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TOPICAL REVIEW

Decision Support for Smart Distribution System Against Natural Disasters During Health Pandemics Considering Resilience

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ABSTRACT Natural disasters and health pandemics have occurred more frequently in the 21st century. Research show that the large blackouts caused by natural disasters are more intractable, especially striking during health pandemics. In this sense, power grid resilience becomes a topical area both in industry and academia. The resilience can be enhanced by making the grid ‘‘Smarter’’, utilizing advanced techniques such as distributed generation, microgrids, sensing, communication, and computing. In this paper, a structured review framework for decision support for smart distribution system (SDS) resilience against natural disasters during health pandemics is proposed. The challenges and negative impacts of natural disasters during health pandemics on SDS resilience are well illustrated. The stochastic impact assessment methods of natural disasters and human activities on SDSs are extensively discussed. The SDS planning and operation models against natural disasters during health pandemics are comprehensively reviewed. The strategic decision-making for resilient SDS against natural disasters during health pandemics are extensively surveyed. Future research directions are also presented.

INDEX TERMS Decision support, health pandemics, natural disasters, power grids, resilience, smart distribution systems.

I. INTRODUCTION

Natural disasters which are characterized as high impact low probability extreme events can have negative impacts on electrical infrastructures [1], [2]. For example, the 2008 China ice storm, the 2010 Chile earthquake, and the 2017 Harvey hurricane led to billions of dollars of economic losses and millions of customer service interruptions. The statistics in Fig. 1. show the number of major blackouts with greater than 50,000 customers affected, caused by various extreme events in the United States between 1986 and 2006 [3]. The area of bars under the dotted line, representing the number of extreme events associated with all kinds of natural disasters, occupies a large portion of the total area. This highlights the importance of investigating features of natural disasters and ensuing strategies to reduce the risk of blackouts.

In the early 21st century, several severe pandemics have imposed global threats to human health. The 2002 severe acute respiratory syndrome-coronavirus (SARS-Cov), the 2009 H1N1, and the 2012 Middle East respiratory syndrome (MERS) led to thousands of deaths worldwide. As of Mar 4, 2022, the ongoing SARS-CoV-2 (COVID-19), which was declared as a global pandemic by the World Health Organization on March 11, 2020, had struck 221 countries and territories. At that point, it had resulted in 442 million cases of the disease with 6.01 million deaths [4]. In the early stage of a pandemic, as no specific vaccines are available to control the disease, human behaviors such as wearing masks, self-isolation and working-at-home are viable measures to slow down their spread [5].

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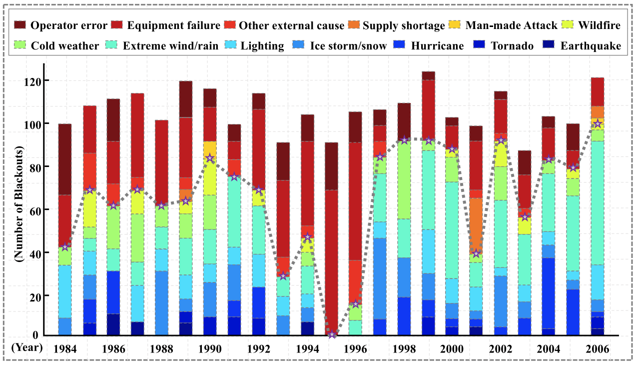


FIGURE 1. The number of major blackouts resulting from extreme events between 1984 and 2006, with greater than 50,000 customers affected [3].

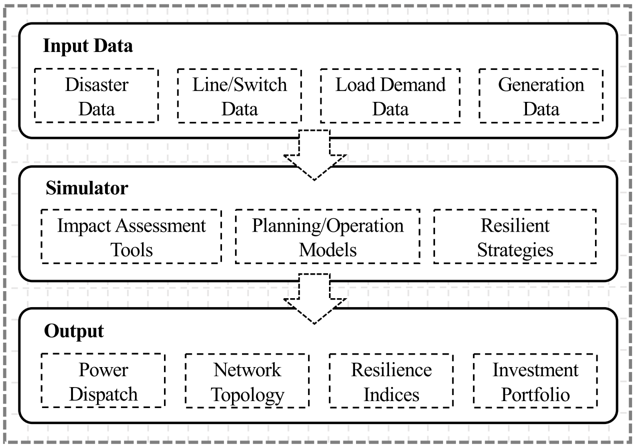


FIGURE 2. An illustration of smart grid architecture and corresponding resilience-oriented countermeasures in terms of different layers [13].

Outbreaks of infectious disease after major natural disasters are often considered as a critical public health problem, e.g., due to food and water pollution, and cross infection [6]. During a health pandemic, the occurrence of natural disasters can obviously aggravate the existing health issue by destroying various critical facilities such as electrical infrastructures [7]. For example, the 2021 Texas power crisis resulted by severe winter storms hampered the government's response to the COVID-19 pandemic [8]. Furthermore, the serious health issue can, in turn, influence human activities and then reshape human behaviors along with dramatic increases in confirmed cases. This response can complicate post-contingency recovery such as power restoration, due to staff health conditions, staff shortages, and life/work pattern-based socio-economic change [9]. Thus, specifically for electric power systems, the impact of a health pandemic can remarkably undermine their resilience against natural disasters. For example, a utility company may have well preparation for a hurricane but not so much for a hurricane during a health pandemic [10].

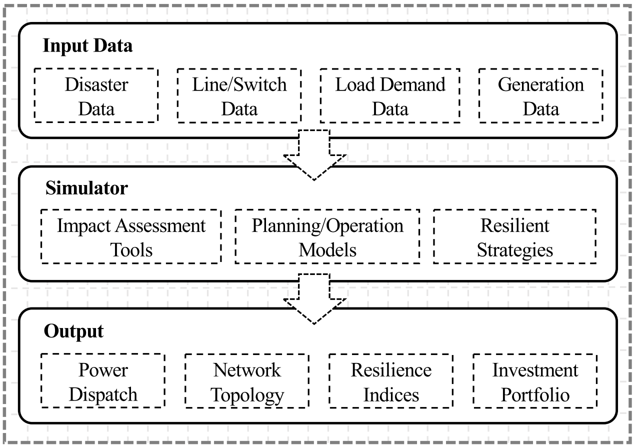


FIGURE 3. Diagram of decision support for SDS considering resilience [17].

The future smart distribution system (SDS), integrated with intelligent decision support, offers an opportunity to address the above challenges. Compared with traditional distribution systems, SDSs are equipped with advanced techniques such as distributed generation, sensing, communication, and computing, which can effectively enhance power distribution system resilience [11], [12]. An illustration of the SDS architecture with resilience-oriented countermeasures is shown in Fig. 2, which contains three layers, i.e., electric power systems, communication systems, and decision support systems [13]. Between two adjacent layers, there are two-way data flow to transfer the grid information upwards and the resilient decisions downwards. Moreover, as shown in Fig. 2, each layer of SDS has its own measures in terms of resilience enhancement. The electric power system improves the SDS resilience from the perspective of advanced electrical techniques and components, such as distributed generators, renewable energy sources, hardened distribution lines, and remotely controlled switches [1]. For the communication system, the resilience is realized through architectural communication frameworks such as Resilience and Survivability for Future Networking (ResumeNet) [14], Resilient Communication Services Protecting End-user Applications from Disaster-based Failures (RECODIS) [15], and Resilient and Survivable Networks (ResiliNets) [16]. Also, the decision support system is used to improve the resilience-oriented decision-making capabilities [17]. As shown in Fig. 3, firstly, the required data, such as line status, distributed generation, and load demand, can be collected from the electric power system layer. Then, the data are forwarded into the simulator, where the stochastic impact of natural disasters can be evaluated by assessment tools. Also, the optimal solution can be optimized by SDS planning and operation models, and the SDS resilience can be enhanced by resilient strategies. Lastly, the resilience-oriented decision-making for SDS, such as power dispatch and topology reconfiguration, can be determined.

In literature, there are several surveys related to the SDS resilience with respect to the following topics:

- Resilience metrics and evaluation [12], [18], [19];
- Resilience on electrical techniques [20], [21], [22];
- Resilience on communication networks [23], [24].

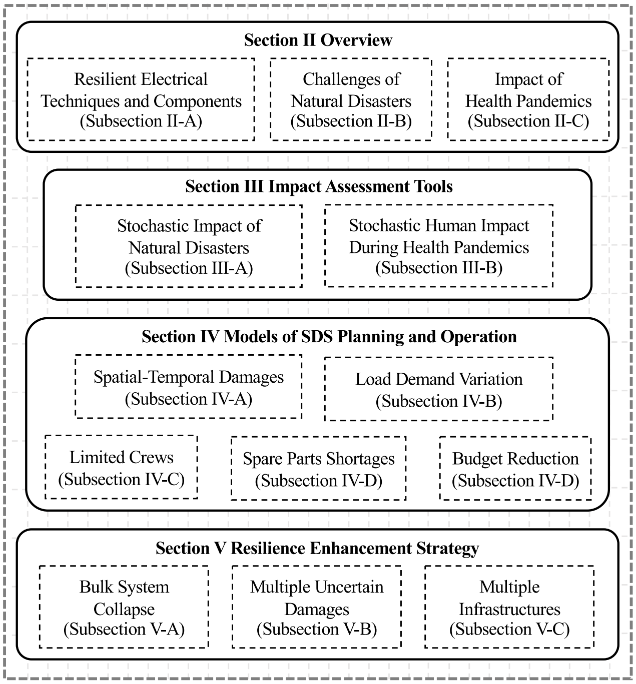


FIGURE 4. **An illustration of the proposed review framework.**

However, a comprehensive review on the decision support for SDS resilience against natural disasters during health pandemics is still required and necessary. This is of critical importance because human activity variation, such as limited crews and load demand changing, resulted by health pandemics, can influence the SDS resilience. In literature, some technical reports [25], [26], [27] have considered the impact of human intervention on power system resilience induced by health pandemics. But as far as we know, there is no detailed literature review concentrated on this research area. To fill this gap, this paper proposes a structured review framework for decision support for SDS resilience against natural disasters during health pandemics. Specifically, the framework is illustrated in Fig. 4. Firstly, an overview of resilience enhancement of SDS is presented considering the challenges of natural disasters and impacts of health pandemics. Secondly, the assessment of stochastic impact on SDSs is illustrated. Thirdly, the models of SDS planning and operation considering resilience are reviewed. Lastly, the strategic decision-making for SDS resilience enhancement are surveyed. Then, the main contributions are summarized as the following:

1) The challenges and negative impacts of natural disasters during health pandemics on SDS resilience are well illustrated. A resilience enhancement time line including stages of extreme events, resilient techniques, and responsive measures is presented;
2) The stochastic impact assessment methods of natural disasters and human activities on SDSs are extensively discussed. The damages of natural disasters and influence of human factors are summarized for the decision support system development considering resilience;
3) The SDS planning and operation models against natural disasters during health pandemics are comprehensively reviewed. Limited staffs, shortages in spare parts and budget, and load demand variation caused by pandemics are well discussed to evaluate their impacts on SDS recovery after natural disasters;
4) The resilience-oriented decision-making strategies for resilient SDS against natural disasters during health pandemics are extensively surveyed. The research on decision support systems for SDS resilience considering blackouts by disasters and human activity variation by pandemics are consolidated.

Accordingly, this paper entails the review of the current research regarding SDS resilience against natural disasters during health pandemics based on the following criteria:

1) Illustrate the challenges of natural disasters and impact of health pandemics on SDS resilience;
2) Review the stochastic impact assessment methods of natural disasters and human activities on SDSs;
3) Investigate the SDS planning and operation models against natural disasters during health pandemics;
4) Survey the strategic decision-making for resilient SDS against natural disasters during health pandemics.

The remaining paper is organized as follows. In Section II, we present an overview of resilience enhancement of SDS, including enhancement stages, advanced electrical techniques, and some representative resilient measures. Also, we illustrate the challenges of natural disasters and the impact of health pandemics in Section II. Then, we review the assessment of stochastic impact on SDSs in Section III, discuss the models of SDS planning and operation considering resilience in Section IV, and survey strategic decision-making for SDS resilience enhancement in Section V. Last but not least, future research directions and conclusion are presented in Section VI.

II. OVERVIEW OF SDS RESILIENCE ENHANCEMENT, CHALLENGES OF NATURAL DISASTERS AND IMPACT OF HEALTH PANDEMICS

SDS resilience is defined as the ability to robustly withstand destructive strikes and rapidly recover from the post-contingency state [28]. Compared with reliability, which are evaluated under high-probability and low-impact events, e.g., accidental equipment failures, SDS resilience is considered based on low-probability and high-impact events, which can be affected by human behavior variation, e.g., caused by health pandemics [18], [29]. In this section, an overview of SDS resilience against natural disasters is presented. A resilience enhancement time line including stages, techniques, and measures is discussed. Also, the challenges of natural-disaster-induced outages, and the impact of health pandemics on SDS resilience are illustrated.

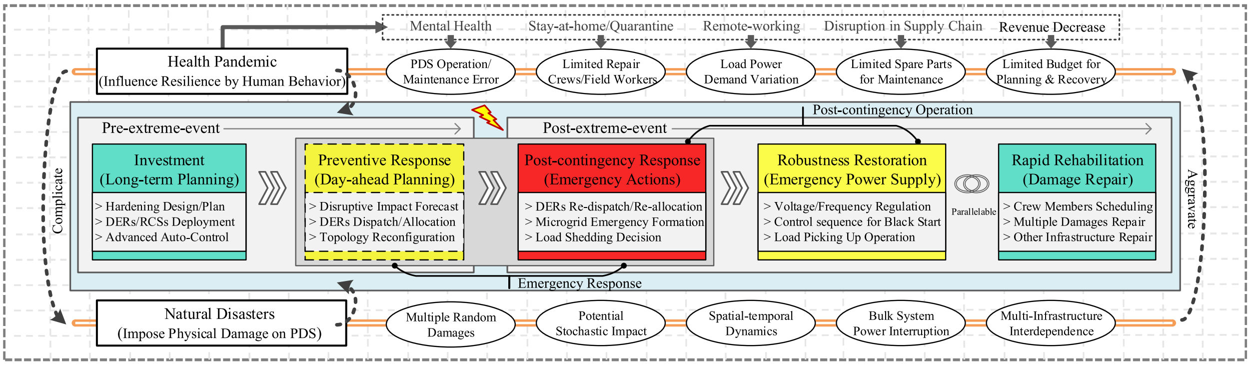


FIGURE 5. An illustration of the SDS resilience enhancement time line, challenges, and impact of health pandemics.

A. OVERVIEW OF RESILIENCE ENHANCEMENT OF SDS AGAINST NATURAL DISASTERS: STAGES, TECHNIQUES, AND MEASURES

Proactively taking proper measures is critical for the enhancement of SDS resilience against natural disasters. As shown in Fig. 5, in chronological order, the enhancement can be broadly summarized into five stages:

1) Potential impact assessment and investment;
2) Natural disaster forecasting and preventive response;
3) Damage data acquisition and emergency response;
4) Voltage/frequency regulation and restoration;
5) Troubleshooting and rapid rehabilitation.

In the investment stage, the resilient planning of a SDS can be determined in the long-term with consideration of a limited budget. To this end, different methods have been applied in literature, which can be summarized as hardening design, installation of remotely controlled switches (RCSs), and placement of distributed energy resources (DERs), as shown in Fig. 5. Hardening design of electrical components such as distribution lines (DLs), electrical poles and substations refers to a structural or physical boost of their robustness and resistance to the external strike resulting from natural disasters. It is an effective preventative measure to improve SDS resilience [30]. In comparison, RCSs and DERs play fundamental roles in post-contingency SDS resilience enhancement through the so-called distribution automation and the active distributed generation, respectively [20]. In terms of distribution automation, RCSs can make the SDS topology reconfiguration more flexible. Also, RCSs can be categorized as sectionalizing RCSs for isolating faulted zones, tie RCSs for offering alternative ways of restoration, and load RCSs for necessary load curtailment [31]. In terms of distributed generation, the placement of DERs can be divided into fixed positioning and allocable positioning. The former one is about stationary DERs (sDERs) such as distributed generators (DGs), energy storage systems (ESSs) and renewable energy sources (RESs), whereas the latter one is related to mobile DERs (mDERs) such as mobile emergency generators (MEGs), mobile energy storage systems (MESSs) and electrical vehicles (EVs) [32], [33].

With the improvement of forecast techniques, the impact of some natural disasters such as hurricanes and ice storms can be pre-assessed, including the intensity and moving path [34]. This provides system operators with extra pre-event time to take some defensive actions. Generally, the preventive response is day-ahead based scheduling which includes the predetermination of distributed generation dispatch and topology reconfiguration to alleviate the damage of forthcoming natural disasters [22]. However, some natural disasters such as earthquakes are impossible to be predicted. Thus, there are no day-ahead preventive measures.

After natural disasters happen, emergency response to the natural-disaster-induced outages will be performed urgently, as shown in Fig. 5. To this end, the distribution supervisory control and data acquisition system will detect damage information first through different fault localization techniques, such as wide-area monitoring based on fluctuation of voltage/current, self-powered fault indicator based on sensing magnetic field induced by the current and advanced metering infrastructure installed at the level, as well as contact from customers and crew member patrols [35]. Once the damage information is collected, the system operators can build up responsive plans utilizing the existing DERs and RCSs as well as load shed based on priorities. Through reasonable dispatch of DERs, self-supported microgrids can be established, and balanced capacity utilization of DERs can be met among different microgrids [36]. By utilization of RCSs, the optimal microgrids can be islanded from the original SDS flexibly. The microgrid topology can also be altered by operating tie RCSs easily [31]. The responsive decision can be obtained by optimization problems with different objectives, such as the shortest outage duration, the largest amount of load restoration, the lowest generation, operational and degradation cost of equipments, and the most resilient networks. Also, by considering power flow analysis and load shed processes, the microgrids can perform with no violations in operational constraints [37].

Subsequently, remedial restoration schemes can be determined, when the optimal responsive plan is ascertained, as shown in Fig. 5. The restoration strategy determines a control sequence of DER starting up and RCS switching, which can be used as guidelines for system operators to restore interrupted customers step-by-step [38]. Similar to the bottom-up approaches in power systems where the generation units are capable of self-starting (i.e. black-start), in a restoration-based microgrid at least one DER should be able to start up by itself and maintain voltage and frequency stability [39]. DGs such as diesel generators and microturbines, and ESSs are applicable for black start operation, whereas RESs such as wind turbines and photovoltaic arrays have less stable performance because of their intermittent nature [40].

Troubleshooting refers to a status of SDSs whereby all damages caused by natural disasters are completely repaired by crew members. Different from the response and restoration stages which are related to post-contingency operations, troubleshooting is fulfilled by physical repairs which can be rather time-consuming. The duration of such a process is a critical factor which also influences the SDS resilience [18], [41]. The reason is that even though the optimal responsive and restorative actions can pick up as much of the loads as possible, full rehabilitation of SDSs can be achieved only when all damages are cleared. Therefore, appropriately scheduling repair to get the faulted zone recovered in the shortest time is very important [42].

B. CHALLENGES OF NATURAL-DISASTER-INDUCED SDS OUTAGES

Compared with the conventional outages, which are caused by single equipment failures or accidents, natural-disaster-induced outages can be more intractable, as shown in Fig. 5 [20]. First, multiple faults with randomness can decompose the SDS into several islands. It requires SDSs to be able to reconfigure their topology to transfer some isolated loads to some other primaries for the access of utility power. If some loads are still out of services, the distributed generation is required to supply emergency power [43].

Second, the stochastic potential impact of natural disasters including occurrence, intensity and duration which are critical but hard to assess makes the problem interdisciplinary. Accordingly, mathematical models, such as hurricane models, are required for inclusion in the resilience enhancement problem formulations to obtain more practical decisions.

Third, the spatial-temporal dynamics of natural disasters makes the failure rate of the same type of electrical components unequal, which means that multi-zone and multi-period SDS fragility needs to be considered in conjunction with SDS pre-event planning or post-event operation [34].

Forth, interrupted faults are very likely to happen on the bulk systems, so that the SDS may get totally disconnected from the utility power. At this time, the distributed generation, as well as flexible topology reconfiguration, is ess-ential to establish post-disaster restoration [37].

Last but not least, multiple infrastructures such as transportation and communication networks are always involved and deteriorated, which in turn affects SDS resilience [44], [45]. For example, interrupted transportation networks or inefficient traffic caused by natural disasters may influence the transition of mDERs or the refueling of DGs [44]. Also, the malfunction of communication devices may cause a loss of remote control of DERs and RCSs [46].

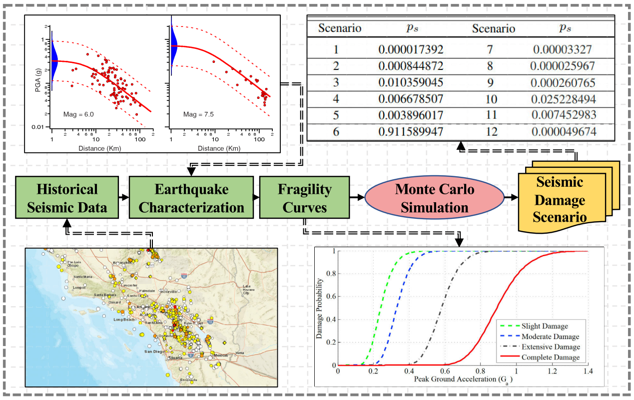
C. IMPACT OF HEALTH PANDEMICS ON SDS RESILIENCE

Health pandemics can significantly affect or reshape human behaviors, and then influence SDS resilience because all actions are conducted by humans, as shown in Fig. 5 [47], [48]. First, mental issues, e.g., fatigue, stress, anger, fear, and depression, can increase operation and maintenance errors [49]. Research have shown that health pandemics can lead to negative psychosocial outcomes among people, in particular for those who possibly contract the disease or who are at high risk of infection due to compromised immune function [50].

Second, rapidly growing cases during health pandemics may force governments to introduce stay-at-home or quarantine policies, affecting individual mobility. Statistics show that an official stay-at-home restriction corresponds to a 7.87% mobility reduction. Even without restrictions, there will be a 2.31% reduction in mobility with a 0.003% rise in the local infection rate as people actively reduce their exposure to the disease by avoiding social contacts [51]. Also, due to the fear of infection, some people would reject a return to work even when they are allowed to come back [52], [53]. Such an individual mobility reduction can result in labor shortages, when utility companies need to urgently respond to natural disasters.

Third, since a growing number of people are staying at home, especially working at home remotely, the residential electricity demand has dramatically increased, whereas the industrial and commercial load demands have decreased due to the lockdown policy [54]. For example, the residential load demand increased by 14% in Australia and by 20% in some parts of the USA during the COVID-19 pandemic. Moreover, the residential load profile also varies along with the change in our work patterns and lifestyle. This is because a longer duration of activity at night such as working and entertainment gives birth to a higher electricity consumption in the midnight to the morning hours. Thus, residential loads can no longer be treated as insensitive loads, and the load demand uncertainty during health pandemics can bring new challenges to load restoration if natural disasters strike [55].

Forth, the supply-side impact on productivity and logistic activities due to staff shortages can disrupt the supply chain [56]. For workers on a production line in a manufacturing company or workers who are responsible for transportation in a logistic company, working from home is not a viable option [57]. This supply reduction also includes spare parts for maintenance of SDSs [58]. Accordingly, if natural disasters occur during a health pandemic, the SDS resilience in terms of repair will be highly subject to spare parts management.



Scenario	p_s	Scenario	p_s
1	0.000017392	7	0.00003327
2	0.000844872	8	0.000025967
3	0.010359045	9	0.000260765
4	0.006678507	10	0.025228494
5	0.003896017	11	0.007452983
6	0.911589947	12	0.000049674

FIGURE 6. **A Monte-Carlo simulation-based model of seismic scenarios [66].**

Last but not least, the industrial and commercial load demand reduction brings about another challenge. It imposes a noteworthy impact on the revenue of utility companies, since a majority of their profit is made from these eletricity customers. This can result in a heavy financial burden as some of the budget related to SDS resilience may need to be reduced [54]. Limited cash flow can also affect the ability of utility companies to respond to natural disasters.

III. ASSESSMENT OF STOCHASTIC IMPACT ON SDSS

The impact assessment constitutes the first step to develop decision support for SDS resilience against natural disasters during health pandemics. In this section, we will discuss the stochastic impact caused by natural disasters, and the stochastic human impact during health pandemics.

A. STOCHASTIC IMPACT OF NATURAL DISASTERS

The stochastic characteristic of natural disasters brings about significant difficulties on the resilience-oriented decision-making. To address this challenge, the stochastic impact of natural disasters is necessary to be evaluated. Historical statistics can be used via regression methods to model the disruptive events and their corresponding damages, however their prediction accuracy depends on the appropriateness of the selected model and the sufficiency of acquired data [59]. By contrast, simulation-based models can offer another way to estimate the disruptive behavior via generating forecast outages scenarios with parameters of natural disasters as input. The model can establish the physical damage mechanism analysis of electrical components. Then, the destructive forces imposed on electrical components are obtained, and the failure probability can be derived by comparing the force with its designed strength [60]. Moreover, it is important to evaluate SDS resilience against natural disasters. In [61], an availability-based engineering resilience metric is proposed considering reliability engineering. The resilience metric, which incorporates engineering system structures and maintenance resources, can provide an implementation guidance for resilient system planning and operation. Also, the Bayesian network offers a powerful tool for knowledge representation and inference under uncertainties, which attracts increasing attention in the field of resilience evaluation [62]. For example, in [63], a novel resilience evaluation method is developed by using Markov models and dynamic Bayesian networks. The uncertain failure rate of components is obtained by actual physical models of natural disasters. Then, the resilience value can be calculated through the integral of the disrupted performance curve.

For seismic hazards, based on the HAZUS seismic risk assessment methodology [64], the potential seismic impact can be simulated through Monte-Carlo simulation to estimate the vulnerability of DLs under a huge set of seismic damage scenarios [65], [66], as shown in Fig. 6. Based on the assessment of potential impact, the optimal routing and scheduling of mDERs and SDS reconfiguration for restoration are carried out in [65], and the location of ESS placements is optimized in [66]. For extreme wind, a method for the risk assessment of power line outages is proposed in [67]. With consideration of wind conditions and line conductor temperature, an outage rate model is presented based on historical outage statistics and a wind-dependent power line damage mechanism, which considers physical damages by strong winds, trees falling, or trees contacting. Also, a spatiotemporal model of hurricane-induced outages is proposed in [68] considering the trajectory path and the uncertain intensity of hurricanes. The resilient decision of SDS is modeled as a sequential Markov decision process, and a deep reinforcement learning framework is presented to build an intelligent resilience controller to obtain a near-optimal DG dispatch strategy. For ice storms, ice load with thickness assessment and wind load with speed assessment are considered to model the pressure imposed on overhead lines in [69]. Then, the failure rate is estimated by comparing ice storm force with overhead line tolerable weight.

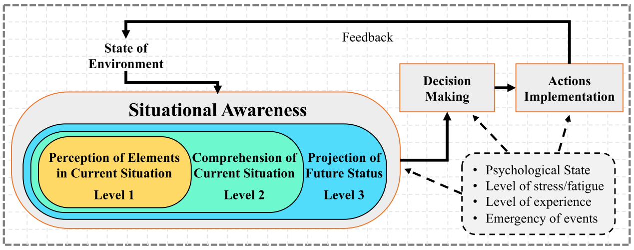
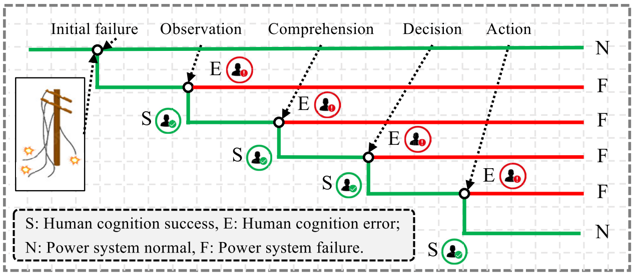


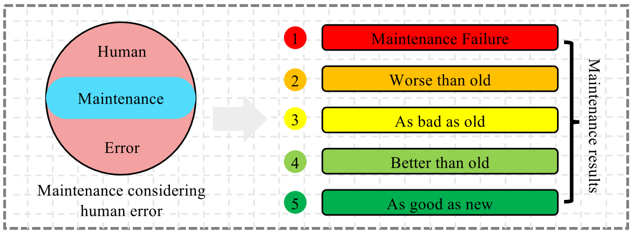
FIGURE 7. **Cognitive process in power systems [72].**

B. STOCHASTIC HUMAN IMPACT DURING HEALTH PANDEMICS

As discussed in Section II, SDSs are becoming increasingly intelligent and resilient against natural disasters by involving distributed generation and distribution automation techniques. However, the human impact can never be ignored since there are always human activities existing in the loop [70]. This impact can be negative and disruptive especially when human errors occur. It can escalate a small



(a) Evaluation model for cognitive process



(b) Evaluation model for maintenance error

FIGURE 8. **Illustration of evaluation models for human errors [74], [75].**

initial failure triggered by natural disasters into a large-scale blackout, which could have been avoided if proper actions were taken [71].

1) IMPACT OF HUMAN ERRORS

Human errors due to health pandemics are not causes but consequences. They are induced by upstream factors such as the level of stress and fatigue, the psychological state, the level of experience, and the emergency of extreme events, all of which can directly lead to poor cognition [47], [49], [72]. As shown in Fig. 7, a cognitive process can be divided into three stages: situational awareness including perception, comprehension and projection (which refers to the timely observation of accidents, the accurate analysis of the acquired data and the effective development of preventive plans for future undesirable situations, respectively), decision making, and action implementation [73]. To evaluate the involvement of human activities, an evaluation model is proposed in [74], which includes the failure and normal state transition of situational awareness, decisions and actions in power systems, as shown in Fig. 8 (a). Any step of failure caused by human errors can lead to a failed system. Also, at the physical action step, maintenance failure is considered in [75] by a periodic maintenance model to assess the impact of maintenance errors, as shown in Fig. 8 (b). The probability of each maintenance result including as good as new, better than old, as bad as old, worse than old, and complete failure are included based on the stochastic repair duration. The results of both the above models show the significant impact of human errors, indicating that the increasing number of human errors can lead to a severe failure of restoration and recovery.

2) QUANTIFICATION OF HUMAN ERRORS

To quantify human errors in the process of handling the contingency of natural disasters, human error assessment methods must be investigated. To this end, performance shaping factors are widely used to describe task features and the mental health of human operators [75]. For health pandemics, fatigue, stress, attention, emotion and physical state at different levels can all be used to set up the quantitative analysis of human activities. Also, the level of experience, available time for response, and the complexity of actions should be considered since these factors can be indirectly involved in human errors during health pandemics. For example, an operator can perform correctively even when feeling extremely fatigued due to her/his excellent operating skills [71]. In this regard, the Markov chain is utilized to model the state transition of power system based on the performance shaping factors in [71], [72], and [76]. The stochastic human factor can then be coupled with SDSs to generalize the resilience analysis. Also, in [47], a modified cognitive reliability and error analysis method is proposed to capture the human behavior and calculate the human error probability. Moreover, other methodologies established to analyze human errors, such as techniques for human error rate prediction, and human error assessment and reduction techniques can be applied by customization in terms of SDS resilience [47].

3) MANAGEMENT OF HUMAN ERRORS

The increasing human errors made during health pandemics can remarkably affect SDS resilience, therefore appropriate measures to mitigate this impact are necessary. The empirical measures are summarized as follows [49], [75], and [77]:

a) Make a well-designed shift roster to minimize fatigue;
b) Assign flexible tasks among skilled and fresh staffs;
c) Group employees based on the level of experience;
d) Double-check to reduce emotional mistakes;
e) Reduce operation steps to simplify the complexity.

Note that the listed measures are related to the reduction of human errors during extreme events. Regular ones such as individual training and team cooperation building are not included. Also, in [78], a human error reduction approach is proposed for maintenance activities. First, the potential human errors will be identified according to historical data and expert judgments. Second, a list of possible preventive risk controls is evaluated, by which the decision maker can select the most effective solutions to reduce human errors. In [79], the working conditions at the workplaces can affect the reliability of the operator activity. Thus, taking measures to improve the working environment is an effective way to manage the risks of human errors.

Moreover, the management of human errors via technical measures are well-studied in some research. For example, to avoid human subjective factors which may lead to errors in power line inspection, a software based on computer vision and machine learning is developed in [80] to assist the analysis of the acquired data. It shows that by using software instead of human judgments, the system operators' workloads can be reduced, followed by a decreased human

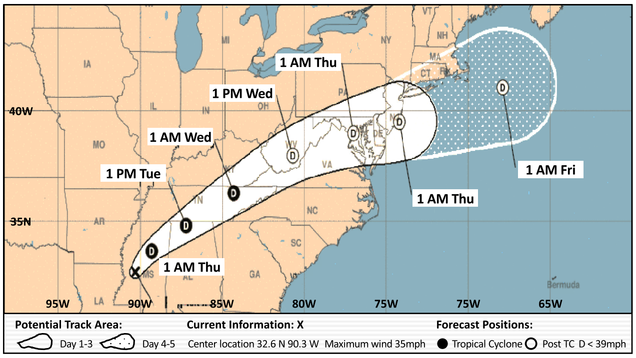


FIGURE 9. An illustration of a typical evolution of a hurricane [83].

error rate. Also, according to [81], by integrating smart devices into power systems, the system operation can be conducted through automation control. Accordingly, some operations dependent on human activities are not required any more, then the related errors can be avoided.

IV. MODELS OF SDS PLANNING AND OPERATION CONSIDERING RESILIENCE

Natural disasters during health pandemics bring new challenges to SDS planning and operation. For example, limited staffs, shortages in spare parts, and load demand variation caused by health pandemics can complicate the SDS recovery after natural disasters. In the rest of this section, we try to select among natural disaster related literature, as summarized in Table 1, and discuss the resilient models for SDS planning and operation against natural disasters during health pandemics.

A. SPATIAL-TEMPORAL DAMAGES BY NATURAL DISASTERS

The spatial and temporal dynamics of natural disasters make the multiple damages more complicated than the traditional $N-k$ contingency criterion. In paticular, the occurrence and duration of natural disasters are time-dependent, and the intensity of damage varies along with the location of interest [82]. For example, a hurricane often has a traveling path that consists of several associated geographic zones which can be struck in different periods [83], as shown in Fig. 9. Also, an earthquake propagates via seismic waves with the epicenter as the starting point, and it can return many times in the form of aftershocks [65]. Such unique features bring randomness to the failure probability of electrical components [84].

A multi-stage and multi-zone uncertainty set is presented in [34] to model the spatial-temporal dynamics of hurricanes. The occurrence of uncertain hurricanes is modeled based on bi-level programming. A resilient investment decision is determined considering the worst-case hurricane scenario. In [85] a hybrid stochastic process with deterministic casual structure is proposed to model the uncertainties resulted from spatial-temporal extreme weather events. In order to model repeatable natural disasters, e.g., earthquakes with aftershocks, which can strike one certain area for multiple times, a robust multi-period model is proposed in [86] to obtain the optimal solution of DL hardening and sDER allocation, which minimizes load shed over all the attacks.

TABLE 1. A summary of models of resilient SDS planning and operation.

Reference	Main Contributions
[65],[66], [68],[84],[85]	Modeling the spatial-temporal correlation among considering uncertainties of natural disasters.
[83],[130]	Incorporating the time-varying uncertainty in the optimization model to evaluate the system resilience.
[124] [129],[131]	Connecting transportation networks and SDSs using temporal-spatial models for resilience enhancement.
[96]-[102]	Considering the repair crew shortage problems, and its impact on PDS resilience after natural disasters. Presenting resilient crew dispatch models.
[88]-[92]	Tackling uncertain load demand when restoration by different models, such as decentralized multi-agent, networked MGs, and RES compensation.
[103]-[107]	Considering logistic problems, such as the impact of limited spare parts, limited depots and limited crew carry-ability, for maintenance when disasters strike.
[89],[102], [110],[111]	Analyzing the impact of limited available budget to reduce the restoration cost, and help utilities make economic resilient decisions.

B. LOAD DEMAND VARIATION DURING HEALTH PANDEMICS

Health pandemics can cause various supply-demand problems in the electricity market such as a mismatch between the forecast and the real load demand. As aforementioned, due to human behavior variation during health pandemics, residential load demands increase greatly whereas industrial and commercial demands decrease because of lockdowns. Moreover, the residential load profile becomes more uncertain as a result of human activities at home, e.g., higher energy consumption in the midnight which is typically off-peak hours or demand valleys [55]. Such uncertain change poses new challenges to SDS operation, especially the restoration if a natural disaster strikes during an extraordinary time. Specifically, in terms of COVID-19, population-level mobility data, which can show how people are changing their behaviors, are utilized in [87] to forecast load profile during the pandemic, with consideration of uncertain weather conditions as well.

For emergency restoration during health pandemics considering natural disasters, RESs and ESSs, which can compensate for unstable output of RESs, are promising solutions to handle the load demand uncertainty with lower cost [88], [89]. In [90], a decentralized multi-agent model is proposed to establish service restoration using DGs, RESs, EVs and ESSs. The impact of load demand uncertainty on service restoration is demonstrated. That is without considering demand uncertainty, the load may be overestimated, which leads to an underestimated solution. Also, a coordinated power exchange model is proposed in [91] based on networked microgrids to alleviate the uncertainty of load demand. Each microgrid decides to support others according to its forecast generation-demand balance and others' requests. Moreover, the model of repair crew dispatch considering stochastic load profile scenarios within the future 24 hours is investigated in [92]. The benefit of forecasting uncertain demand to enhance SDS resilience in the damage repair problem is demonstrated.

C. LIMITED REPAIR CREWS FROM HEALTH PANDEMICS

Soaring confirmed cases during health pandemics can lead people to refuse social contact due to the fear of infections even without a stay-at-home restriction, not to mention a strict quarantine policy [51]. This human behavior variation imposes a considerable influence on the labor market. For example, the available repair crews for electrical infrastructures can be decreased [93]. If an area is struck by a natural disaster during a health pandemic, shortages in repair crews can severely slow down the SDS recovery process and prolong the outage duration [94]. In [95], a metric of the waiting-time probability for crews based on Monte Carlo simulation is proposed to verify the impact of the number of available repair crews in the restoration process, given different levels of hurricanes. It shows that the SDS resilience decreases obviously along with the reduction of available crews [96].

To optimally utilize the limited number of crews during a health pandemic, resilient strategies against natural disasters must include repair models such as scheduling, task assignment, and travel route selection [97]. To this end, the co-optimization of repair crew dispatch and real-time mDER allocation as well as topology reconfiguration can greatly boost service restoration [98], [99]. A disaster recovery logistics model is investigated in [99]. The routing and scheduling of limited repair crews, which are considered as traveling salesman problem, are coordinated with the travel and dispatch of mDERs to better enhance SDS resilience. Also, in [100], the optimal repair sequence of faulted components is solved based on the vehicle routing problem. The problem of limited repair crews is considered through optimal scheduling repair of faulted components within a time horizon and reasonable removal of partial faulted components following load priorities. Besides coordination of restoration and repair, resilient planning such as the investment of hardening decisions can also be carried out based on limited crew members in future natural disasters [101]. In [102], a SDS component hardening strategy is formulated into a two-stage stochastic problem based on an assumption of single crew member, with hardening decisions as here-and-now variables and the repair sequence as wait-and-see variables to maximize SDS resilience over all possible disaster scenarios. The impact of the number of repair crews is evaluated via the proposed algorithm which converts a single crew schedule to a multi-crew schedule.

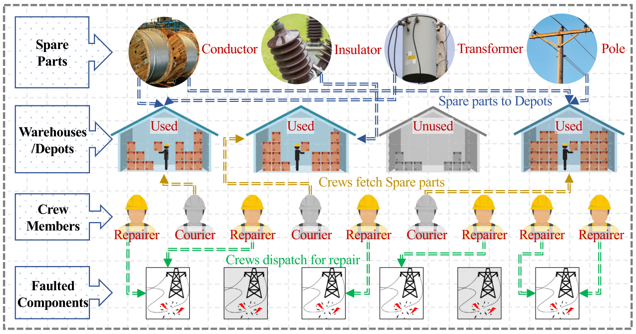


FIGURE 10. **Illustration of limited spare parts and crews allocation [105].**

D. SPARE PARTS SHORTAGES DURING HEALTH PANDEMICS

A sufficient number of spare parts for maintenance is critical for economic post-contingency recovery of SDSs. Most of resilience-oriented strategies related to repair are built up based on such a sufficiency assumption. However, health pandemics like COVID-19 have proven to be capable of disrupting the supply chain globally [58]. Also, the lack of resources including spare parts for electrical infrastructure is a major challenge after natural disasters [103]. Thus, it is essential to investigate the spare parts inventory pre-disaster from an economic perspective [104]. Fig. 10 shows a stochastic multi-commodity logistic model proposed in [105] for pre-hurricane preparation. The number of spare parts including poles, conductors and transformers are stored in different depots before disasters. The crew assignments are optimized by a two-stage stochastic problem over different outage scenarios. It demonstrates the advantage of optimizing spare parts inventory in terms of SDS resilience enhancement. In [106], an optimal spare part capacity planning model is proposed for substation restoration. The models of transformer manufacturing and inventory capacity are incorporated in the optimization problem. The economic management of spare parts are investigated through mixed-integer programmings to make a trade-off between substation restoration risks and transformer planning cost.

Moreover, the efficient utilization of parts in stock after natural disasters during health pandemics is necessary. To this end, the model of limited spare parts considering crew carry-ability and the location of multi-depots after disasters strike is studied in [107]. Accordingly, a customized vehicle routing problem is proposed to determine the optimal repair schedule for a better utilization of limited spare parts and crews. In [97], a mixed-integer linear programming model is presented to coordinate the optimization of crews dispatch, spare parts management, and SDS operation. The spare part management is considered through logistic constraints of repair resources. In [108], a repair rule set is proposed to schedule the repair process of SDS infrastructures. The set of repair tasks considering spare parts are determined such that the load shed cost can be minimized. In addition, considering that transportation networks may not be available, a cost-optimal operation and recovery method is proposed

TABLE 2. A summary of resilience enhancement strategies.

Reference	Main Contributions
[37],[112],[123],[124],[127]	Improving SDS resilience using microgrids considering the worst N-k contingencies or multiple faults.
[86],[125],[128]	Bridging the gap between mDER positioning before disasters and emergency reallocation after disasters.
[102], [113]	Coordinating the actions of multiple types of DERs, including DGs and RESs to reduce the cost.
[45],[114],[133]	Connecting the online DG regrouping and dynamic management using communication network.
[117],[118]	Considering the uncertainties of post-restoration failures when making the resilience-oriented decisions;
[119]	Analyzing load restoration in a secondary network, e.g., inrush currents and DG synchronization.
[122],[129],[131]	Connecting transportation networks and SDSs by temporal-spatial model for resilience enhancement.
[134],[135]	Co-optimization of SDSs and natural gas systems to address the integrated energy system interdependence.

in [109] by including logistics constraints of multiple flexible resources. A cooperative repair scheduling restricted by the transportation networks can be obtained, which can inform utilities in terms of spare part utilization and crew dispatch.

E. AVAILABLE BUDGET REDUCTION FROM HEALTH PANDEMICS

Changes in lifestyle and work patterns during health pandemics challenge utility companies considerably. For example, the lock down due to the COVID-19 significantly reduces the electricity demand of industrial and commercial customers, which are the main source of revenue for utility companies [54]. Such revenue decreases undoubtedly lead to budget cuts which can also affect preventive upgrading before disasters and recovery actions after disasters. In [102], the impact of a hardening budget on SDS resilience is modeled by calculating metric of aggregate harm. The inverse proportion between budget and aggregate harm caused by hurricanes is demonstrated, which indicates the importance of budget considerations. Also, an information gap decision theory-based resilient SDS planning model is proposed in [110]. The trade-off analysis between the investment of DGs and DL hardening considering a limited budget is carried out to find the optimal portfolio, which can contribute to the best resilient solution under the minimum network load shed level. Moreover, the emergency actions after natural disasters are also highly subject to the limited budget [111]. In this regard, the emergency budget of operation of DGs, ESSs and load control are defined in [89], which aims to help utility companies in economic decision-making. The simulation results show that the increase in budget leads to a more efficient restoration of load. Such improvement will not continue when the budget is higher than a certain value due to the available number of resources such as DERs.

V. STRATEGIC DECISION-MAKING FOR SDS RESILIENCE ENHANCEMENT

The resilience enhancement strategies have been well studied for decision-making. They process the data collected from the electric power system layer, and then generate and execute the resilient decisions through advanced electrical techniques, such as distributed generation, and microgrids. In this section, we will review resilience enhancement strategies towards bulk system collapse, multiple uncertain damages, and multiple infrastructure interdependence, as summarized in Table 2.

A. RESILIENT STRATEGIES AGAINST BULK SYSTEM COLLAPSE

Utility power disconnection due to the bulk system collapse resulting from natural disasters is serious for customers. Fortunately, new related techniques such as distributed generation and distribution automation can realize the emergency restoration efficiently and flexibly [100]. However, due to the limited capacity of distributed generation and operational constraints, the dynamic dispatch of DERs and the optimal topology reconfiguration of SDSs become essential [112]. Accordingly, a two-stage responsive decision-making method is presented in [113] to determine the optimal actions coordinating multiple sDERs including DGs, RESs and ESSs to serve critical loads after blackouts. With coordination, MGs in SDSs can interconnect with each other through tie-lines and distribution feeders, which positively results in a higher amount of load restoration. Also, a distributed secondary control strategy for microgrids with dynamic boundaries is proposed in [114], which can obtain real-time online DERs regrouping during a utility power interruption. The seamless topology reconfiguration with the desired stability margin can be achieved by frequency and voltage regulation and power sharing among DERs. In [115], a multilevel islanding approach is proposed for restoration. The k-way ratio cut spectral partitioning is applied, and an aggregation approach based on slow coherency grouping is presented to improve the computational efficiency.

Since SDS resilience in terms of post-contingency operation depends not only on the duration but also on the robustness of the emergency power supply against post-restoration failures, survivability of the established restoration is also a critical factor [116]. A resilient restored subtree network searching method with the objective of maximizing the resilience of restored critical loads evaluated by restoration path unavailability metric is proposed in [117]. In [118], an adaptive microgrid formation strategy is proposed to restore critical services using mDERs with the minimum overall scale of radial or looped topology against post-restoration failure. In addition, the integration of DGs into the secondary network of SDSs is investigated in [119] when the utility power is unavailable. A transient simulation is performed to evaluate the synchronization conditions when connecting DGs to a secondary main. A load removal process is conducted to avoid violations of dynamic constraints.

B. RESILIENT STRATEGIES AGAINST MULTIPLE UNCERTAIN DAMAGES

Generally, natural disasters can simultaneously cause multiple damages with randomness in SDSs. To solve this challenge, resilient planning including hardening measures, DER deployment and RCS installation can be utilized defensively pre-disaster [120], [121]. In [85], multiple damaged DLs are considered for hardening planning of poles with different structural strengths. A resilience-oriented strategy is formulated as a two-stage stochastic programming. The first stage determines the cost of hardening investment, and the second stage handles the expected cost of load shed, operation, and repair over different multi-damage scenarios. In comparison, a tri-level robust model for resilient hardening is proposed in [83] to cope with the uncertainties of multiple out-of-service DLs. The optimal investment is evaluated under the worst-case scenario given a specific hardening decision. Moreover, the increasing penetration of RESs and MESSs can coordinate with DGs to facilitate SDS restoration under multiple damages [122]. In [123], a robust line hardening strategy considering the utilization of DGs and RESs is proposed against the worst $N-k$ contingencies. The multi-damages of DLs which decompose the SDS into several islands are addressed by multiple provisional microgrids with self-sufficient ability. Also, in [124], an imitation learning framework is proposed to improve the self-healing capability of SDSs under $N-k$ contingencies. It trains an agent based on the mixed integer programming to perform service restoration online, including SDS reconfiguration and reactive power dispatch. In addition, the investment and pre-positioning of MESSs against multiple damages are studied in [125]. The mobility and charging/discharging properties of MESSs are addressed by the stochastic programming with the objective of minimizing the investment cost, operational cost and degradation cost over all normal and multi-damages emergency scenarios. In [126], the optimal construction of tie-lines is investigated for resilient distribution network. It demonstrates that the optimal tie-line planing can effectively improve the service restoration performance.

In addition, post-contingency operations are essential after natural disasters strike. In [127], a sophisticated solution based on the spanning tree search strategy is proposed. It can reconfigure the topology of microgrids using sectionalizing and tie RCSs to alleviate the multiple damage impact. Also, a resilient framework of coordinately routing and scheduling different kinds of mDERs (e.g., MEGs, MESSs, and EVs) against multiple damages is proposed in [128]. The interdependence of MEGs and MESSs/EVs in terms of emergency load restoration is presented. Specifilcally, MESSs/EVs tend to discharge when the system load demand is high, and be charged by MEGs when the system load demand is low. The restoration capability can be boosted via such energy exchange between MEGs and ESSs, which is attributed to the supplementary power supply of MEGs [100]. Moreover, focusing on the restorative control sequence of RCSs, DGs and ESSs, a multi-time step service restoration methodology considering multiple damages is presented by [38]. This can minimize the number of interrupted customers by energizing the system step-by-step without violating operational constraints.

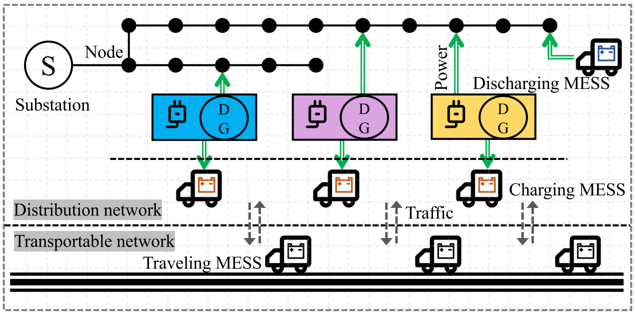


FIGURE 11. Illustration of energy exchange mechanism between DGs and MESSs based on transportation networks in terms of restoration [136].

C. RESILIENT STRATEGIES CONSIDERING MULTIPLE INFRASTRUCTURES

Besides power supply, natural disasters can destroy other infrastructures such as transportation networks and communication networks, which can also influence SDS resilience. For example, road collapse and traffic jams can impose a considerable impact on the travel routes and the effectiveness of mDERs [129]. To address such challenges, a real-time dispatch strategy applying MEGs to restore critical loads is proposed in [36]. The traffic-related issue is considered through the vehicle routing problem, which can obtain the shortest travel duration when taking into account the road damage and congestion. Similarly, research work in [130] considers day-ahead pre-event transportation of MEGs based on the stochastic prediction of extreme events and post-event traveling of MEGs based on the realization of outage scenarios concurrently. Also, a joint post-contingency restoration scheme that coordinates dynamic scheduling of MESSs and reconfiguration of SDSs is proposed in [131]. A spatial-temporal MESS model considering both of transportation networks and SDSs is adopted to model the travel of MESSs and the energy transportation mechanism from microgrids to SDSs via MESSs, as shown in Fig. 11. Moreover, considering the uncertainty of load consumption and transportation network damages, a rolling optimization framework is adopted by [122] to dynamically update system information and coordinates MESSs and microgrids.

On the other hand, after natural disasters, device malfunction may occur in communication networks. The conventional centralized communication method is costly and more vulnerable to single-point failures, whereas the decentralized one can be more resilient as the links between agents can be formed dynamically [132]. In [37], a distributed multi-agent coordination scheme is proposed to improve the distribution automation survivability. The agents are divided into two groups. One is the local agents that represent individual devices, and the other is the regional agents with enhanced computation. Each local agent exchanges information with its adjacent neighbor iteratively, and then the global information can be obtained by a regional agent within certain iterations. Similarly, the limited links of regional agent are evaluated in [133] to capture the dependency of sDERs and RCSs on the communication system that sustains their remote operation. It shows that the communication network can influence the resilient actions significantly. Therefore, the co-simulation of dynamic SDSs and communication systems under extreme events is necessary. This is also demonstrated by [45] that the co-simulation can be used to determine the necessary communication infrastructure for a given SDS to maintain the resilient operations.

In addition, the resilience of electric systems and natural gas systems are highly interdependent. The damages on one system can lead to cascading failures on another. To this end, a multi-objective restoration scheme is proposed in [134] to improve the resilience of the integrated electricity and natural gas distribution systems. The simulation results validate that by considering such an integrated energy system, the restoration performance can be significantly improved. In [135], a novel resilience assessment framework is presented to investigate the influence of the gas-thermal inertia and power-gas-heat interdependency. The natural gas system and district heating system vulnerabilities are quantified by a set of interdependency metrics developed based on multi-stage resilience curves. The results show that the proposed metrics can provide useful upgrade information to enhance the integrated energy system resilience.

VI. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper proposes a structured review framework focusing on the research progress of decision support for SDS resilience against natural disasters during health pandemics. Specifically, the stochastic impact assessment methods of natural disasters and human activities on SDSs, the SDS planning and operation models against natural disasters during health pandemics, and the resilience-oriented decision-making for SDS considering health pandemics are comprehensively surveyed. Compared to the existing works which only consider the challenges arising from natural disasters, the proposed review framework incorporates the impact of health pandemic on resilience in the form of human behavior variation. An illustration in Fig. 12 presents the resilience with or without human behavior involvement. When considering natural disasters without health pandemics, the human behavior impact on SDS resilience is insignificant. Hence, a reliable operation and maintenance can be achieved. By contrast, when natural disasters strike during health pandemics, the human behavior variation can lead to employee shortages, uncertain changes in load demand, and limited spare parts and budget. As a result, the restoration and repair process becomes more complicated and intractable. In addition, based on the review, we observe that the SDS resilience against natural disasters during health pandemics still faces enormous challenges. In particular, the resilience-oriented decision-making considering human behavior variation are lack of study. In the rest of this section, we will discuss the challenges and highlight the potential future research directions.

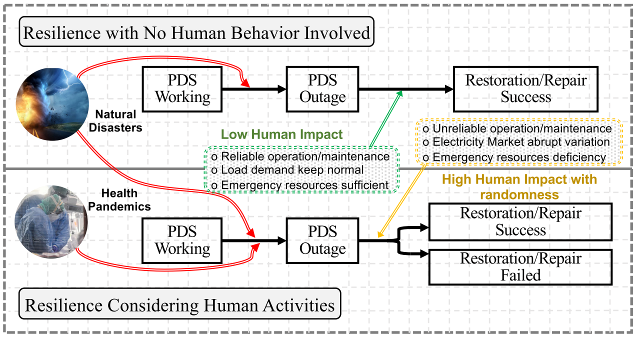


FIGURE 12. Illustration of involving human activity in terms of SDS resilience against natural disasters during health pandemics.

A. CO-OPTIMIZATION OF RESILIENT STRATEGIES AND COGNITIVE PROCESS AGAINST NATURAL DISASTERS DURING HEALTH PANDEMICS

Appropriate measures are essential to mitigate the impact of human errors on SDS resilience against natural disasters during health pandemics. However, systematic research works are still lacking in the evaluation of resilient strategies and cognitive process correlation. In other words, the negative impact on SDS resilience caused by potential human errors that arise from situational awareness, decision-making and action implementation still needs investigation. A majority of the existing research is based on reliable human activities. Such an assumption is not practical, especially when natural disasters strike during health pandemics. Since as long as an operation is with human participation, there will be potential human errors to break down the SDSs. Therefore, the co-optimization of resilient strategies and cognitive processes needs further study.

For example, stochastic fatigue/stress assessment can be included in the restoration and repair problem to model more realistic scenarios and obtain more reasonable shift roasters for safe operation as well as maintenance. In addition, considering the level of experience and psychological endurance of different employees, flexible workload distribution, and staff grouping mechanisms are beneficial to ensure that all the post-contingency tasks can be fulfilled with high quality and on time. Also, an uncertain amount of extra time can be advantageous to alleviate emotional impact during different stages of health pandemics. A more simplified sequence of actions by sacrificing some loads or supplementary budget is also likely to improve operation and maintenance reliability.

B. SOLUTIONS TO THE DEPENDENCY OF RESTORATION AFTER NATURAL DISASTERS AND DEMAND VARIATION DURING HEALTH PANDEMICS

The challenges of health pandemics on the electricity market can be summarized as follows: 1) Uncertain residential load profile with variable on-peak hours and demand valleys, 2) Increased consumption of residential customers distributed in a large geographic area, and 3) Variation of load priority due to the non-negligibility of residential customers. These challenges during health pandemics bring a large amount of difficulties to SDS operation in particular when emergency distributed generation is needed. Among the different types of DERs, DGs and MEGs have large capacity and refuelable properties, which make them suitable in dealing with long-lasting outages, and being able to black start due to stable output performance [130]. In comparison, ESSs and MESSs are good at ancillary services such as load leveling, peak shaving, and reactive power support [131], [136]. RESs can enhance SDS resilience by offering a low-cost renewable power, while their intermittent energy output needs to be addressed by coordinating with other techniques such as ESSs and MESSs as well as advanced energy management strategies [137]. In this respect, several research works have already analyzed the microgrid formation after blackouts considering uncertain load profile and unstable RESs output [90], [91], and the energy transport mechanism from DGs, MEGs and RESs to ESS and MESSs to compensate power in dealing with peak demand in SDSs [100], [128], [138].

However, strategies in tackling the dependency and interaction of emergency power supply after natural disasters, and variable load consumption, profiles and priority during health pandemics are not well studied. First, resilient planning such as DERs and RCSs placement against natural disasters can be compatible with that during health pandemics in case of load demand variation. Second, new difficulties on voltage or frequency regulation during the emergency restoration, which is resulted by geographically distributed residential customers with uncertain load profiles, can be addressed via new techniques. Third, the utilization of ESSs, MESSs and EVs in coordination with DGs, MEGs and RESs can be further studied to be more concentrated on residential customers with uncertain load profiles. Fourth, the schedule and route of repair crews can be matched with the alteration of load priority during health pandemics, and built up in conjunction with the restoration of uncertain load demand.

C. RESILIENT STRATEGIES AGAINST NATURAL DISASTERS CONSIDERING LIMITED RESOURCES DURING HEALTH PANDEMICS

Limited crews, spare parts and budget will result in deteriorated responsiveness and prolonged outage duration when dealing with natural disasters during health pandemics. For crew members, the existing research is mostly concentrated on electrical components repair, while other types of crews such as tree trimming members, DGs refueling workers and mDERs drivers, which can similarly affect SDS resilience, are rarely considered. Also, how health pandemics reduce the number of available crews during a natural disaster is not clear. Thus, related models are necessary to develop and incorporated into the optimization problem. Moreover, how the reduced number of crews in a team can influence team coordination or tasks implementation, probably leading to an increased human errors, needs to be further studied. For spare parts, inventory management can be more effective if proper preparation can be made in advance. For example, if the risk of health pandemics can be evaluated at the very early stage, and natural disasters at a high risk of happening can be identified, then utility companies can properly decide the inventory based on co-optimization of health pandemic models, natural disaster models, vulnerability of SDSs, and future repair possibilities.

For budget, the existing research is mainly focused on controlling the budget within limitation, and shedding loads if the budget is not available. Yet, this is not the case in terms of natural-disaster-induced outages during health pandemics. Since all the residential customers should be treated equally in getting emergency power, distributed generation will become deficient to restore a large amount of load simultaneously. To address this issue, novel restoration strategies need to be investigated. For example, on the customer-side, demand response can be a helpful starting point. In [139], the temporary demand reduction are demonstrated to be able to improve SDS resilience. This can be achieved by using smart meters. Accordingly, the residential customers can be informed of the real-time price and postpone some tasks to another demand valley with lower price. Alternatively, residential customers can be restored with power in a minimum range as communicated with utility companies in advance. On the supply-side, the rolling blackout is an intentional measure conducted by utility companies to avoid demand exceeding supply. For example, in 2011, an earthquake with magnitude M_L 9.0 hit eastern Japan, which caused 15 days of power shortages. The Tokyo Electric Power Company started a rolling blackout plan to divide the affected region into several areas, supplying them with emergency power alternately [140].

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