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**Recognizing the Role of Transmission in  
Electric System Resilience**

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PREPARED FOR



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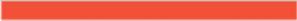
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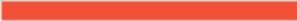
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## Table of Contents

Executive Summary .....	ii
I. Introduction.....	1
II. The Transmission Network Enables Bulk-System Resilience.....	3
III. Transmission System Investments Improve Electricity System Reliability and Resilience....	7
A. Developing a More Robust Transmission Network .....	8
B. Ameliorating Damage Arising From an Event .....	11
C. Recovering Quickly to Restore Service After an Event.....	13
D. Learning Resilience Lessons .....	14
IV. Anticipating Resilience Challenges.....	15
A. Operational Response Exercises .....	15
B. Transmission Planning.....	16
V. Conclusion .....	19

## Executive Summary

Resilience of the electric power system is the ability of the nation's electricity infrastructure to prevent or diminish damage from high-impact, low-probability events without undue disruption and to rapidly restore service when such disruptions occur. The robustness and flexibility of the high-voltage transmission grid will be critical to the FERC's consideration of electric system resilience for two reasons that track the definition of resilience itself:

- First, the transmission grid can absorb the damage potentially arising from multiple local generator outages without customer service disruptions by providing access to a network of technologically diverse and geographically dispersed set of power supplies. When sufficiently robust to maintain the flow of power under stressful conditions, transmission systems are inherently resilient.
- Second, the transmission sector has been pursuing investments in both physical assets and operational changes that strengthen the ability of the regional and inter-regional transmission grid to keep operating when challenged by adverse events and to aid the rapid restoration of service when damage and customer outages do occur.

The Federal Energy Regulatory Commission (FERC) can recognize the central role of the transmission grid in promoting electric system resilience by: (1) continuing to support an array of investments to strengthen the transmission grid and (2) expanding the role of resilience in regional and inter-regional transmission planning to build upon and expand the inherent resilience benefits that the transmission grid already provides.

Transmission planning has thus far focused primarily on the distinguishable (and valid) need for reliability in the short run. Accounting for the "insurance value" of a more flexible and robust transmission grid in the long-run can protect consumers from costly disruption during severe adverse events that likely will happen without forewarning of their timing, location, and severity. Like any insurance policy, transmission-focused planning and investments could provide cost-effective solutions to address fuel security concerns in some regions without requiring a redesign or rethinking of the competitive generation markets that have produced substantial consumer benefits. Finally, the FERC should consider resilience in addition to the Order 1000 goals of reliability, economics, and public policy, as a planning objective for both regional and inter-regional transmission expansion to help insure against large-scale disruption of electricity supply. This would represent an important step forward in transmission planning analysis and improve overall electric system resilience.

## I. Introduction

The business of generating, transmitting and delivering electric power has always involved a singular focus on “keeping the lights on” under all possible conditions, regardless of what labels – such as “reliability” or “resilience” – are used to describe the primary goal. Recently, concerns about the security and availability of generating fuels such as natural gas have been identified as potential threats to the resilience of the electricity system. This recent focus on generation has diverted attention from other key segments of the industry – particularly the high-voltage transmission grid – that traditionally have been and should continue to be a central focus of efforts to enhance resilience. This study explores the important role that transmission plays in grid resilience and how policies and investments directed at strengthening the transmission system can cost-effectively enhance the resilience of electricity supply.

In contrast to the well-developed and intensively-managed issue of electric service reliability, the understanding and analysis of electricity grid resilience is still developing. The concept of resilience focuses on how critical infrastructure manages through and, when necessary, recovers from high-impact, low-probability events such as severe weather or physical or cyber-attacks. For this report, we follow the widely-cited 2009 National Infrastructure Advisory Council (NAIC) definition of infrastructure resilience as:

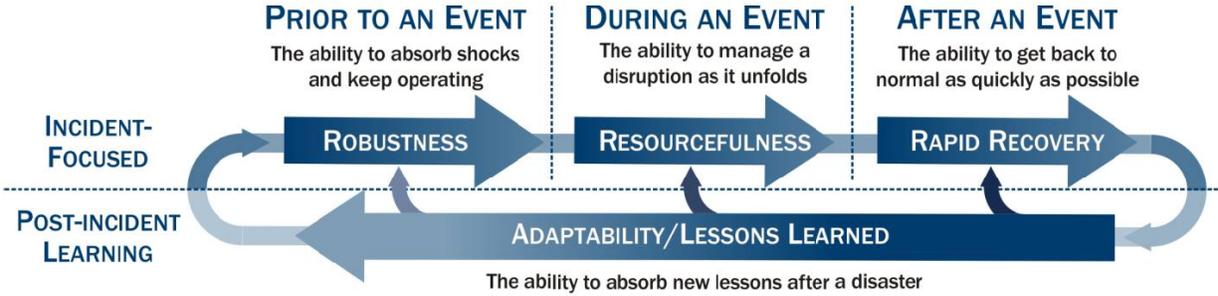
The ability to reduce the magnitude and/or duration of disruptive events. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and or rapidly recover from a potentially disruptive event.<sup>1</sup>

This definition was expanded upon in a follow-up 2010 report, *A Framework for Establishing Critical Infrastructure Resilience Goals*, to include a resilience construct based on robustness, resourcefulness, rapid recovery, and adaptability as shown in Figure 1.

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<sup>1</sup> National Infrastructure Advisory Council, *Critical Infrastructure Resilience: Final Report and Recommendations*, September 8, 2009, p. 17.

**Figure 1: The Sequence of the NIAC Resilience Construct**



Source: National Infrastructure Advisory Council, *A Framework for Establishing Critical Infrastructure Resilience Goals: Final Report and Recommendations by the Council*, October 19, 2010.

The evolution of the modern bulk power system, from municipal central stations serving local customers to large regional and interregional networks connecting distant resources to growing loads, has been driven by the inextricably linked goals of resilience, reliability, and economics. Increasing the geographic size or “footprint” of the bulk power system through transmission interconnection allows customers to capitalize on economies of scale and scope in energy, capacity, and reserves. As far back as the 1965 blackout that affected 30 million customers in the eastern United States and Canada, the recommendation has been to move toward more connected systems. The official report on the 1965 blackout states, “Isolated systems are not well adapted to modern needs either for purposes of economy or service” and recommended “... an acceleration of the present trend toward *stronger transmission networks within each system and stronger interconnections between systems* in order to achieve more reliable service at the lowest possible cost.”<sup>2</sup>

As the connection between bulk power generation and the local distribution system to serve retail customers, the transmission system is critical to the overall performance of the power sector and its resilience when challenged by infrequent but significantly adverse events. Strengthening the resilience of individual generators or the generation fleet overall will not increase the overall resilience of the system if the power cannot be delivered into an intact distribution system to serve customer loads. This applies within a recognized transmission region within Regional Transmission Organizations (RTOs) and between regions. Within regions, the

<sup>2</sup> Federal Power Commission, “Report to the President on the Power Failure in the Northeastern United States and the Province of Ontario on November 9-10, 1965,” December 6, 1965. p. 43 (emphasis added).

transmission network connects a diverse set of generators to distribution systems that serve customers. Inter-regionally, the transmission network connects neighboring systems to increase overall reliability and resilience by providing access to additional generation resources to increase benefits of trading across regions and for providing resources during emergency situations. Finally, transmission has been recognized as critical infrastructure since the resilience concept was defined, and therefore policies and investments to strengthen the transmission system have been central to the electricity industry's overall effort to promote and enhance resilience.<sup>3</sup>

This report highlights how existing transmission contributes to power system resilience and describes how evolving policies and new investments in transmission will further enhance power system resilience. In the next section, we explain how the transmission system helps maintain or restore power in cases where multiple simultaneous generation failures might threaten customer disruptions. We follow this with a discussion of how policies and investments in the transmission system mitigate vulnerabilities of the transmission system to high-impact low-probability events that can compromise resilience, and then we conclude by discussing how transmission owners and operators anticipate future resilience challenges through preparation and planning.

## **II. The Transmission Network Enables Bulk-System Resilience**

The power system can be vulnerable to disruptions originating at multiple levels, including events where a significant number of generating units experience unexpected outages. The transmission system provides an effective bulwark against threats to the generation fleet through the diversification of resources and multiple pathways for power to flow to distribution systems and ultimately customers. By providing customers access to generation resources with diverse geography, technology, and fuel sources, the transmission network buffers customers against extreme weather events that affect a specific geographic location or some external phenomenon (unavailability of fuel and physical or cyber-attacks) that affect only a portion of the generating units. In addition to other economic and reliability benefits, these resilience benefits occur both within and between regions.

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<sup>3</sup> See, for example, *Hardening and Resiliency: U.S. Energy Industry Response to Recent Hurricane Seasons*, U.S. Department of Energy, August 2010.

On a regional basis, transmission networks provide customers with access to a variety of generators, where resource and fuel diversity decreases the vulnerability to common mode failures and promotes resilience. For example, the transmission networks provide Southern California customers access to hydropower from the Pacific Northwest, nuclear energy from Arizona, solar and wind power from neighboring states, and natural gas generation from neighboring states. As a result of this diversity, customers did not experience interruption when the 2.2 GW San Onofre nuclear power plant unexpectedly shut down in 2012 and then officially retired in 2013. Likewise, southern California customers did not experience outages from the 2011-2016 drought, which affected the state's entire hydropower fleet,<sup>4</sup> or the 2015 Aliso Canyon gas leak, which affected natural gas availability for a whole fleet of generating plants in southern California. While the fuel diversity among generators may exist over geographic regions, customers only benefit from such diversity when these resources are interconnected through the transmission network.

The broad geographic scope of the transmission system provides resilience to the system. For example, severe or extreme weather events typically affect only a portion of the region served by the wider grid. During and following such an event, customers in the affected regions are able to draw power from unaffected generating plants through the regional transmission system. For example, during a cold snap in January 2018 that significantly affected MISO South, power flows from MISO into MISO South (parts of Arkansas, Louisiana, Mississippi and Texas) briefly exceeded the contractual regional directional transfer (RDT) limit, enabling MISO South to avoid load shedding. By drawing power from the rest of MISO, the southern region maintained power delivery during a period of record demand and significant generator outages.<sup>5</sup>

The diversity of the resources interconnected through the transmission network also provides robustness to cyber or physical attacks waged against a specific generator type, fuel source, or utility service area. From a reliability perspective, the bulk power system is designed to withstand outages, and a certain level of unexpected generator outages are part of standard

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<sup>4</sup> According to the California Department of Water Resources, this included four of the driest consecutive years on record, 2012-2014. California Department of Water Resources, "Water Year 2017: What a Difference a Year Makes," September, 2017. p.2

<sup>5</sup> See "Exceeding transmission limits prevented MISO South blackouts in Jan: IMM" by Mark Watson, *MW Daily*, March 27, 2018.

operating and planning procedures within the power system. From a resilience perspective, should multiple units within a region or a type of generating station across regions become unavailable to supply power, operators will be able to draw from other, unaffected and available resources to the extent enabled by the transmission network.<sup>6</sup>

If an adverse event overwhelms the regional ability to absorb or manage the event, inter-regional transmission connections allow regional operators to “lean” on neighbors for emergency support. Thus, in cases where generation outages in one region threaten reliability, interties with neighboring regions can substitute for the inadequate generating capacity within that region. The weaknesses associated with lack of inter-regional transmission were vividly on display during the 1965 Northeast Blackout, which affected more than 80,000 square miles and 30 million customers across the United States and Canada with most outages lasting several hours.<sup>7</sup> Recognition that stronger interregional transmission links could have prevented these outages led to the expansion of the transmission grid into the large regional networks we rely on today.

The reliability benefit of such regional and interregional transmission network has not changed since. A 2013 study that Brattle and Astrape Consulting conducted for FERC found that interties offer substantial benefits from both a physical reliability and economic perspective:

Strong interties with neighboring regions provide both economic and physical reliability value during peaking conditions. Load and generation diversity mean that the most extreme scarcity conditions are unlikely to occur at the same time in neighboring markets.<sup>8</sup>

As the quote above implies, when regional resource adequacy is threatened because of a lack of generation diversity, then interties with neighboring systems with a different fuel and technology mix (one less affected by the conditions adversely affecting specific regional

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<sup>6</sup> This does not negate the potential for events for which insufficient power is capable of importing into the region or regions with units unexpectedly out of service.

<sup>7</sup> A tripped relay in Ontario caused the outage, which then cascaded through New York and New England; all service was restored within 14 hours. Additional interregional transmission capacity could have mitigated the outage. See Federal Power Commission, “Report to the President on the Power Failure in the Northeastern United States and the Province of Ontario on November 9-10, 1965,” December 6, 1965.

<sup>8</sup> See Johannes P. Pfeifenberger, Kathleen Spees (Brattle) and Kevin Carden, Nick Wintermantel (Astrape) *Resource Adequacy Requirements: Reliability and Economic Implications*, September 2013, p. 57, found at <https://www.ferc.gov/legal/staff-reports/2014/02-07-14-consultant-report.pdf>.

resources) can provide a cost-effective alternative to retaining or building new resources to address generation diversity or overreliance on a particular fuel. One of the steps taken by PJM during the Polar Vortex episode in the Eastern U.S. in January 2014 was to access energy and reserves from adjacent regions on an emergency basis, which helped manage shortages within the RTO.<sup>9</sup> The potential value of creating resource diversity through inter-regional interconnection is well illustrated by ISO New England’s analysis of diminishing its heavy reliance on natural gas combined with natural gas delivery constraints.<sup>10</sup> One option studied to address the current lack of fuel diversity in New England is the expansion of interregional transmission from New York, Quebec, and New Brunswick designed in part to access more hydro and other renewable generation facilities located in Canada.<sup>11</sup>

The ability for transmission systems to increase reliability and resilience of regional or inter-regional power systems is dependent upon the strength of interconnections. This strength depends both on the number of lines and the capacity of those transmission lines. In its comment to FERC, PJM noted that transmission designs that are “robust and electrically dense” (compared with sparse networks) provide resilience benefits.<sup>12</sup> A dense network with many interconnections is more resilient as power can flow over many parallel routes. The ability for that power to flow, however, is dependent upon having sufficient capacity. Thus, to realize resilience benefits, the transmission network must be able to provide capacity beyond the normal day-to-day level, and perhaps even beyond the anticipated stress scenario utilization of the facilities.<sup>13</sup> Transmission planning should take into account the potential resilience value of investments when considering expansion projects.

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<sup>9</sup> See *Analysis of Operational Events and Market Impacts During the January 2014 Cold Weather Events*, PJM Interconnection, May 8, 2014, p. 19-20.

<sup>10</sup> See for example, ISO New England, “Operational Fuel-Security Analysis,” January 17, 2018.

<sup>11</sup> Ibid.

<sup>12</sup> *Comments and Responses of PJM Interconnection, L.L.C.*, Docket No. AD18-7-000, March 9, 2018, p. 43.

<sup>13</sup> Transmission lines are typically rated for both “normal” and “emergency” operation, with the “emergency” rating available for short time periods of overloading. For the transmission system to accommodate unanticipated and potentially large flows for a sustained period, the headroom created through emergency ratings may be insufficient.

### III. Transmission System Investments Improve Electricity System Reliability and Resilience

Although recent concern surrounding electric system resilience has focused on fuel security and resource adequacy, inadequate generation almost never results in customer outages. Instead, the vast majority of customer outages occur from damage to distribution systems caused by such events as severe storms. According to the Quadrennial Energy Review:

Failures on the distribution system are typically responsible for more than 90 percent of electric power interruptions, both in terms of the duration and frequency of outages. Damage to the transmission system, while infrequent, can result in more widespread major power outages that affect large numbers of customers and large total loads.<sup>14</sup>

Because the transmission system has been designed to withstand contingencies and adverse conditions, the transmission network routinely experiences severe weather events without causing customer outages. When the robustness of the transmission infrastructure is overwhelmed, however, sustained and widespread customer outages can occur, for example when extreme weather topples transmission towers across a wide region or operators are unable to manage grid instability arising from faults or outages. Due to their broad impact, these rare events are extensively studied *ex post* to advance understanding of vulnerabilities and explore and adopt measures to reduce future impacts. As a result, much of the analysis of resilience in the bulk power system focuses on high-impact, low probability events that directly affect transmission, which has supported some policy reforms and investments to address transmission resilience issues. Nevertheless, much more can be achieved, and we discuss the evolving policies and investments relating to transmission planning, physical infrastructure development and operations below, using the four NIAC resilience elements – robustness, resourcefulness, rapid recovery, and adaptability – as a framework to describe their overall role in responding to a resilience threat or event.<sup>15</sup>

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<sup>14</sup> U.S. Department of Energy, *Transforming the Nation's Electricity Sector: The Second Installment of the QER*, January 2017, Chapter 4 “Ensuring Electricity System Reliability, Security and Resilience” p. 4-29.

<sup>15</sup> It should be noted that transmission and distribution facilities share some failure modes, particularly extreme weather damage. Because distribution facilities are more vulnerable to storm damage, some of the programs that we highlight below primarily focus on distribution infrastructure; however,

## A. DEVELOPING A MORE ROBUST TRANSMISSION NETWORK

The robustness of the transmission network, its ability to absorb shocks and continue functioning, continues to be enhanced by the hardening of existing infrastructure and increasing connectivity within and between regions. Hardening the current infrastructure makes it less vulnerable to equipment failure as a result of major events, such as severe weather or human attack. This hardening of the existing infrastructure can include upgrading the physical strength of existing infrastructure (e.g., storm resilience), relocation of assets to less vulnerable locations, increasing transmission system capacity and connectivity, adding physical or cyber security, and improving operational practices.

Storm damage to the transmission network frequently results in reinvestment into more robust infrastructure. While not nearly as vulnerable to storm damage as local distribution systems, the transmission network has suffered damage from especially severe weather events, such as the catastrophic ice storm that hit New England and Eastern Canada in 1998. That storm resulted in the collapse of 770 transmission towers,<sup>16</sup> and in eastern Maine, a damaged switch affected about 40% of Eastern Maine Electric Coop's customers for nine hours.<sup>17</sup> Overall, the transmission damage which, combined with extensive damage to distribution systems, caused outages affecting hundreds of thousands of customers for three weeks or more. Hurricane Katrina in 2005 destroyed 1,515 transmission structures and forced 300 substations offline.<sup>18</sup> Likewise, Superstorm Sandy affected over 200 transmission lines across the northeast and mid-Atlantic.<sup>19</sup>

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storms can damage high voltage power lines and substations through flooding, high winds, ice accumulation and other modes that can and do affect both transmission and distribution elements.

<sup>16</sup> National Academies of Sciences, Engineering and Medicine, 2017, *Enhancing the Resilience of the Nation's Electricity System*, p. 13.

<sup>17</sup> Jones, Kathleen and Nathan Mulherin, U.S. Army Corps of Engineers, *An Evaluation of the Severity of the January 1998 Ice Storm in Northern New England: Report for FEMA Region 1*, April 1998.

<sup>18</sup> These events are described in National Academies of Sciences, Engineering and Medicine, 2017, *Enhancing the Resilience of the Nation's Electricity System*, p. 13. It should be noted that when severe weather damages both transmission and distribution systems, attributing the length of customer outages to restoring transmission or distribution may not provide an accurate appraisal of the relative impacts for specific cases.

<sup>19</sup> Office of Electricity Delivery and Energy Reliability U.S. Department of Energy, *Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure*, April 2013.

After the 2004-2005 hurricane season in Florida, the state legislature ordered the Public Service Commission to “conduct a review to determine what should be done to enhance the reliability of Florida’s transmission and distribution grids during extreme weather events, including the strengthening of distribution and transmission facilities.” The resulting program included inspection, forensic analysis of failed transmission structures and a schedule for upgrading and replacing vulnerable equipment.<sup>20</sup>

In response to physical attacks, utilities have added physical security measures following the creation of the NERC Critical Infrastructure Protection (CIP) standards. In April 2013, PG&E’s Metcalf Transmission Substation was targeted by gunman, resulting in the damaging of 17 transformers. Former FERC Chairman Jon Wellinghof referred to the attack as “the most significant incident of domestic terrorism involving the grid that has ever occurred.”<sup>21</sup> The attack caused more than \$15 million in damage and took nearly a month to repair, but did not result in service disruption to customers due to the resilience of the local transmission and distribution system.<sup>22</sup> In Nogales, Arizona, a failed attempt to detonate an explosion at a peaking plant by igniting the diesel fuel tank in June 2014 would have affected 30,000 customers if the attack had damaged the adjacent substation. As a large infrastructure system with thousands of exposed assets, including substations and transmission lines, individual assets are vulnerable to physical attack,<sup>23</sup> and the CIP standards, authorized under FERC Order 802, were put in place following the Metcalf substation attack. These standards require utilities to identify and protect

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<sup>20</sup> Florida Public Service Commission, *Report to the Legislature on Enhancing the Reliability of Florida's Distribution and Transmission Grids During Extreme Weather*, July 2007.

<sup>21</sup> Smith, Rebecca, “Assault on California Power Station Raises Alarm on Potential for Terrorism,” Wall Street Journal. Published February 4, 2014.

<sup>22</sup> Barker, David, “FBI: Attack on PG&E South Bay Substation wasn’t Terrorism,” SF Gate. Published September 11, 2014.

<sup>23</sup> In addition to the incidents discussed here, transmission insulators are frequent targets for vandalism, and transmission lines may be targeted for protest. For example, in the 1970s, protesting against a new transmission line in Minnesota, a group called the Bolt Weevils shot out over 5,000 insulators and destroyed 8 transmission towers.

Minnesota Historical Society, Minnesota Powerline Construction Oral History Project, Ed Schrom narrator and Edward P. Nelson interviewer, 1981.

key assets.<sup>24</sup> As physical threats to the system increase and new assets are identified as critical to system operation, transmission owners will continue to enhance physical security.

The robustness of the transmission system also has been enhanced by increasing the connectivity of the network and the transfer capabilities on those connections. When unanticipated failures do occur on the network, increased connectivity can help diminish the impact on the system and may lessen the importance of any single element failure. Essentially, operators can re-route power in response to economic, reliability, or resilience events. The 1965 blackout was an illustration of the lack of interconnectivity, but following the blackout, the transmission capacity was increased within and between New England, New York, and the mid-Atlantic regions, greatly improving the power system's reliability and resilience.

Nationally and across regional networks, transmission system regulators and operators have responded to resilience challenges by improving operational practices and creating standardization and information sharing protocols. In reaction to the 1965 blackout, NERC was created and initially established voluntary protocols. Forty years later in 2005, NERC guidelines and protocols that set forth common reliability metrics, definitions, and requirements became mandatory, in part as a response to the operational failings that precipitated the blackout that affected the U.S. Northeast/Midwest and Canada on August 14, 2003.

A December 2015 cyber-attack in Ukraine that resulted in service interruptions to 225,000 customers clearly demonstrated the potential impact of a cyber-attack on the transmission and distribution sectors. These attacks disconnected seven 110 kV substations and twenty-three 35 kV substations for three hours through disruption of the Supervisory Control and Data Acquisition System (SCADA). While focused mostly on a local transmission and distribution system assets, the event highlighted the potential vulnerability of regional power system networks to malicious cyber intrusion. In March 2018, the Department of Homeland Security issued an alert outlining how Russian government cyber actors were actively targeting U.S. energy and other critical

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<sup>24</sup> These key assets are those that, "if rendered inoperable or damaged as a result of a physical attack, could result in instability, uncontrolled separation, or cascading within an interconnection." NERC Standard CIP-014-2. p.1

infrastructure sectors.<sup>25</sup> Although cyber-attacks against U.S. utilities have not yet caused sustained reported damage, the vulnerability is widely acknowledged and the industry has been actively sharing information and establishing protocols to harden against such an attack for nearly two decades. As far back as 2000, NERC established the Electricity Information Sharing and Analysis Center (E-ISAC) to share information on potential vulnerabilities, and in 2018 the Department of Energy (DOE) launched its own Office of Cybersecurity, Energy Security, and Emergency Response to prepare for and respond to cyber-attack, physical attacks, and storm damage.

## **B. AMELIORATING DAMAGE ARISING FROM AN EVENT**

Investments in sensing equipment and control operations can allow transmissions system operators to react more quickly and effectively to system disturbance by isolating the damage and re-routing power to non-damaged areas. Re-routing power and isolating damaged areas relies on operators having access to up-to-date information on component status and access to tools and technology to re-route power flows without causing more problems. Ongoing investments in sensing equipment and potential investments in technologies that allow operators greater control of flows increase the ability of operators to manage an event as it unfolds.

Operator responses to transmission events can be prophylactic, adapting the system to accommodate a particular asset approaching failure, or responsive to an event, such as a physical attack, on the grid. Whether anticipatory or responsive, transmission owners have installed additional sensing equipment to the transmission system to provide system operators with accurate real-time system status information. For example, during hurricanes in Florida, operators were unaware in real-time of flooding in substations. Without this knowledge, operators were unable to triage the situation by removing the substations from service. In response to the outages caused by damaged substations, Florida Power and Light installed real-time water monitors at 223 substations to allow the company to proactively shut-down substations to limit and mitigate damage.<sup>26</sup>

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<sup>25</sup> See U.S. Computer Emergency Readiness Team (US-CERT) Alert TA 18-074A, “Russian Government Cyber Activity Targeting Energy and Other Critical Infrastructure Sectors” found at <https://www.us-cert.gov/ncas/alerts/TA18-074A>.

<sup>26</sup> This type of investment also enhances rapid recovery by avoiding repair or replacement needs.

During the 2003 Northeast/Midwest U.S. blackout, operators did not have access to accurate information on the wider-system status, which could have helped limit the blackout's reach. The 2003 blackout was, at a high level, caused by transmission line outage in combination with operator errors. The initiating event for the blackout was a transmission line that was heated up through heavy usage, sagged, came into contact with vegetation, and then tripped offline. When that transmission line tripped offline, power flowed through alternative routes, overloading those lines, and causing cascading failures before operators were able to understand and react to the event. While the power system is planned to withstand the loss of one or several major elements, operators were initially unaware of the system outages and then failed to communicate with neighboring systems. The cascading blackout resulted in the loss of power to over 50 million customers in Canada and the United States, and the outage lasted for up to four days in some areas.<sup>27</sup> The economic cost of this event has been estimated between \$4 billion and \$10 billion.<sup>28</sup> In response to the need to understand and communicate operational status, over 800 phase measurement units (PMUs) that provide real-time system-status data were installed, and this data is shared within and across regions.<sup>29</sup> The measurements from these devices could have allowed operators to isolate the transmission failure and prevent the wide-area outages in the 2003 blackout.

New technologies and tools have the potential to allow transmission operators greater control over the flows on the network and proactively manage events. One of the central challenges to operating the transmission system is that flows on individual transmission lines are largely dictated by physics rather than a system operator's preferences or needs. The ability to actively control power flows would allow an operator to avoid, for example, overloading certain lines that may result in cascading failures. Technologies such as Flexible AC Transmission System (FACTS)

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Florida Power and Light, "FPL expects approximately 4.1 million customers may lose power at some point as a result of Hurricane Irma." News release published September 8, 2017.

<sup>27</sup> U.S.- Canada Power System Outage Task Force, *Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations*, April 2004. p. 1

<sup>28</sup> National Academies of Sciences, Engineering, and Medicine. *Enhancing the Resilience of the Nation's Electricity System*. Washington, DC: The National Academies Press. 2017. p.13

<sup>29</sup> North American SynchroPhaser Initiative, *PMUs and synchrophasor data flows in North America as of March 19, 2014*, No date.

devices and “topology control” can enhance a system operator’s availability to respond to events, as well as increase the efficiency of unit dispatch.<sup>30</sup> Investment in FACTS devices have the potential to allow operators to change flows by modifying transmission line properties through power electronics. Likewise, transmission switching, which is actively used by ISO/RTOs, allows operators to re-route flows by disconnecting and reconnecting lines; however, this is usually executed on longer timescales (*e.g.*, seasonal). Several RTOs have analyzed new approaches that would allow topology control on operational timescales.

### C. RECOVERING QUICKLY TO RESTORE SERVICE AFTER AN EVENT

Rapid recovery following a transmission event requires the inspection, replacement or repair of damaged transmission system components. These actions can require specialized workforces and components that can be expensive for individual utilities to maintain or replace; specialized workforce personnel might include helicopter pilots, and required components may include multi-million dollar assets such as large transformers. In response, utilities have been expanding sharing agreements to improve restoration time through increased access to components and workforces.

The most visible recovery initiatives in the power sector are utility mutual assistance programs, which dispatch lineman and other skilled workers to respond to large-scale events; these programs have reacted to major resilience events through a focus on nation-wide events and reorganization for improved efficiency. Electric companies organize into voluntary Regional Mutual Assistance Groups (RMAGs) and respond to regional and national events that affect multiple regions. For example, during the 2012 derecho that caused more than four million customers to lose power across the mid-Atlantic and Ohio, crews came from as far as Canada, Texas, and Wyoming to restore power,<sup>31</sup> and restoration following Superstorm Sandy involved crews from all RMAGs.<sup>32</sup> The scale of the response required for Superstorm Sandy revealed weaknesses in the organization for national-scale responses, and as a result, three RMAGs in New England consolidated into a single entity and the Edison Electric Institute (EEI) members

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<sup>30</sup> Topology control refers to the re-routing of power by adding and remove transmission lines from service.

<sup>31</sup> Edison Electric Institute, *Understanding the Electric Power Industry’s Response and Restoration Process*, No date. p. 4

<sup>32</sup> Ibid. p. 5

developed a framework to coordinate national responses.<sup>33</sup> EEI runs storm drills to prepare utilities for the nation-wide events as well table-top drills with federal organizations.<sup>34</sup> The scale and duration of these events qualify as tests to resilience, and although they involved damage to both distribution and transmission system elements, the repair to the transmission system was a necessary part of the restoration process.

In addition to personnel, utilities maintain spare components and form pools to maintain spare components that are too expensive or difficult to obtain for restoration purposes. There are currently industry-led sharing programs, including NERC's Spare Equipment Database, Edison Electric's Spare Transformer Equipment Program (STEP), SpareConnect, Grid Assurance, Wattstock, and the Regional Equipment Sharing for Transmission Outage Restoration (RESTORE) group. The RESTORE group, for example, includes 28 utilities that agree to sell equipment to other members following a triggering event.<sup>35</sup> Several of these groups arose from vulnerabilities associated with the availability of Large Power Transformers (LPTs), which have limited domestic production capabilities, long lead times, and cost millions of dollars each. Utilities also maintain stockyards with spare conductors, towers, and related equipment for restoration purposes.

#### **D. LEARNING RESILIENCE LESSONS**

Because transmission resilience events have the potential to affect a broad geography, the events are closely studied and frequently result in changes to the system and system operations. That is, lessons learned provide the basis for improvements that reduce the impact of similar future events. These studies of transmission-related events mark the importance of the event and range from storm reports required by state governments to reports by the Federal Emergency Management Agency (FEMA), NERC, DOE, and others. As discussed in the sections above, these reports have resulted in actions including transmission line hardening, increased sharing of threat information, changes in reliability planning and system design standards, and improvements to wide-area sensing.

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<sup>33</sup> Fishbach, Amy, "Tactical Tips for Utility Mutual Assistance," T&D World. Published August 30, 2017.

<sup>34</sup> Ibid.

<sup>35</sup> Peter Maloney, "28 utilities join RESTORE program to boost grid resilience, reliability," Utility Dive, October 4, 2017.

## IV. Anticipating Resilience Challenges

The ongoing policy reforms and investments in the transmission sector largely reflect an adaptive response to major events and disturbances. However, the industry also proactively plans for unprecedented events that could plausibly threaten grid resilience. We highlight two of these activities below: war-game type response simulations and enhanced transmission planning.

### A. OPERATIONAL RESPONSE EXERCISES

As mentioned above, cyber-attacks in the U.S. have not yet disabled a significant transmission component or system, but the industry intensively prepares for that threat. In addition to the information sharing discussed previously, utilities practice responding to physical and cyber-threats through national simulations. NERC organizes biennial exercises, called GridEx, that allow utilities, law enforcement, federal agencies, and other operators of critical infrastructure systems to test and improve protocols in case of attack. The GridEx exercises include two day simulations for utilities and their partners as well as a one day executive-level tabletop game. Thus far, NERC has executed four GridEx events with 2017's GridEx IV drawing participation from over 450 entities, including water utilities, oil and natural gas companies, and telecommunication utilities.<sup>36</sup> The executive tabletop game in 2017 included participants from the White House National Security Council, DOE, the Department of Homeland Security, FEMA, the Department of Defense, the Federal Bureau of Investigation, the state of Maryland, the state of Virginia, and the National Guard in Illinois and Wisconsin.<sup>37</sup>

The GridEx simulations result in recommendations for policies, procedures, and investments within the power sector to increase readiness, including recommendations for regional and national programs and tools. During GridEx III, the need for cyber mutual assistance, analogous to the RMAGs for physical infrastructure, was highlighted. In response, a Cyber Mutual Assistance (CMA) program was developed that provides a pool of cyber security experts that are able to assist during an event, and the CMA program now includes more than 140 organizations, including natural gas and electric utilities, regional transmission operators, and independent

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<sup>36</sup> NERC, *Grid Security Exercise GridEx IV: Lessons Learned*, March 2018. p. 1

<sup>37</sup> *Ibid.* p.2

system operators across the United States and Canada.<sup>38</sup> Likewise, GridEx IV identified the need for alternative communications when actors were unable to communicate effectively due to a simulated communications blackout and produced a recommendation to establish contingency plans and make use of existing federal communication programs.<sup>39</sup>

## **B. TRANSMISSION PLANNING**

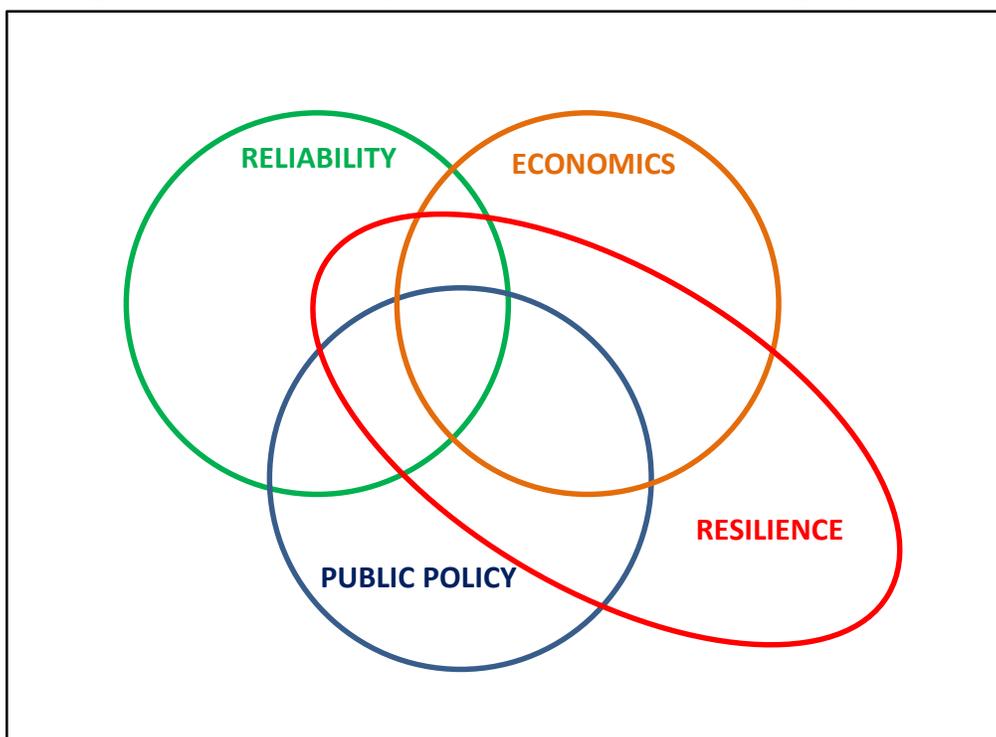
The goals for transmission planning arising from FERC Order 1000 are sometimes listed as reliability, economics and public policy; so-called “multi-value projects” serve these needs by enhancing reliability, increasing market efficiency and supporting public policies. It is reasonable to ask how “resilience” might fit into this framework, although that is not straightforward to answer. Resilience is related to reliability, but broader. It is a public policy goal, but other public policy goals, such as support for clean energy, may also be considered. Resilience is an economic issue in the same way that insurance and disaster preparedness has an economic dimension. In other words, resilience can involve all three Order 1000 objectives while remaining distinct in some ways. The Venn diagram below in Figure 2 shows the relationship between resilience and other transmission planning objectives, where resilience encompasses the entire area where economics, reliability and public policy intersect. This representation suggests that transmission planning that appropriately values economics, reliability and public policy objectives will also further resilience goals, and that considering resilience will enhance the benefits attributed to multi-value projects. It also suggests that stand-alone “resilience projects” could warrant consideration in planning processes, although that possibility remains unlikely in the current environment. Regardless of the degree of potential overlap between resilience and the other goals, however, a valuation of potential resilience benefits should help inform a more comprehensive analysis of the benefits of transmission projects.

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<sup>38</sup> Electricity Subsector Coordinating Council, *The ESCC's Cyber Mutual Assistance Program*, January 2018.

<sup>39</sup> NERC, *Grid Security Exercise GridEx IV: Lessons Learned*, March 2018. p. 15

**Figure 2: The Relationship between Transmission Planning Objectives**



Reliability planning for the transmission system already incorporates some high-impact, low-probability events, such as single or multiple large contingencies during 90<sup>th</sup> percentile peak load conditions, or simultaneous outages of the largest transmission and generation facilities during summer heat waves. To further incorporate potential resilience considerations, more extreme conditions could be evaluated, such as situations where a significant portion of the generating fleet becomes unavailable for an extended period of time, when assessing the expected benefits of constructing and sizing of a proposed transmission line.

Such assessments of low-probability, high-impact events are sometimes included in the economic assessment of transmission investments. For example, in a 2015 study, The Brattle Group recommended that “anticipatory” transmission planning also assess the economic benefits that might arise in unlikely but extremely adverse scenarios, in order to fully capture the insurance value of transmission.<sup>40</sup> The Brattle study examined the 2004 analysis of a second Palo Verde to

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<sup>40</sup> Johannes Pfeifenberger, Judy Chang, and Akarsh Sheilendranath, *Toward More Effective Transmission Planning: Addressing the Costs and Risks of an Insufficiently Flexible Electricity Grid*, The Brattle Group, April 2015. See also Johannes Pfeifenberger and Judy Chang, *Well Planned Electric Transmission Saves Customer Costs: Improved Transmission Planning is Key to the*

Devers line (PVD2) that would enable imports from Arizona into California. One high-impact, low-probability event considered was a long-term outage at the San Onofre nuclear plant—an outcome that actually occurred in 2012. While the case study focused on the economic benefits from lower-cost replacement power enabled by the PVD2 line, comparable reliability and resilience benefits would arise if other conditions impaired generation availability elsewhere in California.

Both economic and reliability benefits are highly correlated with resilience benefits, although these benefits (e.g., protection against high costs and possible service disruptions) are typically quantified in the context of analyzing a less extreme range of adverse conditions or scenarios. Quantifying the expected benefit of transmission under more severe disruptions will augment the overall benefits from transmission investment. Because additional transmission capacity can enhance the overall level of reliability and resilience of the bulk power system, planning should increasingly assess the potential resiliency benefit of adding transmission within and between RTOs and other market areas. A 2013 Brattle Group report for WIRES found that estimating the benefits of mitigating the impacts of extreme events and system contingencies was crucial to a comprehensive analysis of transmission benefits:

Transmission upgrades can provide insurance against extreme events, such as unusual weather conditions, fuel shortages, and multiple or sustained generation and transmission outages. Even if a range of typical generation and transmission outage scenarios are simulated during analyses of proposed projects, production cost simulations will not capture the impacts of extreme events; nor will they capture how proposed transmission investments can mitigate the potentially high costs resulting from these events. Although extreme events occur very infrequently, when they do they can significantly reduce the reliability of the system, induce load shed events, and impose high emergency power costs. Production cost savings from having a more robust transmission system under these circumstances include the reduction of high-cost generation and emergency procurements necessary to support the system. Additional economic value (discussed further below) includes the value of avoided load shed events.

The insurance value of additional transmission in reducing the impact of extreme events can be significant, despite the relatively low likelihood of occurrence.

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*Transition to a Carbon-Constrained Future*, The Brattle Group, June 2016, pp 6-11 for a synopsis of studies that address the economic benefits of transmission, including under severe adverse conditions.

While the value of increased system flexibility during extreme contingencies is difficult to estimate, system operators intrinsically know that increased system flexibility provides significant value. One approach to estimate these additional values is to use extreme historical market conditions and calculate the probability-weighted production cost benefits through simulations of the selected extreme events. For example, a production cost simulation analysis of the insurance benefits for the Paddock-Rockdale 345 kV transmission project in Wisconsin found that the project's probability-weighted savings from reducing the production and power purchase costs during a number of simulated extreme events (such as multiple transmission or nuclear plant outages similar to actual events that occurred in prior years) added as much as \$28 million to the production cost savings, offsetting 20% of total project costs.<sup>41</sup>

Transmission planning should incorporate resilience considerations. In addition, transmission options should be considered to address resilience concerns such as regional resource shortage or fuel diversity/security issues. Secure electricity imports enabled by expanded transmission may provide cost-effective resilience benefits even in cases where generation fuel security is identified as the proximate resilience threat. Analysis of interregional transmission proposals could also incorporate the potential to avoid or mitigate damage from high-impact, low-probability events that pose resilience threats.<sup>42</sup> Because resilience is a systemic issue, the design of public policy to enhance resilience should look broadly at potential solutions.

## V. Conclusion

Transmission has occupied a central role in the discussion of critical infrastructure resilience since that discussion began over a decade ago, and it continues to play an important role in the current resilience debate because:

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<sup>41</sup> See Judy Chang, Johannes Pfeifenberger, J. Michael Hagerty, *The Benefits of Electric Transmission: Identifying and Analyzing the Value of Investments*, Prepared by The Brattle Group for WIRES, July 2013, p. 39; for additional detail on the Paddock-Rockdale analysis see American Transmission Company LLC, Planning Analysis of the Paddock-Rockdale Project, April 5, 2007 (filed in PSCW Docket 137-CE-149, PSC Reference #75598) pp. 50-53.

<sup>42</sup> Of course, interregional transmission planning faces unique challenges. See Johannes Pfeifenberger, Judy Chang, and Akarsh Sheilendranath, *Toward More Effective Transmission Planning: Addressing the Costs and Risks of An Insufficiently Flexible Electricity Grid*, April 2015, pp. 25-37.

- Transmission can *enable* or *enhance* resilience, for example, when power from neighboring regions can flow to a region beset by outages of available generation (e.g., multiple outages associated with a particular fuel or technology);
- The transmission sector has *invested steadily* in enhanced reliability and resilience owing to rare but significant, widespread customer outages that can occur when transmission systems suffer physical damage or operations fail to avoid or contain delivery outages; and
- *Additional investments* in transmission expansion, innovative technology and operational controls can enhance grid resilience cost-effectively in the face of emerging threats.

The current focus on increasing the resilience of generation fleets in certain regions should not obscure or divert attention from the importance of the transmission grid to the overall resilience of the power system. Even as the generation fleet faces new and intensified challenges, the transmission system is needed to deliver the generated power to the distribution system and retail customers. Because the critical role of transmission to system reliability and resilience has long been recognized, continuous improvements have made the transmission more resilient over the past decades. Continuing attention and focus on transmission operation and investments will be necessary to identify and address existing and new threats to power system reliability and resilience.

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