Informing the **Transmission Discussion**

A Look at Renewables Integration and Resilience Issues for Power Transmission in Selected Regions of the United States

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WIRES®

Resilience

Contents

Resilience Background

- **Defined:** FERC defines resilience as the ability [of the electric system] to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event.
- **Regional variation:** Resilience issues vary between regions and even within large regions. Some resilience issues are common because they are global in nature or not peculiar to a region, including cyber and physical threats, geomagnetic disturbances, or electro-magnetic pulses. Many threats vary because of location and vulnerability of infrastructure, proximity to resources (including fuel), weather patterns, climatic trends, and seismic conditions.
- **NERC Framework:** NERC, along with the National Infrastructure Advisory Council (NIAC) and numerous other state and federal agencies, have been studying resilience needs for the U.S. electric system. NERC, tasked with overseeing bulk power system reliability, is also developing a resilience framework. These resilience activities are especially focused on long-duration events that can impact other critical infrastructure as well as first response and core social services. NERC's framework envisions four elements, reflecting different parts of an event occurrence:
  - Robustness – the ability to absorb shocks and continue operating
  - Resourcefulness – the ability to detect and manage a crisis as it unfolds
  - Rapid Recovery – the ability to get services back as quickly as possible in a coordinated and controlled manner, taking into consideration the extent of the damage
  - Adaptability – the ability to incorporate lessons learned from past events to improve resilience
- **Enhancement focus:** As the DOE has observed, resilience enhancement is generally focused on three primary goals: "(1) preventing or minimizing damage to help avoid or reduce adverse events; (2) expanding alternatives and enabling systems to continue operating despite damage; and/or (3) promoting a rapid return to normal operations when a disruption occurs (i.e., speed the rate of recovery). Resilience relates both to system improvements that prevent or reduce the impact of risks on reliability and to the ability of the system to recover more quickly." (QER2, at p. 4-42)
- **Two key questions:** One key question is how the increasing proliferation of renewable resources and their integration may affect these resilience elements and what kinds of complementary capabilities might grid integration bring to system robustness, resourcefulness, and recovery. Another important question is how can transmission investment support resilience.

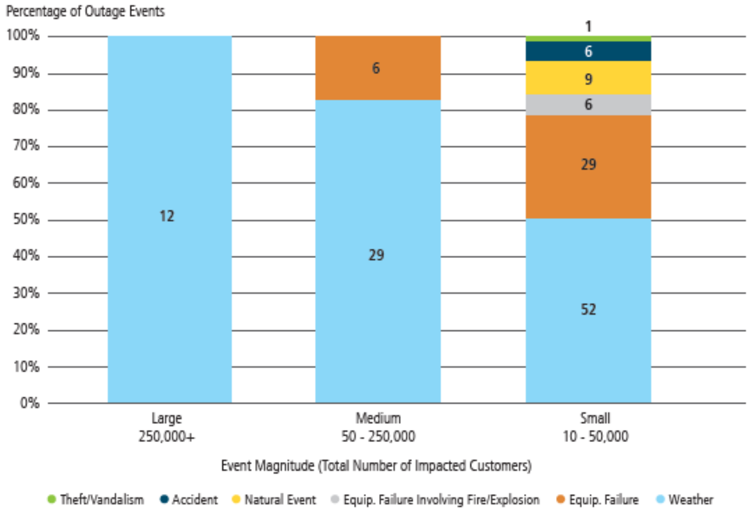
Sources: NIAC; NERC Steering Comm.; QER2

Access to Reserves in Fuel-Constrained Situations

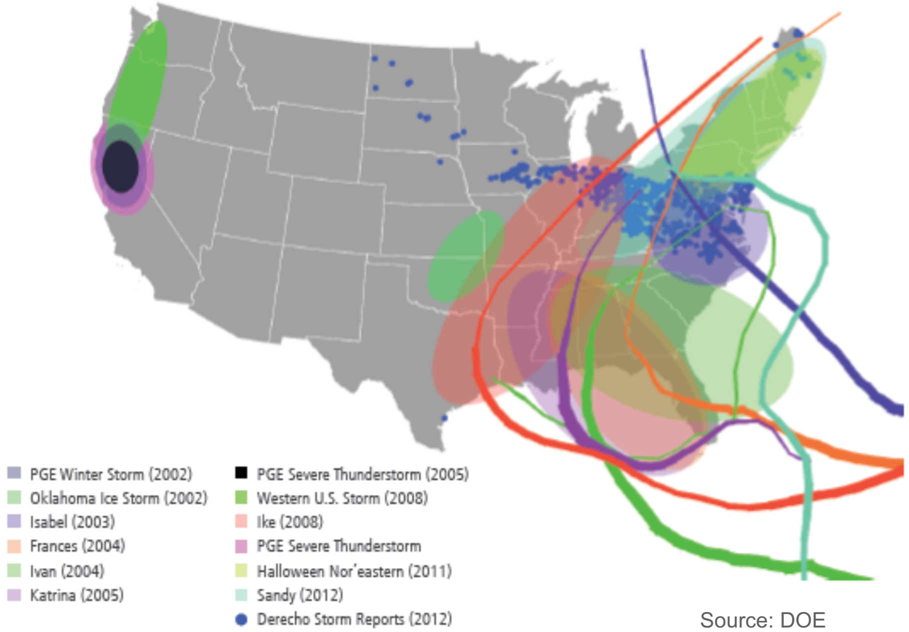
Access to Reserves in Fuel-Constrained Situations

- **Role of Weather:** Extreme weather continues to be a significant cause of outages, particularly widespread outages that affect large numbers of customers.
- **Generation shift:** Meanwhile, the grid is undergoing a shift in its generation mix. Driven by state policies and extended low natural gas prices, older thermal generation is being displaced by new, significant quantities of gas-fired and renewable (principally wind and solar) generation.
- **Limits of "just-in-time" resources:** These changes can have positive effects on emissions profiles and furtherance of state climate policy goals. But recent winter weather events have tested the increased dependency of the power system on dispatchable, gas-fired generation, which can comprise "just-in-time" resources in gas-constrained areas, because they rely on just-in-time delivery of natural gas across interstate pipelines to the region's generating stations. During cold winter conditions in regions like New England (but increasingly affecting other regions), these pipelines rapidly reach capacity and are either unable to fuel power plants or ambient conditions may cause performance issues for gas-fired generators. It must be acknowledged that renewable resources, which can be variable in output, can also constitute just-in-time resources.

U.S. Electric Outage Events by Cause and Magnitude (2015)



Major Weather-Related Outages Requiring a National Response (2002–2012)



Source: DOE

Sources: QER2; ISO-NE Fuel Security Analysis; ISO-NE Improvements

Access to Reserves in Fuel-Constrained Situations (Cont’d)

Access to Reserves – New England Case Study

- **Fuel challenges in New England:** According to ISO-New England (ISO-NE), the ISO, on multiple occasions in recent winters, has had to manage the system with uncertainty about whether power plants could arrange for the fuel—primarily natural gas—needed to run. It has addressed the effects of insufficient fuel supplies on the power system by employing real-time emergency-operating procedures and implementing market design changes to incentivize generators to arrange for adequate fuel supplies. The ISO has also worked on improving communication and coordination with natural gas pipeline operators.
- **Role of emergency procedures:** The ISO has been able to maintain power system reliability during severe winter conditions without using all of its emergency procedures. However, with its evolving generation mix, the region is vulnerable to variable and uncertain factors: gas pipeline constraints, liquefied natural gas and fuel oil import logistics, weather impacts on fuel deliveries, and the amount and timing of renewable energy generation.
- **Cold weather scenario planning and interregional transmission needs:** ISO-NE studied various resource combinations in a winter 2024–25 scenario, which included retirements of coal- and oil-fired generators, the availability of LNG, dual-fuel generators’ oil tank inventories (i.e., how often on-site fuel tanks can be filled at dual-fuel generators that can switch between natural gas and oil), electricity imports, and addition of renewable resources on the ISO-NE system. ISO-NE’s analysis revealed the following:
  - The loss of some key facilities would result in frequent energy shortages that would require frequent and long periods of rolling blackouts.
  - The New England system will largely depend upon two key elements: sufficient injections of LNG and electricity imports from neighboring regions.
  - Robust levels of imported electricity from neighboring power systems are essential to continued power system reliability. However, imports also present a degree of uncertainty and risk, since neighboring areas Québec, New York, and New Brunswick all experience similar winter weather as New England. The question is whether New England’s neighbors have sufficient supply to serve their own customers and supply New England with its needs.
  - Renewable energy can mitigate the region’s fuel-security risk, but it depends upon the resource type and deliverability. Winter peak occurs after sunset. While solar arrays can help reduce consumption of oil and natural gas for power generation on sunny winter days, preserving more oil and gas to help meet peak demand, solar PV itself does not help meet the daily winter peak in demand. Wind energy is not always available, but offshore wind tends to produce more steadily than onshore wind. Development of wind facilities and import capacity for clean energy will require more transmission investment.

The New England experience, then, demonstrates that additional transmission can be a tool for diversification and optionality of resources, including renewables, from both within New England (from onshore and offshore wind development) as well as adjacent regions.

Source: ISO-NE Fuel Security Analysis

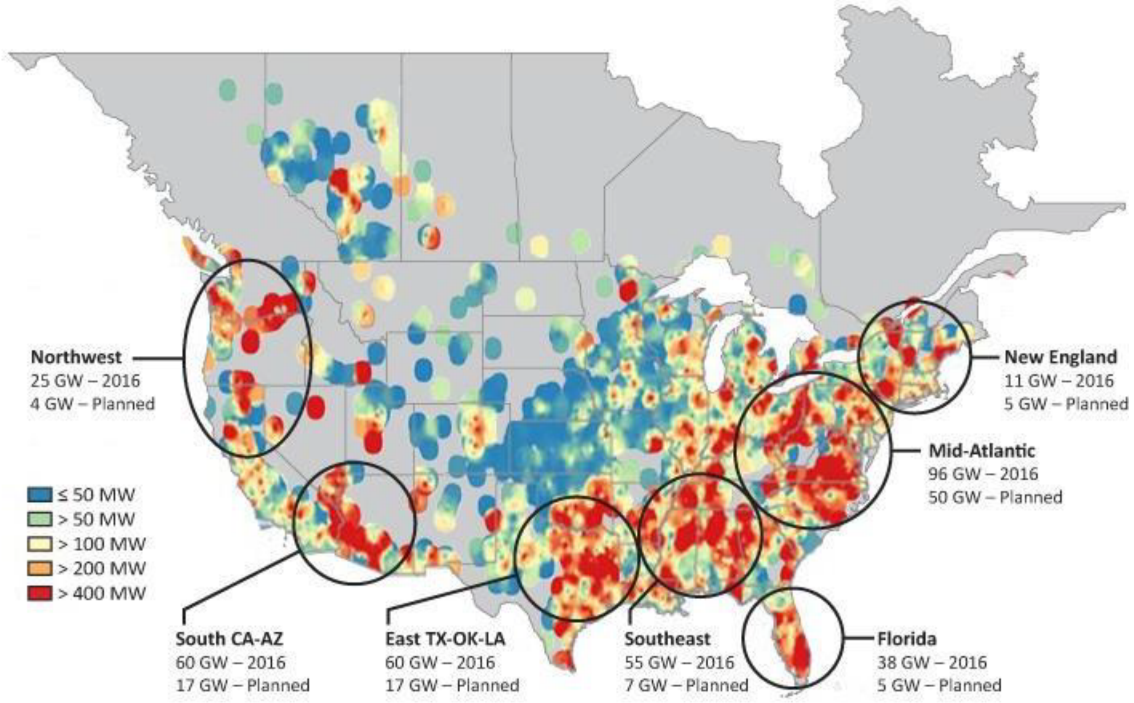
Access to Reserves in Fuel-Constrained Situations (Cont'd)

Access to Reserves – Southern California and Arizona Case Study

- **Southwest U.S. gas dependency:** Similar mitigation efforts for fuel constraints have been effected in southern California and Arizona. According to NERC, "This area has a high degree of dependence on natural gas storage, notably the Aliso Canyon storage facility. Ramping needs, due to an increased penetration of DERs and utility-scale solar PV, have made storage needs more significant in this area." (NERC SPOD, at p. 6)
  - **Aliso Canyon impacts:** In winter 2015, a significant leak was discovered in the Aliso Canyon facility, affecting price and supply of natural gas to the region. While there were no reliability effects, there was concern about gas curtailments that could result in electricity interruptions. Through operational coordination, tariff changes, and demand-side actions, risk was mitigated. Other mitigation measures included transmission upgrades, including a 500 kV line, phase shifters, synchronous condensers, and series reactors.
  - **NERC view:** As noted by NERC, "During peak demand or system element contingencies, additional generation may be needed to meet electric reliability. If natural gas supply cannot accommodate additional generation, southern California entities may need to rely on assistance from neighboring Balancing Authorities. This assumes ample supply outside southern California and adequate transmission capacity to move that power into the southern California system." (NERC SPOD, at pp. 30-31)

Transmission capacity can provide reliability and resilience benefits, where gas infrastructure is inadequate or constrained, and to mitigate impacts of disruptive and potentially long-lived events, like gas line breaks, freeze-offs, or storage facility outages.

Large Generation Clusters That Could Be Susceptible to Natural Gas Disruption

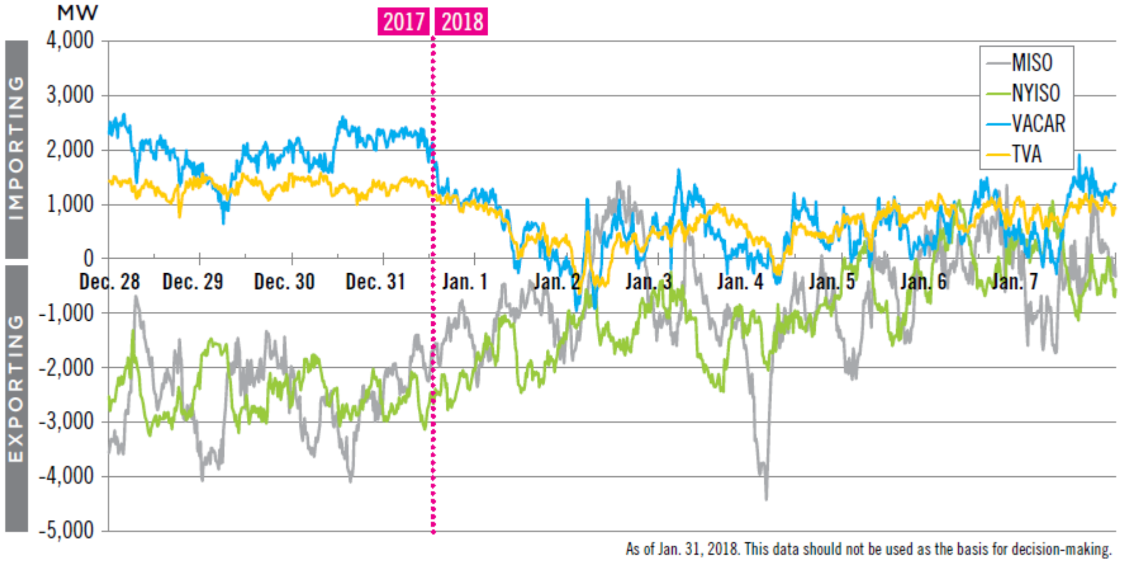


Source: NERC
Note: Each cluster represents at least 2 GWs of natural gas-fired power plants.

Sources: NERC SPOD; Southwest Blackout Even Report

Energy Imports and Exports During Extreme Conditions

PJM Transmission Tie Line Interchange (December 28, 2017 through January 7, 2018)



Source: PJM Interconnection

Energy Imports and Exports During Extreme Conditions – PJM "Bomb Cyclone" Experience

- A cold snap from December 27, 2017, to January 7, 2018, was accompanied by a "bomb cyclone" event from January 2 to 5. Prolonged cold temperatures were seen along the Eastern Seaboard, with snow and ice as far south as northern Florida.
- During the bomb cyclone week, prices in eastern PJM were about three times higher than in western PJM. For example, in Virginia, prices averaged about $222/MWh versus $76/MWh in northern Illinois (see Grid Vision, at p. 14).
- As PJM notes, during late December, PJM's interchange with its neighbors tracked normal patterns, importing from neighboring southern regions and exporting to MISO and NYISO. On January 1, transactions started flowing southward to VACAR (Virginia-Carolinas) and Tennessee Valley Authority (TVA), as they were experiencing some of their coldest weather. The flows did not return to normal until the end of the cold snap (PJM Benefits of Transmission, at pp. 36–37).

By maximizing the power transfer capability of the system in the most resilient way possible (using heavy-load voltage schedules and warnings), transmission played a key role in dealing with energy needs during extreme weather.

Sources: PJM Benefits of Transmission; Grid Vision

Situational Awareness, System Visibility, and Flexible Grid Technologies

Situational Awareness, System Visibility, and Flexible Grid Technologies*

- **Situational awareness is key:** System visibility and situational awareness are key elements of reliability, enhanced by processes, tools, and capabilities. Those capabilities are also critical in resilience terms of resourcefulness (i.e., the ability to detect and manage an unfolding crisis).
- **Changing nature of resources:** As grid operations become more reliant on accommodations of variable energy resources on both the bulk side (utility-scale wind and solar) and on the user side (DERs, energy efficiency, and demand response), one challenge is that the latter are less visible to bulk system operators. Indeed, as NERC has stated, “Increasing installations of DERs modify how distribution and transmission systems interact with each other. Transmission planners and operators may not have complete visibility and control of these resources, but as growth becomes considerable, their contributions must be considered in system planning, forecasting, and modeling.” (NERC 2018 LTRA, p. 9)
- **Lessons from past events:**
  - A key cause of the Northeast blackout of 2003 was the loss of a transmission line together with operational errors as a localized failure in northern Ohio cascaded throughout the region, resulting in a blackout affecting 50 million customers in the United States and Canada and lasting, for some, up to four days. The event caused $7 billion to $10 billion in economic losses. As summarized by The Brattle Group and WIRES, “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” (WIRES Grid Resilience Docket Comments, at Appendix p. 12). Among the identified causes were lack of visibility of loss of key transmission elements and awareness of the vulnerability of the system to the next contingency (Northeast Blackout Report, p. 108).
  - In September 2011, about 2.7 million customers in the Pacific Southwest lost power, with an estimated economic impact of more than $100 million. According to NERC, “The outages affected parts of Arizona, southern California, and Baja California, Mexico. All of the San Diego area lost power, with nearly 1.5 million customers losing power, some for up to 12 hours. The disturbance occurred near rush hour, on a business day, snarling traffic for hours. Schools and businesses closed, some flights and public transportation were disrupted, water and sewage pumping stations lost power, and beaches were closed due to sewage spills. Millions went without air conditioning on a hot day.” The root cause was the loss of Arizona Public Service Company’s Hassayampa-North Gila 500 kV transmission line, but the event was attributed to grid operators’ lack of real-time situational awareness of conditions throughout the Western Interconnection (Southwest Blackout Event Report, at p. 7).

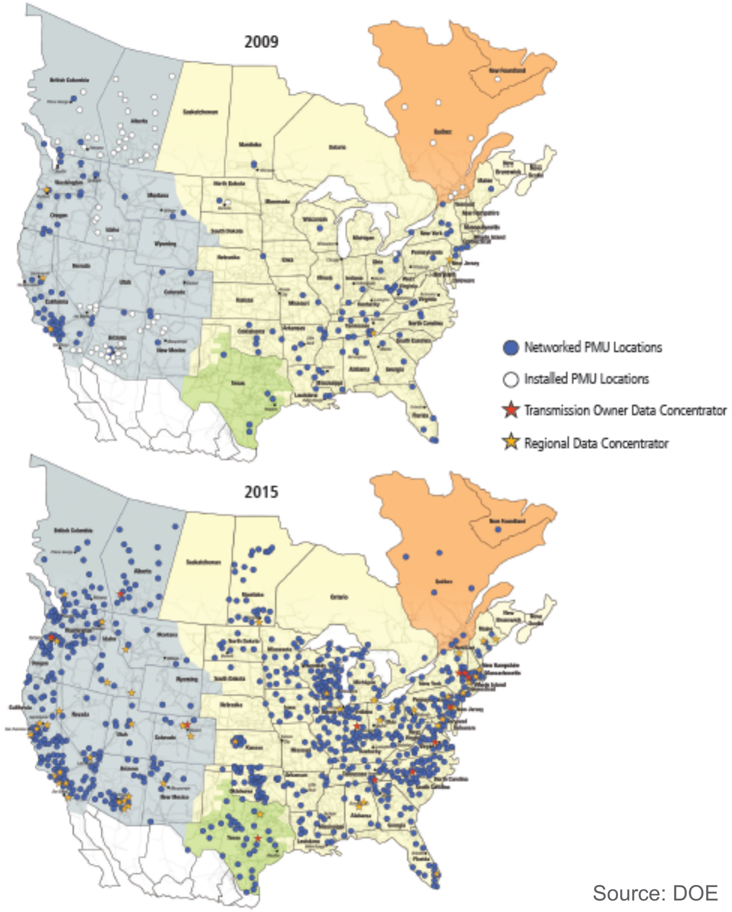
Note: *FERC has characterized flexible grid technologies as “grid-enhancing technologies” in recent technical conferences.
Sources: Nat’l Academies Studies; QER2; NERC 2018 LTRA; WIRES Grid Resilience Docket Comments; Northeast Blackout Report; Southwest Blackout Even Report; DOE; Grid-Enhancing Technologies Workshop

Situational Awareness (Cont'd)

Transmission Technologies

- **New and established transmission technologies:** Deployment of both emerging and well-established technologies have potential benefits. Deploying these as part of a broader reliability/resilience strategy will yield benefits for both. For example, certain transmission technologies can be employed to provide deeper awareness of the grid situation and increased flexibility of the system in response to changing grid conditions in the event of weather-related and other threats (such as wildfires) to resilience, as well as the ability to monitor and respond to unexpected changes in variable resource output and flows. For example, dynamic line-rating systems can aid in wind integration, by providing higher line capacity during periods of higher wind farm output. This technology can also provide critical information during high ambient temperatures, such as heatwaves and wildfires.
  - Phasor measurement units: Synchrophasor technology is being used to improve system awareness. Conventional instrumentation provides measurement of system conditions every two to four seconds. With the installation of phasor measurement units (PMUs) communicating up to 30 times per second, transmission operators have greater and more timely insight into system disturbances, improving efficiency, reliability, and resiliency of the system by detecting and correcting instabilities before an interruption of service (QER2, at pp. 4–50; PJM Benefits of Transmission, at pp. 59–60). Of course, sensors alone are insufficient; to secure full benefits of PMUs, other enabling monitoring and analysis technologies must be implemented in tandem.
  - Other technologies: Increasing variable resources and low shoulder seasonal and overnight loads are leading to higher-voltage variability on the transmission system. Flexible AC Transmission System (FACTS) devices, such as static VAR compensators, reactors, and static compensators, help regulate system stability, particularly at high-voltage levels. These are increasingly of interest: for example, more than $1.3 billion in reactors and static VAR compensators were installed on the PJM system between 2008 and 2018 (PJM Benefits of Transmission, at pp, 39–40, 61).*

North American Deployment of Phasor Measurement Units



Source: DOE

Note: *FERC has characterized flexible grid technologies as "grid-enhancing technologies" in recent technical conferences.
Sources: LBNL Resilience; QER2; PJM Benefits of Transmission; MIT Future of the Grid; Grid-Enhancing Technologies Workshop

Situational Awareness (Cont'd)

Transmission Technologies (Cont'd)

- **New and established transmission technologies (Cont'd)**
  - Dynamic line ratings: Current transmission system operations rely on fixed ratings of transmission line capacity that are established to maintain reliability during worst-case conditions (e.g., hot weather) or reduced based upon ambient conditions. There are times when the conditions associated with establishing line ratings are not constraining, and transmission lines could be operated at higher-usage levels. Dynamic line-rating systems help operators provide real-time awareness, identify available capacity, and increase line transmission capacity by 10% to 15%, potentially facilitating integration of wind generation. (QER2, at pp. 4–44). There remain discussions about the reliability and operational complexity of dynamic line ratings, now being examined by FERC (see, e.g., Grid-Enhancing Technologies Workshop, FERC Docket No. AD19-19-000).
- **New technologies and higher interconnectivity to provide inertia:** Generators and motors that are synchronously connected to a power system store kinetic energy from rotating masses. This energy, called synchronous inertia, helps provide system frequency support upon the sudden loss of generation. If frequency goes below a certain level, then the system risks under-frequency load shedding. Inertia arrests and stabilizes frequency (ERCOT Inertia Report, at pp. 4–5).
  - Traditionally, synchronous inertia was provided from natural gas, coal, and nuclear plants, but some of those units are retiring. Increasing amounts of non-synchronous, inverter-based resources, such as wind and solar resources, reduce the amount of synchronous inertia. For example, ERCOT, the Texas grid operator, has faced increasing challenges as more wind generation has come online and comprises a bigger part of the resource mix, as much as 50% of system mix at times (NERC 2018 LTRA, at pp. 30–35).
  - Wind can, when properly equipped, provide some synthetic inertia. Moreover, fast frequency response reserves can provide frequency support; those resources include solar and energy storage systems. Smart inverters have capabilities that can mimic inertia, but they are not yet widely deployed to provide that service. **Importantly, new transmission-related technologies, such as synchronous condensers, are being used for inertia support. Moreover, inertia levels are assessed by NERC on an interconnection-wide level, reinforcing the importance of transmission linkages between regions.**

In summary, investments in grid modernization, particularly in new technologies, will have resilience benefits for system visibility and flexibility. And both transmission solutions, such as synchronous condensers and increasing interconnectivity, can help alleviate declining inertia.

Sources: QER2; FERC Staff DLR Report; ERCOT Inertia Report; NERC 2018 LTRA; Grid-Enhancing Technologies Workshop

Upgrading an Aging Transmission System

- **The aging power system:** A concern for both reliability and resilience is the aging of the nation's transmission infrastructure, including lines, transformers, and substations. According to PJM: "Transmission facilities continue to age. Some assets date to the 1960s or even earlier. Two-thirds of all system assets in PJM are more than 40 years old; over one-third are more than 50 years old. Some local, lower-voltage transmission facilities, especially below 230 kV, are approaching 90 years old. Asset owners are identifying serious structural deterioration leading to system enhancements to avoid facility failure and customer service interruptions. These replacements have economic benefits as well and have, in certain instances, reduced average annual congestion costs by an order of magnitude or more. Asset modernization goes beyond simple replacement. Such projects have provided the opportunity to learn from history and adopt new knowledge, capabilities and technologies that did not exist when the original facilities were built." (PJM Benefits of Transmission, p. 5)
- **Upgrade with replacement:** In 2017, Hurricane Maria devastated Puerto Rico's power grid, requiring a significant, and ongoing, rebuilding of its electric infrastructure. But it has found that significant investment in getting its grid up and running will require replacement to make the Puerto Rican grid truly resilient against other similar events. According to the DOE, recommended long-term planning should include "ensuring that investments will result in modern, intelligent infrastructure systems that are affordable, reliable, and resilient." (LBNL Resilience, at p. 34).
- **New construction evaluation criteria:** Upgrading is not limited to replacement. In New York, for example, two approved major public policy projects included some heavier duty structural design, such as drilled shaft concrete foundations (versus crushed rock backfill foundations), full-length concrete poles (versus multi-piece steel poles), and more dead-end structures. While more expensive than standard construction (e.g., concrete foundations are about 2.5 times the cost of direct embedded rock foundations), these features were factored into the project evaluation because of the incremental resilience benefit to withstand icing and wind events (NYISO Policy Plan Addendum, at pp. 11–13).

Sources: PJM Benefits of Transmission; LBNL Resilience; NYISO Policy Plan Addendum

Upgrading an Aging Transmission System (Cont'd)

- **Tailored regional needs:** Of course, resilience needs are region-specific, based upon likely risks and lessons learned from past high-impact, low-frequency events, like major hurricanes. Other considerations are resource mix, current system configuration and age, and interdependencies with other essential services. Grid hardening has been pursued by, for example, Florida and New Jersey utilities in the wake of major weather events.
  - New Jersey was impacted significantly by Hurricane Irene (August 2011) and Superstorm Sandy (October 2012). For Newark-based Public Service Electric & Gas, Sandy damaged 31 substations, 1,000 transformers, and 2,500 utility poles (Northeast Storm Report, at pp. 8–10). Damage came from wind and significant flooding. In the wake of the storms, the utility established a $1.22 billion Energy Strong program to proactively protect its electric and gas systems against severe weather damage. About $620 million of this investment is for protecting, raising, or relocating 29 switching and substations.
  - In Florida, in the wake of 2005's Hurricane Wilma, which caused more than three million customers to lose power, Florida Power & Light has hardened its system, spending $3 billion since 2006 on pole inspection and replacement (using steel and concrete poles), vegetation clearing, and targeted undergrounding. Average time required to restore power after 2017's Hurricane Irma was 2.1 days compared to 5.4 days after Hurricane Wilma. Additional work on feeders and undergrounding is under way.

The grid is aging and many of its components are approaching the end of their useful lives. Further, major events that prematurely damage parts of the grid can afford an opportunity to consider and weigh resilience-enhancing transmission investments in their wake. A well-planned, strategic investment strategy can provide the opportunity to upgrade an aging grid with better than like-for-like components and to enhance system resilience.

Sources: PSEG; FP&L; industry news

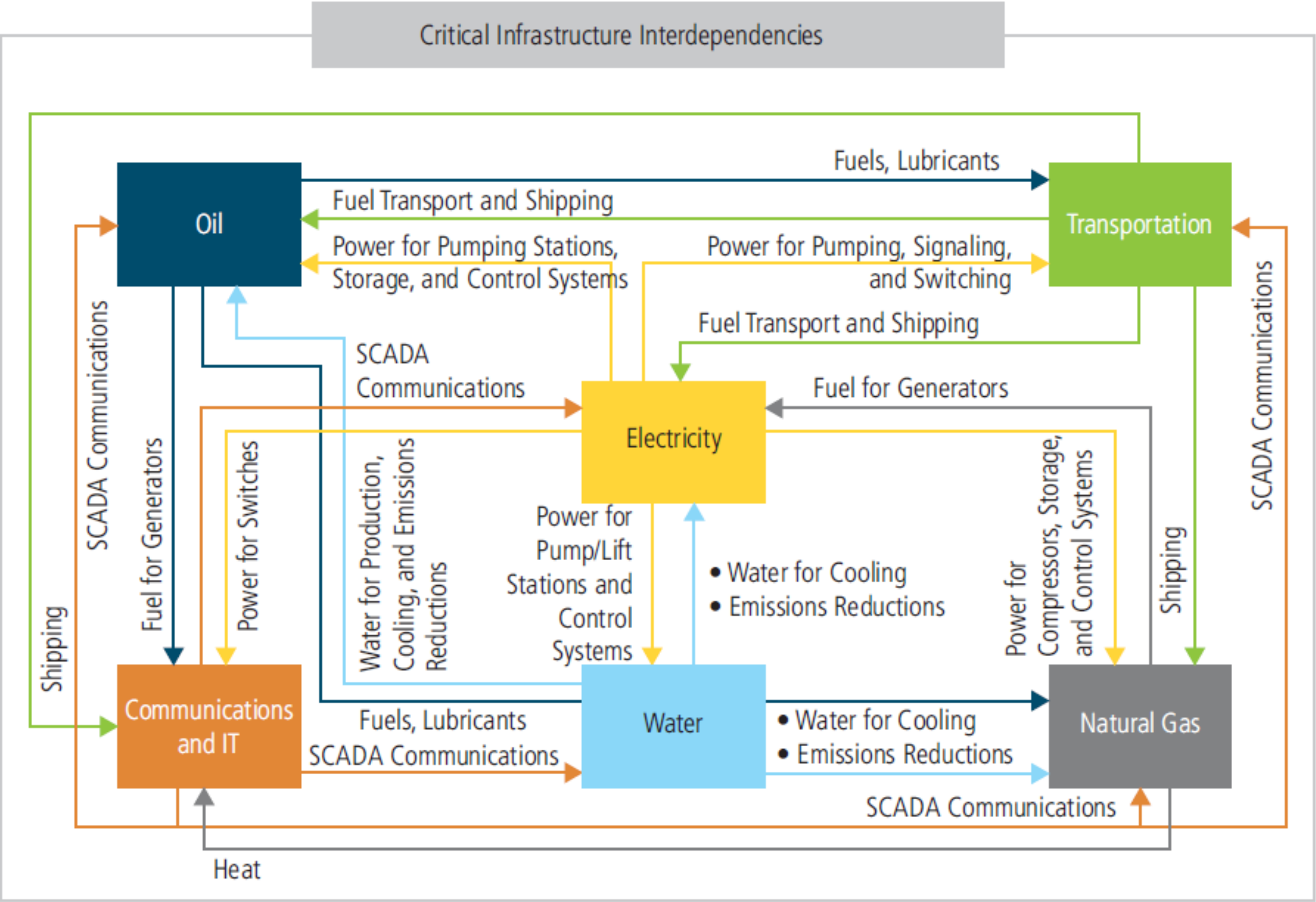
Preparing for High-Impact, Low-Frequency Events

Initiatives to Prepare for a High-Impact, Low-Frequency Event Affecting the Grid

- **Programs and equipment for transmission system recovery:** Recovery of the transmission system from a significant event involves the ability to coordinate with bordering grid operators and governmental authorities, to inspect and repair or replace damaged facilities, and to re-energize the grid. In preparation for response to major resilience events, utilities collaborate in regional mutual assistance groups, which provide access to skilled utility workers to respond to large-scale events (WIRES/Brattle, at pp. 13–14). Utilities also maintain spare components (poles, transformers, etc.), and there are currently a number of industry-sharing programs through NERC, the Edison Electric Institute, and other programs. In particular, the industry is focused on large power transformers (LPTs), which are costly and lengthy. The loss of several LPTs can overwhelm the bulk power system and cause widespread outages, possibly affecting multiple regions. DOE and the industry are considering risks, including design concepts, and the potential need for a strategic transformer reserve (QER2, at pp. 4–48).
- **Worst-case planning and interrelated infrastructure considerations of increasing interest:** The utility industry performs tabletop exercises, such as GridEx, that consider widespread power outages, including those caused by cyber-physical events. However, increasing attention is being paid to the potential impact of a catastrophic power outage, which is severe, widespread, and long-lasting. This risk goes beyond that of a large storm, but it would be of a magnitude beyond experience, causing an outage for months or years and involving cascading loss of critical services that could impede re-energizing the grid. NIAC recently highlighted some potential recommendations to address cross-sector failures that would hamper recovery efforts (see cross-sector linkages next page). In particular, it recommended (i) development of a national approach to catastrophic power outage planning, response, and recovery, and (ii) identification of cascading failures impacting key sectors and identifying actions to improve resilience (NIAC, at p. 7). Of course, establishing design criteria and appropriate incentives for the power sector remain key issues to consider before making changes to existing good planning practices (see Challenges and Policy Implications).

Sources: QER2; NIAC; https://www.energy.gov/oe/addressing-security-and-reliability-concerns-large-power-transformers; National Academies Study

Preparing for High-Impact, Low-Frequency Events (Cont'd)



Source: National Academies Study, Fig. 4.5

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