in microgrids. IEEE Trans Smart Grid 2016;8(1):285–95.
[31] Du Y, Wang Z, Liu G, Chen X, Yuan H, Wei Y, et al. A cooperative game approach for coordinating multi-microgrid operation within distribution systems. Appl Energy 2018;222:383–95.
[32] Hamilton MC, Lambert JH, Connelly EB, Barker K. Resilience analytics with disruption of preferences and lifecycle cost analysis for energy microgrids. Reliab Eng Syst Saf 2016;150:11–21.
[33] Hazelrigg GA. Systems engineering: an approach to information-based design. Pearson College Division; 1996.
[34] Cavalcante PL, Lopez JC, Franco JF, Rider MJ, Garcia AV, Malveira MRR, et al. Centralized self-healing scheme for electrical distribution systems. IEEE Trans Smart Grid 2015;7(1):145–55.
[35] Eriksson M, Armendariz M, Vasilenko OO, Saleem A, Nordström L. Multiagent-based distribution automation solution for self-healing grids. IEEE Trans Ind Electron 2014;62(4):2620–8.
[36] Lin Z, Wen F, Xue Y. A restorative self-healing algorithm for transmission systems based on complex network theory. IEEE Trans Smart Grid 2016;7(4):2154–62.
[37] Quattrociocchi W, Caldarelli G, Scala A. Self-healing networks: redundancy and structure. PLoS ONE 2014;9(2):e87986.
[38] Heisenberg C-P, Bellaïche Y. Forces in tissue morphogenesis and patterning. Cell 2013;153(5):948–62.
[39] George S, Evans D, Davidson L. A biologically inspired programming model for self-healing systems. In: Proceedings of the first workshop on Self-healing systems; 2002. p. 102–4.
[40] Thom R. Structural stability and morphogenesis. CRC Press; 2018.
[41] Kulchin YN, Nakonechnaya OV, Gafitskaya IV, Grishchenko OV, Epifanova TY, Orlovskaya IY, Zhuravlev YN, Subbotin EP. Plant morphogenesis under different light intensity. In: Defect and diffusion forum, vol. 386. Trans Tech Publ; 2018. p. 201–6.
[42] Zahadat P. Self-adaptation and self-healing behaviors via a dynamic distribution process. In: 2019 IEEE 4th international workshops on foundations and applications of self* systems (FAS* W). IEEE; 2019. p. 261–2.
[43] DeLuque I, Shittu E. Generation capacity expansion under demand, capacity factor and environmental policy uncertainties. Comput Ind Eng 2019;127:601–13.
[44] Farzaneh A.. Computational morphogenesis of architectural objects2012;.
[45] Brown TJ, Glass RJ, Beyeler WE, Ames AL, Linebarger JM, Maffitt SL. Complex adaptive system of systems (CASos) engineering applications version 1.0; 2011. Sandia National Laboratories SAND report (in review)(website summary: http://www sandia gov/CasosEngineering/applications html).
[46] Johnson B, Hernandez A. Exploring engineered complex adaptive systems of systems. Procedia Comput Sci 2016;95:58–65.
[47] Bar-Yam Y, Allison MA, Batdorf R, Chen H, Generazio H, Singh H, et al. The characteristics and emerging behaviors of system of systems. In: NECSI: complex physical, biological and social systems project; 2004. p. 1–16.
[48] Diesendruck CE, Sottos NR, Moore JS, White SR. Biomimetic self-healing. Angew Chem Int Ed 2015;54(36):10428–47.
[49] Guimard NK, Oehlenschlaeger KK, Zhou J, Hilf S, Schmidt FG, Barner-Kowollik C. Current trends in the field of self-healing materials. Macromol Chem Phys 2012;213(2):131–43.
[50] Aïssa B, Therriault D, Haddad E, Jamroz W. Self-healing materials systems: overview of major approaches and recent developed technologies. Adv Mater Sci Eng 2012;2012.
[51] Yang Y, Urban MW. Self-healing polymeric materials. Chem Soc Rev 2013;42(17):7446–67.
[52] Mauldin TC, Kessler MR. Self-healing polymers and composites. Int Mater Rev 2010;55(6):317–46.
[53] Zidan A, Khairalla M, Abdrabou AM, Khalifa T, Shaban K, Abdrabou A, et al. Fault detection, isolation, and service restoration in distribution systems: state-of-the-art and future trends. IEEE Trans Smart Grid 2016;8(5):2170–85.
[54] Shahin MA. Smart grid self-healing implementation for underground distribution networks. In: 2013 IEEE innovative smart grid technologies-Asia (ISGT Asia). IEEE; 2013. p. 1–5.
[55] Antunes FAS, Ribeiro PF, Silveira PM. Considerations on self-healing and assisted-healing for power transmission systems in operation centers. In: 2015 IEEE power & energy society general meeting. IEEE; 2015. p. 1–5.
[56] Barati M. Self-healing in microgrid operation and message-passing based demand response. Illinois Institute of Technology; 2013.
[57] Taifeng K, Liang G, Zhihai T, Fengqing Z, Xuzhu D. Investigation on technology framework and key technologies for self-healing smart distribution system. In: Proceedings 2013 international conference on mechatronic sciences, electric engineering and computer (MEC). IEEE; 2013. p. 3240–3.
[58] Liu L, Zhao X. Study on self-healing control strategy of smart distribution network. In: IEEE PES innovative smart grid technologies. IEEE; 2012. p. 1–3.
[59] Li T, Xu B. The self-healing technologies of smart distribution grid. In: CICED 2010 Proceedings. IEEE; 2010. p. 1–6.
[60] Refaat SS, Mohamed A, Kakosimos P. Self-healing control strategy; challenges and opportunities for distribution systems in smart grid. In: 2018 IEEE 12th International conference on compatibility, power electronics and power engineering (CPE-POWERENG 2018). IEEE; 2018. p. 1–6.
[61] Xiao-hui X, Chang-guo Z, Li-juan C, Dong-lei C, Yong-biao Y. Research on smart distribution network system architecture. In: IEEE PES innovative smart grid technologies. IEEE; 2012. p. 1–4.
[62] Elgenedy MA, Massoud AM, Ahmed S. Smart grid self-healing: Functions, applications, and developments. In: 2015 First workshop on smart grid and renewable energy (SGRE). IEEE; 2015. p. 1–6.
[63] Jia D, Meng X, Song X. Study on technology system of self-healing control in smart distribution grid. In: 2011 International conference on advanced power system automation and protection, vol. 1. IEEE; 2011. p. 26–30.
[64] Anderson RN, Boulanger A, Powell WB, Scott W. Adaptive stochastic control for the smart grid. Proc IEEE 2011;99(6):1098–115.
[65] Xu L, Wan Q. Application significance of electronic transformers for smart grid. In: CICED 2010 Proceedings. IEEE; 2010. p. 1–9.
[66] EPRI US. Methodological approach for estimating the benefits and costs of smart grid demonstration projects. US EPRI: Palo Alto, CA, USA; 2010.
[67] Gao X, Ai X. The application of self-healing technology in smart grid. In: 2011 Asia-pacific power and energy engineering conference. IEEE; 2011. p. 1–4.
[68] Pourahmadi F, Hosseini SH, Dehghanian P, Shittu E, Fotuhi-Firuzabad M. Uncertainty cost of stochastic producers: metrics and impacts on power grid flexibility. IEEE Trans Eng Manage 2020.
[69] Shahnia F, Chandrasena RPS, Rajakaruna S, Ghosh A. Autonomous operation of multiple interconnected microgrids with self-healing capability. In: 2013 IEEE power & energy society general meeting. IEEE; 2013. p. 1–5.
[70] Fu Y, Xuan Z, Jinguo D, Chao Q, Rongfei Q. Research and application of distribution grid self-healing based on distribution automation. In: 2014 China international conference on electricity distribution (CICED). IEEE; 2014. p. 1211–14.
[71] Shahnia F, Chandrasena RPS, Rajakaruna S, Ghosh A. Primary control level of parallel distributed energy resources converters in system of multiple interconnected autonomous microgrids within self-healing networks. IET Gener Transm Distrib 2014;8(2):203–22.
[72] Biabani M, Golkar MA, Kasiry AHZ, Akbari M. Smart grid in iran: Driving factors, evolution, challenges and possible solutions. In: 2011 10th International Conference on Environment and Electrical Engineering. IEEE; 2011. p. 1–4.
[73] El-Hawary ME. The smart grid–state-of-the-art and future trends. Electr Power Compon Syst 2014;42(3–4):239–50.
[74] Qiang X, Haibin G, Xugang F, Zhenzhi C. Research on self-healing strategy of smart distribution grid based on improved ant colony algorithm. In: 2016 Chinese control and decision conference (CCDC). IEEE; 2016. p. 390–5.
[75] Amin M. A smart self-healing grid: in pursuit of a more reliable and resilient system [in my view]. IEEE Power Energy Mag 2013;12(1). 112–110.
[76] Shitharth S, Winston DP. A novel IDS technique to detect DDos and sniffers in smart grid. In: 2016 World conference on futuristic trends in research and innovation for social welfare (startup conclave). IEEE; 2016. p. 1–6.

[77] Awad ASA, El-Fouly THM, Salama MMA. Optimal distributed generation allocation and load shedding for improving distribution system reliability. Electr Power Compon Syst 2014;42(6):576–84.
[78] Kwasinski A. Implication of smart-grids development for communication systems in normal operation and during disasters. In: Intelec 2010. IEEE; 2010. p. 1–8.
[79] Mukhopadhyay S, Soonee SK, Joshi R. Plant operation and control within smart grid concept: Indian approach. In: 2011 IEEE power and energy society general meeting. IEEE; 2011. p. 1–4.
[80] Yazdanian M, Mehrizi-Sani A. Distributed control techniques in microgrids. IEEE Trans Smart Grid 2014;5(6):2901–9.
[81] Moslehi K, Kumar R. Smart grid-a reliability perspective. In: 2010 Innovative smart grid technologies (ISGT). IEEE; 2010. p. 1–8.
[82] Gopakumar P, Reddy MJB, Mohanta DK. Stability control of smart power grids with artificial intelligence and wide-area synchrophasor measurements. Electr Power Compon Syst 2014;42(10):1095–106.
[83] Dehghanpour K, Colson C, Nehrir H. A survey on smart agent-based microgrids for resilient/self-healing grids. Energies 2017;10(5):620.
[84] Oualmakran Y, Melendez J, Herraiz S. Self-healing for smart grids: Problem formulation and considerations. In: 2012 3rd IEEE PES innovative smart grid technologies Europe (ISGT Europe). IEEE; 2012. p. 1–6.
[85] Koutsoumpas V, Gupta PK. Towards a constraint based approach for self-healing smart grids. In: 2013 2nd International workshop on software engineering challenges for the smart grid (SE4SG). IEEE; 2013. p. 17–24.
[86] Arefifar SA, Mohamed YA-RI, El-Fouly THM. Comprehensive operational planning framework for self-healing control actions in smart distribution grids. IEEE Trans Power Syst 2013;28(4):4192–200.
[87] Mohammadi-Hosseininejad SM, Fereidunian A, Shahsavari A, Lesani H. A healer reinforcement approach to self-healing in smart grid by PHEVs parking lot allocation. IEEE Trans Ind Inf 2016;12(6):2020–30.
[88] Ng CH, Logenthiran T, Woo WL. Intelligent distributed smart grid network–reconfiguration. In: 2015 IEEE innovative smart grid technologies-asia (ISGT ASIA). IEEE; 2015. p. 1–6.
[89] Chandraratne C, Naayagi RT, Logenthiran T. Smart grid protection through self--healing. In: 2017 IEEE innovative smart grid technologies-asia (ISGT-Asia). IEEE; 2017. p. 1–6.
[90] Wojszczyk B. Deployment of advanced smart grid solutions-global examples & lessons learned. 2012 IEEE PES innovative smart grid technologies (ISGT). IEEE; 2012. 1–1.
[91] Li J, He Z, Bao L, Wang Y, Du L. Condition monitoring of high voltage equipment in smart grid. In: 2012 International conference on high voltage engineering and application. IEEE; 2012. p. 608–12.
[92] Liao Y, Turner M, Du Y. Development of a smart grid roadmap for kentucky. Electr Power Compon Syst 2014;42(3–4):267–79.
[93] Wojszczyk B. Progress in smart grid deployments global examples & lessons learned. 2012 IEEE power and energy society general meeting. IEEE; 2012. 1–1.
[94] Saha Roy BK, Sharma R, Pradhan AK, Sinha AK. Faulty line identification algorithm for secured backup protection using PMUs. Electr Power Compon Syst 2017;45(5):491–504.
[95] Abo-Al-Ez KM, Elaiw A, Xia X. A dual-loop model predictive voltage control/sliding-mode current control for voltage source inverter operation in smart microgrids. Electr Power Compon Syst 2014;42(3–4):348–60.
[96] Gracceva F, Zeniewski P. A systemic approach to assessing energy security in a low-carbon EU energy system. Appl Energy 2014;123:335–48.
[97] Li J, Ma X-Y, Liu C-C, Schneider KP. Distribution system restoration with microgrids using spanning tree search. IEEE Trans Power Syst 2014;29(6):3021–9.
[98] Bui DM, Lien K-Y, Chen S-L, Cheng X-Y, Lin M-S. Standards commonly used for microgrids–a research project to develop an industry microgrid standard in taiwan. ElectrPower ComponSyst 2016;44(19):2143–60.
[99] Oliveira DQ, de Souza ACZ, Almeida AB, Santos MV, Lopes B, Marujo D. Microgrid management in emergency scenarios for smart electrical energy usage. In: 2015 IEEE Eindhoven PowerTech. IEEE; 2015. p. 1–6.
[100] Sujil A, Kumar R, Bansal RC. Multiagent-based autonomous energy management system with self-healing capabilities for a microgrid. IEEE Trans Ind Inf 2018;15(12):6280–90.
[101] Strbac G, Hatziargyriou N, Lopes JP, Moreira C, Dimeas A, Papadaskalopoulos D. Microgrids: enhancing the resilience of the european megagrid. IEEE Power Energy Mag 2015;13(3):35–43.
[102] Pashajavid E, Shahnia F, Ghosh A. Development of a self-healing strategy to enhance the overloading resilience of islanded microgrids. IEEE Trans Smart Grid 2015;8(2):868–80.
[103] Zadsar M, Haghifam MR, Larimi SMM. Approach for self-healing resilient operation of active distribution network with microgrid. IET Gener Transm Distrib 2017;11(18):4633–43.
[104] Kumar YVP, Bhimasingu R. Enabling self-healing microgrids by the improvement of resiliency using closed loop virtual dc motor and induction generator control scheme. In: 2016 IEEE power and energy society general meeting (PESGM). IEEE; 2016. p. 1–5.
[105] Hartono BS, Setiabudy R, et al. Review of microgrid technology. In: 2013 international conference on QiR. IEEE; 2013. p. 127–32.
[106] Lasseter RH. Smart distribution: coupled microgrids. Proc IEEE 2011;99(6):1074–82.
[107] Vine D, Attanasio D, Shittu E. Microgrid momentum: building efficient, resilient power. Center for Climate and Energy Solutions; 2017.
[108] Zhu T, Huang Z, Sharma A, Su J, Irwin D, Mishra A, et al. Sharing renewable energy in smart microgrids. In: 2013 ACM/IEEE international conference on cyber-physical systems (ICCPS). IEEE; 2013. p. 219–28.
[109] Khederzadeh M, Maleki H. Frequency control of microgrids in autonomous mode by a novel control scheme based on droop characteristics. Electr Power Compon Syst 2013;41(1):16–30.
[110] Wang Y, Mao S, Nelms RM. Optimal hierarchical power scheduling for cooperative microgrids. In: 2014 IEEE 11th international conference on mobile ad hoc and sensor systems; 2014. p. 497–8.
[111] Dehghanpour K, Nehrir H. A market-based resilient power management technique for distribution systems with multiple microgrids using a multi-agent system approach. Electr Power Compon Syst 2018;46(16–17):1744–55.
[112] Meenakshi N, Kavitha D. Optimized self-healing of networked microgrids using differential evolution algorithm. In: 2018 National power engineering conference (NPEC). IEEE; 2018. p. 1–7.
[113] Ahmadi SE, Rezaei N. Reliability-oriented optimal scheduling of self-healing in multi-microgrids. In: 2018 Smart grid conference (SGC). IEEE; 2018. p. 1–6.
[114] Pashajavid E, Shahnia F, Ghosh A. Overloading conditions management in remote networks by coupling neighboring microgrids. In: 2015 50th International universities power engineering conference (UPEC). IEEE; 2015. p. 1–6.
[115] Deluque I, Shittu E, Deason J. Evaluating the reliability of efficient energy technology portfolios. EURO J Decis Process 2018;6(1–2):115–38.
[116] Jiang Q, Xue M, Geng G. Energy management of microgrid in grid-connected and stand-alone modes. IEEE Trans Power Syst 2013;28(3):3380–9.
[117] Zhang Y, Gatsis N, Giannakis GB. Robust energy management for microgrids with high-penetration renewables. IEEE Trans Sustainable Energy 2013;4(4):944–53.
[118] Shi W, Xie X, Chu C-C, Gadh R. Distributed optimal energy management in microgrids. IEEE Trans Smart Grid 2014;6(3):1137–46.
[119] Wang Z, Chen B, Wang J, Chen C. Networked microgrids for self-healing power systems. IEEE Trans Smart Grid 2015;7(1):310–19.
[120] Olivares DE, Cañizares CA, Kazerani M. A centralized optimal energy management system for microgrids. In: 2011 IEEE power and energy society general meeting. IEEE; 2011. p. 1–6.
[121] Su W, Wang J, Roh J. Stochastic energy scheduling in microgrids with intermittent renewable energy resources. IEEE Trans Smart Grid 2013;5(4):1876–83.
[122] Shi W, Li N, Chu C-C, Gadh R. Real-time energy management in microgrids. IEEE Trans Smart Grid 2015;8(1):228–38.
[123] Wang Z, Chen B, Wang J, Begovic MM, Chen C. Coordinated energy management of networked microgrids in distribution systems. IEEE Trans Smart Grid 2014;6(1):45–53.
[124] Huang Y, Mao S, Nelms RM. Adaptive electricity scheduling in microgrids. IEEE Trans Smart Grid 2014;5(1):270–81.
[125] Atia R, Yamada N. Sizing and analysis of renewable energy and battery systems in residential microgrids. IEEE Trans Smart Grid 2016;7(3):1204–13.
[126] Chen SX, Gooi HB, Wang M. Sizing of energy storage for microgrids. IEEE Trans Smart Grid 2011;3(1):142–51.
[127] Guan X, Xu Z, Jia Q-S. Energy-efficient buildings facilitated by microgrid. IEEE Trans Smart Grid 2010;1(3):243–52.
[128] Deane JP, Ciaráin MO, Gallachóir BPO. An integrated gas and electricity model of the EU energy system to examine supply interruptions. Appl Energy 2017;193:479–90.
[129] Kanwar N, Gupta N, Niazi KR, Swarnkar A. Optimal allocation of distributed energy resources using improved meta-heuristic techniques. Electr Power Compon Syst 2016;44(13):1466–77.
[130] Mathew RK, Sankar A, Sundaramoorthy K, Jayadeebhai AN. An improved algorithm for power distribution system restoration using microgrids for enhancing grid resiliency. Electr Power Compon Syst 2018;46(16–17):1731–43.
[131] Zidan A, El-Saadany EF. A cooperative multiagent framework for self-healing mechanisms in distribution systems. IEEE Trans Smart Grid 2012;3(3):1525–39.
[132] Baker TE, Epiney AS, Rabiti C, Shittu E. Optimal sizing of flexible nuclear hybrid energy system components considering wind volatility. Appl Energy 2018;212:498–508.
[133] Oon KH, Tan C, Bakar AHA, Che HS, Wong JYR. A novel reactive current injection (RCI) control for microgrid protection with inverter based distributed generation (IBDG). Energies 2019;12(17):3371.
[134] Abdellatif H, Al-Muhaini M, Khalid M. Hybrid distributed generation system modeling for smart self-healing electric microgrid. In: 2018 IEEE industry applications society annual meeting (IAS). IEEE; 2018. p. 1–8.
[135] Wang Z, Wang J. Self-healing resilient distribution systems based on sectionalization into microgrids. IEEE Trans Power Syst 2015;30(6):3139–49.
[136] Jufri FH, Widiputra V, Jung J. State-of-the-art review on power grid resilience to extreme weather events: definitions, frameworks, quantitative assessment methodologies, and enhancement strategies. Appl Energy 2019;239:1049–65.
[137] Baker T, Shittu E, Greenwood S. Valuing the capacity contribution of renewable energy systems with storage. IISE Trans 2020.
[138] Levron Y, Guerrero JM, Beck Y. Optimal power flow in microgrids with energy storage. IEEE Trans Power Syst 2013;28(3):3226–34.
[139] Shafiullah M, Abido MA. A review on distribution grid fault location techniques. Electr Power Compon Syst 2017;45(8):807–24.
[140] Garrab A, Bouallegue A, Bouallegue R. Multi-agent modeling of a meters network used in smart grid. In: 2014 World congress on computer applications and information systems (WCCAIS). IEEE; 2014. p. 1–5.
[141] Leite JB, Mantovani JRS. Development of a self-healing strategy with multiagent systems for distribution networks. IEEE Trans Smart Grid 2016;8(5):2198–206.
[142] Gupta R, Jha DK, Yadav VK, Kumar S. A multi-agent based self-healing smart grid. In: 2013 IEEE PES Asia-Pacific power and energy engineering conference (APPEEC). IEEE; 2013. p. 1–5.
[143] Khederzadeh M. Multi-agent system design for automation of a cluster of microgrids. CIRED-Open Access Proc J 2017;2017(1):1304–7.

[144] Khamphanchai W, Pisanupoj S, Ongsakul W, Pipattanasomporn M. A multi-agent based power system restoration approach in distributed smart grid. In: 2011 International conference & utility exhibition on power and energy systems: issues and prospects for Asia (ICUE). IEEE; 2011. p. 1–7.
[145] Coelho VN, Cohen MW, Coelho IM, Liu N, Guimaraes FG. Multi-agent systems applied for energy systems integration: state-of-the-art applications and trends in microgrids. Appl Energy 2017;187:820–32.
[146] Liu H, Chen X, Yu K, Hou Y. The control and analysis of self-healing urban power grid. IEEE Trans Smart Grid 2012;3(3):1119–29.
[147] Jain R, Lukic S, Lubkeman D. Multi-agent distributed service restoration scheme for distribution systems with embedded microgrids. In: 2018 IEEE/PES transmission and distribution conference and exposition (T&D). IEEE; 2018. p. 1–5.
[148] Lakshminarayanan V, Rajashekara K, Zhu B. Multi-agent system architecture for enhanced resiliency in autonomous microgrids. In: 2017 IEEE power & energy society general meeting. IEEE; 2017. p. 1–5.
[149] Sujil A, Agrwal SK, Kumar R. Centralized multi-agent self-healing power system with super conducting fault current limiter. In: 2013 IEEE conference on information & communication technologies. IEEE; 2013. p. 622–7.
[150] Shum C, Lau WH, Wong TY, Mao T, Chung SH, Tse CF, et al. Modeling and simulating communications of multiagent systems in smart grid. In: 2016 IEEE international conference on smart grid communications (SmartGridComm). IEEE; 2016. p. 405–10.
[151] Felber LA, Ribeiro PF, Bonatto BD, de Souza A, Neto J. Low cost self-healing applied to distribution grid supplying brazilian municipalities. In: 2015 IEEE PES innovative smart grid technologies Latin America (ISGT LATAM). IEEE; 2015. p. 292–7.
[152] O'Dwyer E, Pan I, Acha S, Shah N. Smart energy systems for sustainable smart cities: current developments, trends and future directions. Appl Energy 2019;237:581–97.
[153] El-Sharafy MZ, Farag HEZ. Back-feed power restoration using distributed constraint optimization in smart distribution grids clustered into microgrids. Appl Energy 2017;206:1102–17.
[154] Pathak S. Decentralized self healing solution for distribution grid automation: a must need of indian distribution utilities. In: 2013 IEEE innovative smart grid technologies-Asia (ISGT Asia). IEEE; 2013. p. 1–6.
[155] Zheng Y, Cong W. Distributed fault self-healing system and identification and management method for topology of the smart distribution network. In: 2017 8th International conference on mechanical and intelligent manufacturing technologies (ICMIMT). IEEE; 2017. p. 148–53.
[156] Min-jie Z, Ming L. The study of distribution grid distributed self-healing under dynamic operating modes. In: 2012 China international conference on electricity distribution. IEEE; 2012. p. 1–4.
[157] Orehounig K, Evins R, Dorer V. Integration of decentralized energy systems in neighbourhoods using the energy hub approach. Appl Energy 2015;154:277–89.
[158] Liang G, Zhihai T, Fengqing Z, Xuzhu D, Liyuan P. An improved self-healing control method of intelligent distribution grid based on feeder group regional model. In: 2014 International conference on power system technology. IEEE; 2014. p. 1817–21.
[159] Yang J, Zhou Y, Yue K, He Z, Cheng C, Liang N. The design of intelligence decision support system (IDSS) based on perfect Bayesian equilibrium. In: 2011 International conference on advanced power system automation and protection, vol. 2. IEEE; 2011. p. 844–7.
[160] Schneider C, Barker A, Dobson S. A survey of self-healing systems frameworks. Software: Practice and Experience 2015;45(10):1375–98.
[161] Al Karim M, Currie J, Lie T-T. Dynamic event detection using a distributed feature selection based machine learning approach in a self-healing microgrid. IEEE Trans Power Syst 2018;33(5):4706–18.
[162] Singh AK, Fozdar M. Real-time automated event analysis and supervisory framework for power systems using synchrophasor measurements. Electr Power Compon Syst 2019;47(9–10):823–37.
[163] Duarte DP, Guaraldo JaC, Kagan H, Nakata BH, Pranskevicius PC, Suematsu AK, et al. Substation-based self-healing system with advanced features for control and monitoring of distribution systems. In: 2016 17th International conference on harmonics and quality of power (ICHQP). IEEE; 2016. p. 301–5.
[164] Jianhua Z, Yue Y, Rong S, Shouxiang W. Switch configuration optimization meeting the requirement of self-healing. In: 2014 China international conference on electricity distribution (CICED). IEEE; 2014. p. 1524–8.
[165] Li D, Wang S, Zhan J, Zhao Y. A self-healing reconfiguration technique for smart distribution networks with DGs. In: 2011 International conference on electrical and control engineering. IEEE; 2011. p. 4318–21.
[166] Maykot AS, Neto EACA, Oliva NA. Automation of manual switches in distribution networks focused on self-healing: a step toward smart grids. In: 2019 IEEE PES innovative smart grid technologies conference-Latin America (ISGT Latin America). IEEE; 2019. p. 1–4.
[167] Ustun TS, Ayyubi S. Automated network topology extraction based on graph theory for distributed microgrid protection in dynamic power systems. Electronics (Basel) 2019;8(6):655.
[168] Sun W, Zhang P, Zhou Q. Optimization-based strategies towards a self-healing smart grid. In: IEEE PES innovative smart grid technologies. IEEE; 2012. p. 1–6.
[169] Yang Y, Pei W, Xiao H, Qi Z. Comprehensive planning of multiple microgrids with self-healing consideration. In: 2014 International conference on power system technology. IEEE; 2014. p. 3275–81.
[170] Shim JW, Nam T, Jang JY, Ko TK, Ahn MC, Hur K. Towards a self-healing electric grid with superconducting fault current controllers. IEEE Trans Appl Supercond 2011;22(3). 5600904–5600904.
[171] LoPorto JM. Application of self-healing technologies on power distribution systems: PHI's automatic sectionalizing & restoration systems. In: PES T&D 2012. IEEE; 2012. p. 1–3.
[172] Taifeng K, Liang G, Zhihai T, Fengqing Z, Hongyuan H, Feijin P, et al. An alarm management framework for self-healing smart distribution system. In: 2014 China international conference on electricity distribution (CICED). IEEE; 2014. p. 293–6.
[173] Khodaei A. Resiliency-oriented microgrid optimal scheduling. IEEE Trans Smart Grid 2014;5(4):1584–91.
[174] Nicolas C, Rentschler J, Potter van Loon A, Oguah S, Schweikert A, Deinert M, et al. Stronger power: improving power sector resilience to natural hazards. World Bank; 2019.
[175] Pescaroli G, Alexander D. Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. Nat Hazards 2016;82(1):175–92.
[176] Francis R, Bekera B. A metric and frameworks for resilience analysis of engineered and infrastructure systems. Reliab Eng Syst Saf 2014;121:90–103.
[177] Zimmerman R, Zhu Q, De Leon F, Guo Z. Conceptual modeling framework to integrate resilient and interdependent infrastructure in extreme weather. J Infrastruct Syst 2017;23(4):04017034.
[178] Cerf VG. Natural disasters and electric infrastructure. IEEE Internet Comput 2011;15(6). 103–103.
[179] Abbey C, Cornforth D, Hatziargyriou N, Hirose K, Kwasinski A, Kyriakides E, et al. Powering through the storm: microgrids operation for more efficient disaster recovery. IEEE Power Energy Mag 2014;12(3):67–76.
[180] Bie Z, Lin Y, Li G, Li F. Battling the extreme: a study on the power system resilience. Proc IEEE 2017;105(7):1253–66.
[181] Xie W, Rose A, Li S, He J, Li N, Ali T. Dynamic economic resilience and economic recovery from disasters: a quantitative assessment. Risk Anal 2018;38(6):1306–18.
[182] Walsh T, Layton T, Wanik D, Mellor J. Agent based model to estimate time to restoration of storm-induced power outages. Infrastructures 2018;3(3):33.
[183] Santos J, Yip C, Thekdi S, Pagsuyoin S. Workforce/population, economy, infrastructure, geography, hierarchy, and time (WEIGHT): reflections on the plural dimensions of disaster resilience. Risk Anal 2020;40(1):43–67.
[184] Panteli M, Mancarella P, Trakas DN, Kyriakides E, Hatziargyriou ND. Metrics and quantification of operational and infrastructure resilience in power systems. IEEE Trans Power Syst 2017;32(6):4732–42.
[185] Kwasinski A. Quantitative model and metrics of electrical grids' resilience evaluated at a power distribution level. Energies 2016;9(2):93.
[186] Bajpai P, Chanda S, Srivastava AK. A novel metric to quantify and enable resilient distribution system using graph theory and choquet integral. IEEE Trans Smart Grid 2016;9(4):2918–29.
[187] Lyster R, Verchick RRM. Protecting the power grid from climate disasters. Research handbook on climate disaster law. Edward Elgar Publishing; 2018.
[188] Dormady N, Rose A, Rosoff H, Roa-Henriquez A. A survey approach to measuring the costeffectiveness of economic resilience to disasters. Resilience of Socio Technical Systems. Cheltenham: Edward Elgar; 2017. Forthcoming.
[189] Shittu E, Parker G, Mock N. Improving communication resilience for effective disaster relief operations. Environ Syst Decis 2018;38(3):379–97.
[190] Kaygusuz A, Tuttokmağı O, Keleş C, Alagöz BB. Possible contributions of smart grids to regional development of countries. In: 2018 International conference on artificial intelligence and data processing (IDAP). IEEE; 2018. p. 1–4.
[191] Oskin B. Japan earthquake and tsunami of 2011: facts and information, livescience. Online at http 2015.
[192] Mitsova D, Esnard A-M, Sapat A, Lai BS. Socioeconomic vulnerability and electric power restoration timelines in florida: the case of hurricane irma. Nat Hazards 2018;94(2):689–709.
[193] Baker E, Nock D, Levin T, Atarah SA, Afful-Dadzie A, Dodoo-Arhin D, et al. Who is marginalized in energy justice? Amplifying community leader perspectives of energy transitions in ghana. Energy Res Soc Sci 2021;73:101933.
[194] Krausmann E, Cruz AM. Impact of the 11 march 2011, great east japan earthquake and tsunami on the chemical industry. NatHazards 2013;67(2):811–28.
[195] Shittu E, Kamdem BG, Weigelt C. Heterogeneities in energy technological learning: evidence from the US electricity industry. Energy Policy 2019;132:1034–49.
[196] Du E, Cai X, Sun Z, Minsker B. Exploring the role of social media and individual behaviors in flood evacuation processes: an agent-based modeling approach. Water Resour Res 2017;53(11):9164–80.
[197] Mas E, Suppasri A, Imamura F, Koshimura S. Agent-based simulation of the 2011 great east japan earthquake/tsunami evacuation: an integrated model of tsunami inundation and evacuation. J Nat Disaster Sci 2012;34(1):41–57.
[198] Wagner N, Agrawal V. An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster. Expert Syst Appl 2014;41(6):2807–15.
[199] Brudermann T, Hofer C, Yamagata Y. Agent-based modeling'a tool for urban resilience research?. In: Urban resilience. Springer; 2016. p. 135–51.
[200] Miles SB, Burton HV, Kang H. Community of practice for modeling disaster recovery. Nat Hazard Rev 2019;20(1):04018023.
[201] Kröger W, Sansavini G. Principles of disaster risk reduction. Protecti Electr Netw NatHazards 2016:11.
[202] Brudermann T, Yamagata Y. Towards an agent-based model of urban electricity sharing. In: 2014 International conference and utility exhibition on green energy for sustainable development (ICUE). IEEE; 2014. p. 1–5.
[203] Asgary A, Pantin B, Saiiar BE, Wu J. Developing disaster mutual assistance decision criteria for electricity industry. Disaster Prevent Manage 2017.
[204] Pei B, Pang W, Testik FY, Ravichandran N. An agent-based framework for modeling the effectiveness of hurricane mitigation incentives. In: Proceedings of the 12th international conference on applications of statistics and probability in civil engineering(ICASP12); 2015. p. 12–15.
[205] Jager W, van der Vegt G. Management of complex systems: toward agent-based gaming for policy. In: Policy practice and digital science. Springer; 2015. p. 291–303.

[206] Sichtermann JR. Slowing the PACE of recovery: why property assessed clean energy programs risk repeating the mistakes of the recent foreclosure crisis. Val UL Rev 2011;46:263.
[207] Crowe CT, et al. Business sustainability: an analysis of three enterprises in charlotte, north carolina. Winthrop McNair Res Bull 2017;3(1):3.
[208] Rihan M, Ahmad M, Beg MS. Developing smart grid in india: background and progress. In: 2011 IEEE PES conference on innovative smart grid technologies-Middle East. IEEE; 2011. p. 1–6.
[209] Xu Z, Xue Y, Wong KP. Recent advancements on smart grids in China. Electr Power Compon Syst 2014;42(3–4):251–61.
[210] Paton D, Johnston D. Disaster resilience: an integrated approach. Charles C Thomas Publisher; 2017.
[211] Liu X, Shahidehpour M, Li Z, Liu X, Cao Y, Bie Z. Microgrids for enhancing the power grid resilience in extreme conditions. IEEE Trans Smart Grid 2016;8(2):589–97.
[212] Blackman D, Nakanishi H, Benson AM. Disaster resilience as a complex problem: why linearity is not applicable for long-term recovery. Technol Forecast Soc Change 2017;121:89–98.
[213] Coetzee C, Van Niekerk D, Raju E. Disaster resilience and complex adaptive systems theory. Disaster Prev Manag 2016.
[214] Hosseini S, Barker K, Ramirez-Marquez JE. A review of definitions and measures of system resilience. Reliab Eng Syst Saf 2016;145:47–61.
[215] Ayyub BM, Chapman RE, Galloway GE, Wright RN. Economics of community disaster resilience workshop proceedings, 1600. NIST Special Publication; 2015.
[216] Gilbert S, Ayyub BM. Models for the economics of resilience. ASCE-ASME J Risk UncertainEng Syst Part A 2016;2(4):04016003.
[217] Rose A, Prager F, Chen Z, Chatterjee S, Wei D, Heatwole N, et al. Validation of computable general equilibrium based models. In: Economic consequence analysis of disasters. Springer; 2017. p. 99–108.
[218] Chen Z, Rose A. Economic resilience to transportation failure: a computable general equilibrium analysis. Transportation (Amst) 2018;45(4):1009–27.
[219] Koks EE, Thissen M. A multiregional impact assessment model for disaster analysis. Econ Syst Res 2016;28(4):429–49.
[220] Okuyama Y, Santos JR. Disaster impact and input–output analysis. Econ Syst Res 2014;26(1):1–12.
[221] Koks EE, Carrera L, Jonkeren O, Aerts JC, Husby TG, Thissen M, et al. Regional disaster impact analysis: comparing input–output and computable general equilibrium models. Nat Hazards Earth Syst Sci 2016;16(8).
[222] Galbusera L, Giannopoulos G. On input-output economic models in disaster impact assessment. Int J Disaster Risk Reduct 2018;30:186–98.
[223] Cantillo V, Serrano I, Macea LF, Holguín-Veras J. Discrete choice approach for assessing deprivation cost in humanitarian relief operations. Socioecon Plann Sci 2018;63:33–46.
[224] Burton HV, Miles SB, Kang H. Integrating performance-based engineering and urban simulation to model post-earthquake housing recovery. Earthquake Spectra 2018;34(4):1763–85.
[225] Eid MS, El-Adaway IH. Sustainable disaster recovery decision-making support tool: integrating economic vulnerability into the objective functions of the associated stakeholders. J Manage Eng 2017;33(2):04016041.
[226] Tobon D, Molina C, Vasco CA. Scope of economic incentives and abatement technologies to regulate a natural system's resilience in a general equilibrium model. World Bank Econ Rev 2015;29(suppl_1):S182–91.
[227] Hallegatte S. The indirect cost of natural disasters and an economic definition of macroeconomic resilience. The World Bank; 2015.
[228] Connelly EB, Lambert JH, Thekdi SA. Robust investments in humanitarian logistics and supply chains for disaster resilience and sustainable communities. Nat Hazard Rev 2016;17(1):04015017.
[229] Carone MT, Marincioni F, Romagnoli F. Use of multi-criteria decision analysis to define social resilience to disaster: the case of the EU LIFE PRIMES project. Energy Procedia 2018;147:166–74.
[230] Hosseini SMA, de la Fuente A, Pons O. Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: acase study in bam, 2003. SustainCitiesSoc 2016;20:38–51.
[231] Alshehri SA, Rezgui Y, Li H. Disaster community resilience assessment method: a consensus-based delphi and AHP approach. Nat Hazards 2015;78(1):395–416.
[232] Pozzi M, Memarzadeh M. A sequential decision making prospective on resilience. In: Safety, reliability, risk, resilience and sustainability of structures and infrastructure 12th int. conf. on structural safety and reliability, Vienna, Austria, 6–10 August 2017, vol. 1; 2017.
[233] Day JM. Fostering emergent resilience: the complex adaptive supply network of disaster relief. Int J Prod Res 2014;52(7):1970–88.
[234] Rudnick H.. Natural disasters. 2011.
[235] Vaiman M, Bell K, Chen Y, Chowdhury B, Dobson I, Hines P, et al. Risk assessment of cascading outages: methodologies and challenges. IEEE Trans Power Syst 2012;27(2):631.
[236] Araneda JC, Rudnick H, Mocarquer S, Miquel P. Lessons from the 2010 chilean earthquake and its impact on electricity supply. In: 2010 international conference on power system technology. IEEE; 2010. p. 1–7.
[237] Chertkov M, Pan F, Stepanov MG. Predicting failures in power grids: the case of static overloads. IEEE Trans Smart Grid 2010;2(1):162–72.
[238] Wang Z, Scaglione A, Thomas RJ. A markov-transition model for cascading failures in power grids. In: 2012 45th Hawaii international conference on system sciences. IEEE; 2012. p. 2115–24.
[239] Soltan S, Mazauric D, Zussman G. Analysis of failures in power grids. IEEE Trans Control Network Syst 2015;4(2):288–300.
[240] Parandehgheibi M, Modiano E, Hay D. Mitigating cascading failures in interdependent power grids and communication networks. In: 2014 IEEE international conference on smart grid communications (SmartGridComm). IEEE; 2014. p. 242–7.
[241] Bernstein A, Bienstock D, Hay D, Uzunoglu M, Zussman G. Power grid vulnerability to geographically correlated failures'analysis and control implications. In: IEEE INFOCOM 2014-IEEE conference on computer communications. IEEE; 2014. p. 2634–42.
[242] Fang X, Yang Q, Wang J, Yan W. Coordinated dispatch in multiple cooperative autonomous islanded microgrids. Appl Energy 2016;162:40–8.
[243] Kamdem BG, Shittu E. Optimal commitment strategies for distributed generation systems under regulation and multiple uncertainties. Renewable Sustainable Energy Rev 2017;80:1597–612.
[244] Olivares DE, Mehrizi-Sani A, Etemadi AH, Cañizares CA, Iravani R, Kazerani M, et al. Trends in microgrid control. IEEE Trans Smart Grid 2014;5(4):1905–19.
[245] Anwar A, Mahmood A. Cyber security of smart grid infrastructure; 2014.
[246] Pong PWT, Annaswamy A, Kroposki B, Zhang Y, Rajagopal R, Zussman G, et al. Cyber-enabled grids: shaping future energy systems. Adv Appl Energy 2020:100003.
[247] Ogunrinde O, Shittu E, Dhanda KK. Distilling the interplay between corporate environmental management, financial, and emissions performance: evidence from US firms. IEEE Trans Eng Manage 2020.
[248] Gai DHB, Ogunrinde O, Shittu E. Self-reporting firms: are emissions truly declining for improved financial performance? IEEE Eng Manage Rev 2020;48(1):163–70.