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News & Highlights

Enhancing the Resilience of Electricity Systems

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1. Introduction

The need for resilient electricity systems has come into prominence in the United States after major disruptions such as those associated with Superstorm Sandy; Hurricanes Harvey, Irma, Jose, Maria, and Katrina; the 2003 northeast US blackout; and growing awareness of the vulnerability of electric infrastructure to malicious physical and cyber attacks. Although such events generate significant press coverage in the immediate aftermath, the processes of preparing for and recovering from such events can stretch over years and decades. A new report from the National Academies of Sciences, Engineering, and Medicine (NASEM) titled "Enhancing the Resilience of the Nation's Electricity System" [1,2] was released on 20 July 2017. The report draws attention to the need to better understand the evolving threats and vulnerabilities of the US power system and makes recommendations for technologies, policies, and operational strategies to enhance the resilience of the US electricity system that may offer insights for other nations' electricity systems as well.

2. Background

Electricity is essential for our day-to-day lives. It powers homes, commercial and industrial activities, critical social services such as hospitals and emergency responders, and other vital infrastructures such as telecommunications, natural gas delivery, and transportation. However, electricity systems are vulnerable to diverse and evolving threats that can cause large-area outages that last for days, weeks, or longer. These outages can be caused by natural disasters such as hurricanes, earthquakes, and ice storms; manmade threats such as physical or cyber attacks; and low-probability events such as solar storms and other electromagnetic threats (Fig. 1) [1]. Different threats have different characteristics—for example, the amount of warning time that is available to grid operators—and cause different types of damage with different recovery needs. Recent hurricanes in Texas, Florida, and Puerto Rico provide a sobering reminder that when major outages happen, everyday tasks become difficult, economic damages can add up to billions, and lives can be lost.

To help provide guidance to US policy makers and others involved in the planning and operation of the electric power grid, the 113th US Congress requested that NASEM organize a committee of experts to identify technologies, policies, and organizational strategies that can increase the resilience of the US electricity system. The committee adopted the resilience framework presented by the National Infrastructure Advisory Council [3], and modified it slightly to emphasize the actions taking place in each stage: preparing, ameliorating, recovering, and learning (Fig. 2) [3]. Resilience is not just about lessening the likelihood that these outages will occur. It is also about limiting the consequences and disruptions caused by outages while power is out, restoring service rapidly afterwards, and learning from these experiences in order to better deal with events in the future.

In this way, resilience is a different concept than reliability, which has relatively well-established metrics. While US electricity system operators have a long history of maintaining high marks in reliability, it is difficult to measure resilience or compare the potential resilience benefits of different investment strategies. The committee recommended further research into the development of resilience metrics that can be used by industry and regulators, as well as studies into customer and economic valuation of more resilient electric service.

Implementing any strategy to improve the resilience of the US electricity system on a large scale is difficult, partly because of the complex organization of the power system and the many different entities involved in its functioning. Thousands of different organizations own, operate, service, or regulate the grid across the United States, including private, public, and cooperative utilities as well as state, regional, and federal agencies. Most electricity is generated

Cyber attacks Drought and water shortage Earthquakes Floods and storm surge	Hurricanes Ice storms Major operations errors Physical attacks Regional storms and tornados	Space weather and other electromagnetic threats Tsunamis Volcanic events Wildfires

Fig. 1. Large electricity outages can be caused by many diverse threats (shown in alphabetical order). (Reproduced from Ref. [1])

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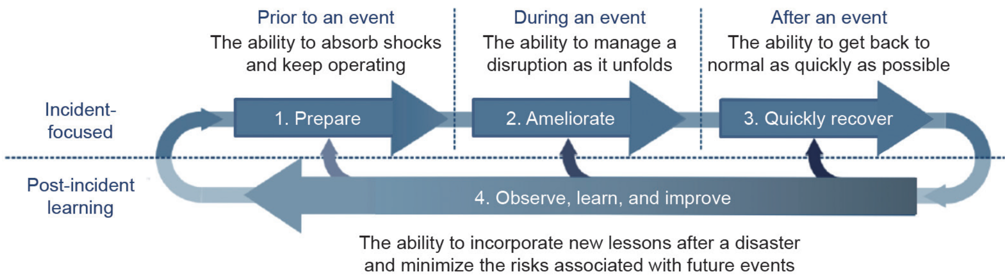

Fig. 2. The resilience process involves not only preparing to prevent outages (Stage 1), but also minimizing the impacts of outages during events (Stage 2), recovering quickly after outages (Stage 3), and continually learning to improve performance during future events (Stage 4). The committee organized much of the report following these stages. (This figure was modified slightly from the original produced by the National Infrastructure Advisory Council [3])

in large, centralized power plants, transmitted long distances at high voltages, and then distributed to residential, commercial, and industrial consumers at lower voltages. The network of electricity generators and high-voltage transmission lines, which is called the bulk power system, is subject to numerous operational, physical, and cyber security standards developed at a national level. Electricity distribution systems begin at substations, where high-voltage electricity from the bulk power system is converted to lower voltage and sent to end-users. Individual distribution utilities are regulated by state and local authorities or by oversight boards, and have different resource availability, technological sophistication, ownership structure, and oversight mechanisms. Because the grid—which is composed of both the bulk power system and local distribution networks—is a system governed by many independent decision-makers, it is a system without a single organization in charge or responsible for ensuring resilient electric service.

3. Drivers of change shaping the future of the US grid

In the context of this organizational complexity, the US electricity system has been undergoing dramatic change, driven in part by local and federal policies and market forces. In some parts of the country, power is still supplied by vertically integrated utilities that generate electricity in large power plants, move that power out over high-voltage transmission systems, and distribute it to end-use customers—all under a single utility's control. In other parts of the country, state regulators have tried to promote competitive markets, particularly in wholesale power sales between generators and electricity distribution companies, by breaking up vertically integrated utilities and separating generation, transmission, and distribution services. Today, in many areas of the United States, the high-voltage transmission lines that connect distribution and generation are controlled by independent regional transmission organizations or independent system operators that provide open access to transmission systems for generation facilities. In areas with restructured utilities, power flows over wires, and even customers' responses are increasingly determined by market forces.

In addition to institutional and regulatory changes, the electricity system in the United States has been undergoing dramatic technological change. There have been significant improvements in instrumentation and automation in both the bulk power and distribution systems. The grid in the United States is a complex "cyber-physical" system of innumerable physical, computing, and networked components spread out across the country. This allows the system to operate more efficiently and provides system operators with much better situational awareness, which can improve grid reliability and resilience in the face of outages.

There have also been changes in the generation resources used, with some states such as Hawaii and California rapidly adopting distributed energy resources (DERs) including distributed solar generation, demand response, dispatchable energy efficiency, customer-owned storage, and even microgrids. As these become an increasing fraction of the overall resource mix, grid planning, operation, and management must evolve to maintain grid reliability, resilience, and security. The committee noted that despite the increasing penetration of DERs, most US customers will continue to depend on the functioning of the large-scale, interconnected, tightly organized, and hierarchically structured electric grid for resilient service over at least the next two decades. Nevertheless, there are many opportunities to design and plan for DERs in ways that can improve resilience, as described in a number of the specific recommendations made by the committee.

In the longer term, many other factors will influence the design and operation of the electricity system, including: further changes in regulatory structures, particularly regarding the balance of federal and state oversight; changes in the sources of bulk power, including the larger fraction of natural gas generation and the shrinking fraction of nuclear and coal; greater penetration of DERs, including intermittent renewables; larger implementation of microgrids; and the uncertain impacts of a changing climate on grid planning and operations. Planning for grid resilience needs to take into account the expectation that the grid and its various institutions, technological features, legal structure, and economics will change—and in ways unknown today. This is particularly challenging given the fact that many investments in the grid are expensive, long-lived, and can be expected to be operating and recovering investments decades into the future.

Based on this important context, the National Academies Committee on Enhancing the Resilience of the Nation's Electric Power Transmission and Distribution System elaborated numerous findings and recommendations that detail strategies to enhance grid resilience. There is no "one-size-fits-all" solution to avoiding, planning for, coping with, and recovering from major outages, and strategies must take an all-hazards perspective, recognizing that systems are vulnerable to a variety and combination of potential disruptions.

4. Strategies to prevent outages and make them smaller

Resilience begins with preparative and preventative actions to make outages less likely or smaller in extent. Although the report focuses predominantly on large-scale outages, many of the approaches described may also reduce the occurrence of small routine outages and increase utility performance on common reliability metrics. The report [1] describes and recommends multiple strategies to make outages less frequent or smaller, including:

- Improving the health and reliability of individual grid components, for example through preventative maintenance;
- Designing the system's cyber-physical architecture to reduce the criticality of individual components;
- Rapidly providing better information and control strategies to operators through increased deployment of sensors and advanced data analytics; and

- Avoiding over-reliance on any single fuel source, particularly natural gas, which has vulnerable supply networks.

Many of these strategies focus on the bulk power system of large generators and high-voltage transmission lines; however, the rapid pace of technological change for distribution systems in some regions is bringing new opportunities to light. DERs and advanced automated controls on local distribution systems could play a larger role in preventing or limiting the spread of outages, for example, through automatic reconfiguration of circuits to isolate broken components or using DERs to maintain power quality (e.g., voltage and frequency within specified limits). A critical challenge in implementing any of these strategies on a meaningful scale is navigating the complex economic, institutional, and regulatory structures that oversee the US grid.

5. Strategies to reduce the costs and disruptions of outages while they occur

The second stage in the resilience framework is to minimize the impacts of outages when they do happen. Although large-scale outages are rare, some will occur and restoration may take a long time. It is essential that utilities, public agencies, and society more broadly prepare for prolonged periods of electricity loss and the subsequent loss of vital public services including heating and cooling, water and sewage pumping, traffic control, financial systems, healthcare, and emergency response. The effects of power outages vary depending on the weather, the types and locations of customers affected, and the duration of the outage. A central theme of this report is the need to improve how different elements of society imagine the diverse consequences of prolonged power outages. The report [1] recommends several strategies to help prepare for such unimaginable scenarios, including:

- Improving the reliability of customer-purchased backup power equipment (e.g., diesel generators) through more systematic testing and upkeep;
- Re-evaluating government stockpiles and contracts for the provision of emergency power equipment and fuel during disasters;
- Encouraging critical facility operators to pre-register information about their emergency power needs in a centralized and accessible database;
- Exploring the potential for dynamic and selective provisioning of power to specific circuits or even individual meters on a circuit using advanced technologies such as advanced metering infrastructure, DERs, and smart inverters; and
- Developing strategies to use distributed generation, hybrid vehicles, locomotives, ships, and other non-standard power sources to provide limited electric service during outages.

Advanced distribution technologies including DERs, microgrids that can separate from the larger grid and maintain small pockets of power, and intelligent controls in substations and on individual distribution lines could provide partial service to critical facilities during an outage. The report [1] recommends that state regulatory bodies and distribution system operators evaluate the legal, financial, and technical challenges associated with using customer-owned assets to provide partial service during major outages.

6. Strategies to expedite recovery and improve learning after outages

The last stages in the resilience framework involve recovery and learning from an outage. Effective restoration begins well before the disaster through preparatory activities including drills and stockpiling of key equipment. In the chaotic period after a large-scale power outage, utilities, first responders, and public agencies must work together to restore power quickly. In general, recovery entails an iterative process of assessing damage; coordinated activity to reconfigure, repair, and replace physical components; and a variety of activities to rebuild the cyber monitoring and control systems. However, in practice, restoration processes differ depending on the event and the type of damage caused, such as whether the cyber monitoring and control system is functioning and able to aid in damage assessment. The report [1] recommends several strategies to improve restoration activities for different damage scenarios, including:

- Developing standards for utility cyber control systems so that personnel on loan from other organizations can effectively participate in cyber mutual assistance agreements;
- Continuing research and demonstration activities for advanced power transformers that provide greater operational flexibility;
- Running restoration drills that engage key stakeholders from other critical infrastructure sectors such as communications, natural gas, and transportation; and
- Improving post-incident investigation practices in order to better learn from major outages and improve recovery processes for future outages.

7. Overarching recommendations

While these specific recommendations will incrementally advance the resilience of the nation's electricity system, the committee recognized that alone they may be insufficient, and that the United States must strive to develop a more systematic approach to grid resilience. The committee developed a set of overarching recommendations that described high-level priorities, including implanting available technologies more rapidly and continuing investments in research, development, and demonstration activities through the US Department of Energy. The last overarching recommendations recognize the unique and heterogeneous governance and operational structures of the US grid. The report [1] recommends the creation of multiple resilience assessment groups at the federal level in order to envision and raise awareness of grid vulnerabilities and the potential systemic impacts of large-area long-duration outages, particularly regarding events with which planners, operators, regulators, and responders have little or no experience. These groups should then collaborate with analogous groups formed at state and local levels to provide guidance and support to decision-makers planning and approving investments in grid resilience, thus helping to coordinate across federal, state, and local levels.

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