EXECUTIVE BRIEF

Transmission Reliability Impacts of Retiring Conventional Generation

Purpose

This report examines the transmission system reliability risks associated with retiring synchronous generators. It provides an overview of how transmission planners evaluate the impact of generator retirements including studies of thermal overloading, transient and voltage stability, frequency response, inertia, short-circuit impacts, and other grid reliability metrics. The report explores solution options, including conventional approaches and emerging technologies, that can serve as alternatives to synchronous generator reliability must-run (RMR) agreements. Understanding the underlying grid reliability risks, how transmission planners analyze these risks, and solutions worth exploring can help a diverse range of stakeholders and decisionmakers make informed decisions that ensure a reliable and resilient grid.

Background

The average operating coal-fired generating unit in the United States is 45 years old, and coal plant energy generation has continued to decline since at least 2011 [1,2]. In its place, new lower-cost forms of electricity generation have come online including natural gas, solar photovoltaic (PV), wind, and battery energy storage systems (BESS) [3]. While this shift is lowering costs to consumers, there are technical implications that can impact the successful retirement of large synchronous generation on the bulk power system. In some cases, these resources must remain online under RMR agreements for extended periods to ensure an adequate level of reliability is maintained until system upgrades or generation replacements are constructed and put in service.

RESOURCE ADEQUACY AND ENERGY ASSURANCE CONCERNS

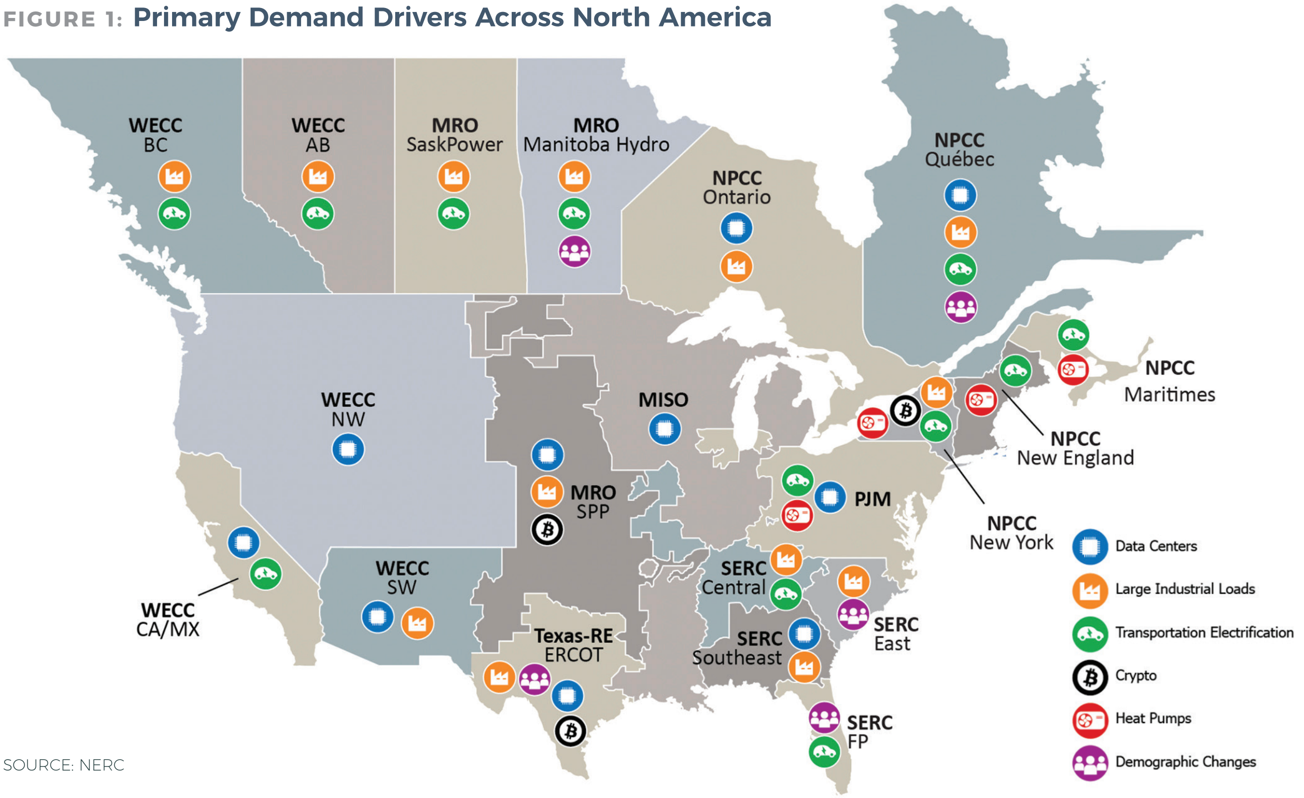
Generation retirements must be balanced with new generation additions, and generation additions across the country are facing interconnection delays. Imbalance in generation additions and retirements can create capacity shortfalls, which are scenarios in which insufficient generation or import capability is available to meet peak demand. It can also introduce energy shortfalls, where insufficient energy is available for periods of time to serve total electricity consumption, often attributed to the variable and intermittent nature of renewable energy resources and short duration storage capabilities. The North American Electric Reliability Corporation (NERC) continues to raise alarms regarding risks to bulk power system reliability and availability of electricity supply during normal peak conditions and in extreme conditions [4].

This paper assumes that resource and energy adequacy concerns are addressed and focuses specifically on the reliability impacts of synchronous generator retirements and how transmission planners study these impacts and develop mitigating measures to address them. Synchronous generators provide more than just capacity and energy to electricity customers, they provide essential reliability services that help maintain a stable and reliable interconnected bulk power system. These services are often more localized and require transmission system studies to adequately assess and mitigate any system performance deficiencies.

A GRID IN FLUX: GENERATION SHIFTS AND DEMAND BOOM

Total installed capacity of conventional synchronous generators continues to decline as older and uneconomic generators retire. Over 79 GW of fossil-fired

FIGURE 1: Primary Demand Drivers Across North America



SOURCE: NERC

and nuclear generating capacity is planned for retirement over the next 10-year horizon [4], primarily comprised of natural gas and coal-fired generators.[1] Conversely, inverter-based resources (IBRs) continue to be the predominant energy resources being added to the system today and looking ahead, driven mostly by solar PV and BESS additions [5].

Concurrently with this dramatic shift in generation technologies, electricity demands are booming at an unprecedented rate nationally. Demand growth is at its highest levels in over two decades and has risen sharply since 2022, signaling the end of an era of relatively flat electricity demands across the nation. Electricity demand projections are fueled by data centers and artificial intelligence, large industrial loads, transportation electrification, cryptocurrency mining, heat pumps, and multi-sector electrification (see Figure 1) [4]. NERC projects summer and winter peak demands to grow by 132 GW and 149 GW, respectively, over the next decade.

Generators Providing Essential Reliability Services

Generators provide capacity and energy for meeting electricity demands while also supporting the interconnected transmission system in other critical ways. Generators play a key role in providing essential services to the transmission system that enable reliable and stable grid operations [6]. These services include, but are not limited to, the following:

- **Frequency Control and Stability:** The ability to naturally resist changes to frequency excursions (i.e., inertial response), autonomously change active power outputs in response to frequency deviations (i.e., primary frequency response), and contribute to secondary automatic generation control (AGC) dictated by the Balancing Authority.
- **Voltage Control and Stability:** The ability to respond to transmission operator voltage schedules and setpoints, provide dynamic reactive power support across operating points, and support system voltage stability through stable and efficient reactive power control.
- **Balancing, Ramping, and Reserves:** The ability to ramp generation up and down to effectively balance net load changes over seconds, minutes, and hours; having sufficient fast-responding resources that balance small fluctuations in supply and demand (i.e., regulating reserves) and to have sufficient generation response that can activate quickly after large system disturbances (i.e., contingency reserves).

1 NERC reported that this capacity number includes generators confirmed for retirement through retirement planning processes or those that have indicated plans to retire to an ISO/RTO or Planning Coordinator.

- **Short-Circuit Current Contribution and Protection System Coordination:** The ability to provide adequate short-circuit current contributions to the grid during faults that allow protection systems (relays and breakers) to operate correctly to ensure equipment health, public safety, and grid stability.
- **System Strength:** The ability to remain stable across normal and emergency operating conditions; interoperable and stable control systems within generating plants and with other devices across the system.
- **Blackstart[2] and System Restoration Capability:** The ability to quickly and effectively restart the bulk power system in the event of a large-scale outage or blackout without relying on neighboring power systems.

These services are crucial for maintaining grid reliability, especially as traditional synchronous generators retire and IBRs take on an increasing role. Renewables are inherently intermittent, variable, and inverter-based; thus, they have unique attributes and operating characteristics that affect the level of essential reliability services they can provide to the grid. **The shift in the generation resource mix itself is not inherently a risk.** However, ensuring sufficient essential reliability services are available on the grid at all times requires transmission planners to adequately study the myriad reliability risks that could materialize during this transition and identify solutions to address those risks years before the risks would be present on the grid.

Generator Retirement Process and Need for Reliability Studies

Confirmation of generator retirements vary according to the processes in different jurisdictions such as planning tariffs in wholesale electricity markets or integrated resource planning processes for vertically integrated utilities and non-market participating states. Overall, the process of retiring a large bulk power system connected generator typically involves the following steps:

1. **Notification and Initial Review:** The Generator Owner submits a notice of intent to the ISO/RTO or transmission provider, which initiates a preliminary assessment of potential reliability impacts of removing that generator from service.
2. **Transmission System Reliability Studies:** Transmission planners then perform detailed reliability assessments including power flow, transient stability, voltage stability, short-circuit, and possibly electromagnetic transient (EMT) studies to determine whether retirement could cause adverse reliability impacts that must be addressed to ensure reliable operation of the bulk power system.
3. **Determination of Reliability Need and Comparison with Retirement Timeline:** If reliability issues are identified, transmission planners evaluate whether mitigating measures such as transmission upgrades or alternative solutions can be deployed before the proposed retirement date to replace the essential reliability services provided by the generator and ensure bulk power system reliability.
4. **Implementation of Mitigating Measures:** If network upgrades or alternative solutions are feasible, they must be implemented prior to resource retirement to ensure system reliability and stability performance metrics are met. If no timely solution is available, then the generator may be designated as a RMR resource to remain in operation temporarily until those solutions can be deployed.[3]

In many areas, one or several mechanisms exist that can prevent or delay generators from retiring before the necessary corrective actions can be taken and implemented to mitigate potential reliability risks, including:

- **RMR Agreements:** Contractual obligations requiring the generator to stay online until adequate transmission upgrades or alternative solutions are deployed.
- **Must-Offer Requirements:** Market rules that mandate certain generators to bid into capacity auctions to ensure reliability.
- **Reliability Planning Tariffs:** Policies allowing transmission planners to delay generator retirements if unresolved reliability risks exist.

The rules and practices around these arrangements vary by jurisdiction, but this paper focuses on the technical transmission issues that could trigger such an arrangement.

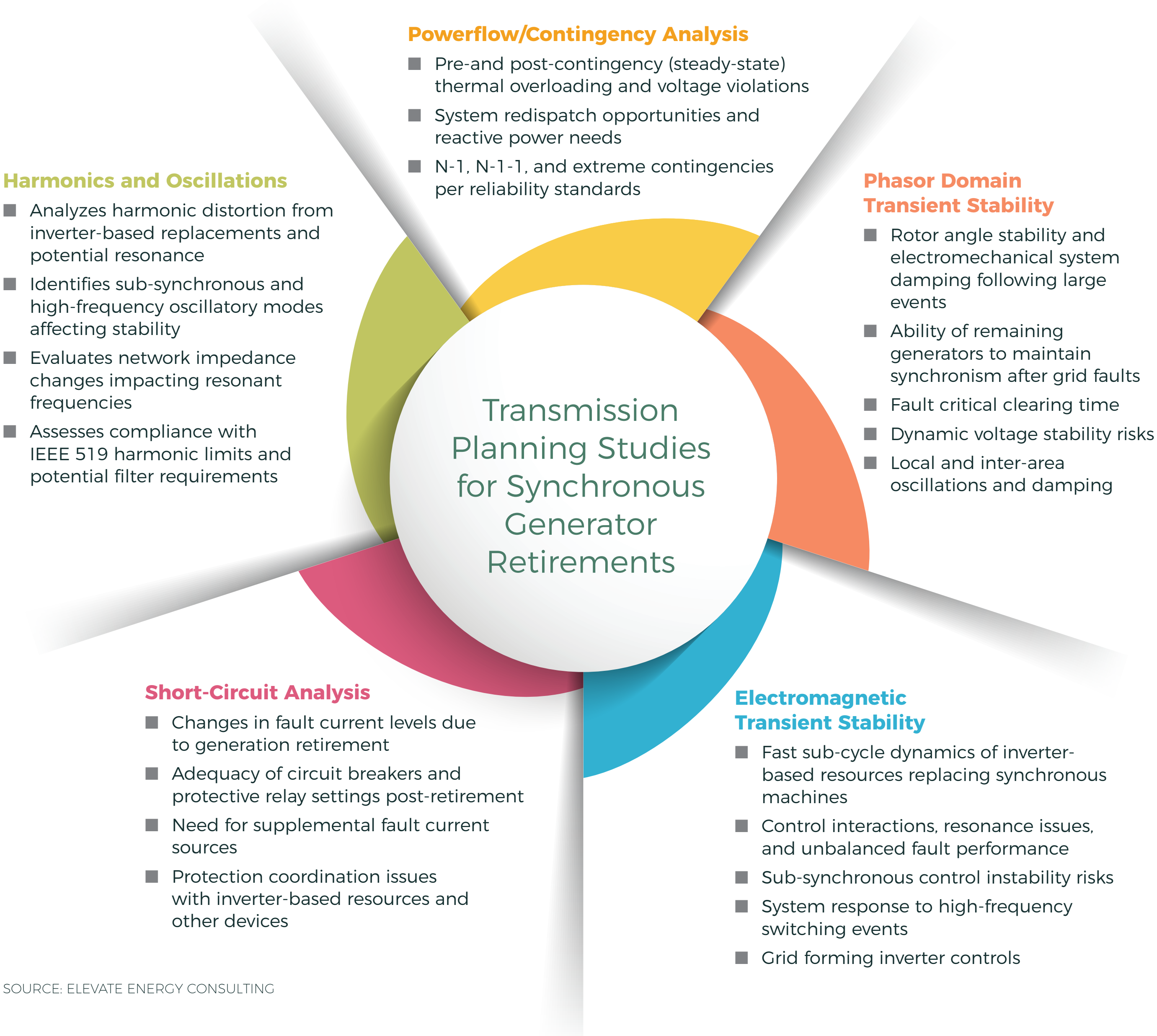
Transmission Planning Studies for Generator Retirements

Synchronous generators have historically played a vital role in maintaining grid reliability by providing essential reliability services such as inertia, dynamic reactive power support, short-circuit current, etc. Retirement of synchronous generators (as with any large generating resource or grid-supporting device) can introduce

2 Not all synchronous generators serve as blackstart resources.

3 There are regional differences in the naming convention, but for the purposes of this paper a Reliability Must-Run arrangement is an agreement between a Generator Owner who seeks to retire a power plant and a Transmission Operator that requests that the generator to stay in operation and provides payment for the service.

FIGURE 2: Types of Transmission Planning Studies for Synchronous Generator Retirement



SOURCE: ELEVATE ENERGY CONSULTING

transmission system reliability risks if adequate mitigating measures are not implemented ahead of time. Once a synchronous Generator Owner seeks retirement, transmission planners conduct a series of studies that evaluate a range of possible reliability risks and identify solutions that could mitigate any risks that appear due to the proposed retirement. Figure 2 illustrates the types of studies that may be conducted when analyzing transmission system reliability for a proposed synchronous generator retirement.

If the studies determine that removing the generator would cause unacceptable reliability risks yet mitigating measures cannot be deployed within the timeframe sought (or no viable solutions are available), then the generator may be required to continue operation under an RMR contract until suitable solutions are put in place. For example, PJM's generator deactivation process identified reliability risks for the requested retirement of Brandon Shores Power Plant (1,280 MW) in 2023. PJM requested that the Brandon Shores plant remain in service through the RMR process until system upgrades were completed to address system voltage issues and other reliability issues. GridLab sponsored work ultimately found that a combination of BESS, transmission circuit reconductoring, and expedited voltage support projects could meet local area reliability needs and potentially save hundreds of millions of dollars [7].

Effective backstops must prevent the loss of critical generators when analysis finds deactivation would violate reliability criteria; however, due diligence should be done to explore alternative solutions that maintain the same degree of reliability yet result in cost savings to ratepayers.

Addressing Reliability Risks with Diverse Solution Options

When a synchronous generator submits a notification of retirement, its void on the bulk power system can create reliability issues for the transmission system such as thermal overloads, voltage violations/instability, reduced short-circuit current, diminished frequency responsiveness, and system stability risks. Different technologies can help mitigate these risks and their effectiveness varies depending on the specific reliability concern. Some solutions can address thermal overloads and help optimize transmission system voltages while other solutions are more focused on providing grid-stabilizing attributes. Table 1 provides a high-level comparative assessment of various solution options, ranking their relative effectiveness in addressing key transmission reliability risks.[4]

Below are some key considerations for the solution options presented:

- **Battery Energy Storage System (BESS):** Provides fast-responding active and reactive power support to the grid; can serve as a transmission asset; can mitigate thermal overloads with short duration; limited ability to support long-term energy needs. [8]
- **Grid Forming (GFM) BESS:** Same attributes as BESS yet with grid-stabilizing controls that help improve transient stability, system strength, inertial response/ fast frequency response (FFR), etc. [9,10,11]
- **Shunt Capacitor:** Supports steady-state voltage control with switchable reactive power devices; no dynamic reactive power capability.
- **STATCOM/SVC:** Provides dynamic reactive power to control voltage and improve voltage stability; can also support oscillatory stability issues and harmonic cancelling capabilities; provides limited short-circuit due to power electronics. [12]
- **Synchronous Condenser:** Significant contributor to short-circuit current and dynamic reactive power

TABLE 1: Relative Effectiveness of Solution Options to Address Key Transmission Reliability Risks

Reliability Risk	BESS	GFM BESS	Shunt Caps	STATCOM /SVC	Synch. Cond.	Series Comp.	GETs (DLR, OPF, top. opt.)	Recond./ Adv. Cond.	Raising Towers	New Transm. Infra.
Thermal Overloads	Med.	Med.	None	None	None	Med.	Low	High	High	High
Voltage Control	High	High	Med.	High	High	Med.	Med.	Low	None	Med.
Dynamic Reactive Power/Voltage Stability	High	High	Low	High	High	Low	None	Low	None	Med.
Inertial Response/ FFR	High	High	None	None	Med.	None	None	None	None	None
Primary Frequency Response	Med.	High	None	None	None	None	None	None	None	None
Transient Stability	Med.	Med.	Low	Med.	High	Med.	Low	Med.	None	Med.
System Strength	Med.	High	None	Med.	High	Med.	Low	Med.	None	High
Short-Circuit Current	Low	Low	None	Low	High	Low	None	Med.	None	High
Protection System Impacts	Low	Low	None	Low	High	Med.	Low	Med.	None	High
Resource Adequacy	Med.	Med.	None	None	None	Low	None	Low	None	Med.

Effectiveness is ranked as High, Medium, Low, or None.

4 Note there are other solution options such as deploying distributed energy resources (DER), virtual power plants (VPP), and flexible loads; however, these are outside the scope of this paper.

support; minimal inertial response and no sustained active power; supports protective relaying. Retiring synchronous coal plants can be converted into synchronous condensers, which can reuse existing infrastructure and reduce costs yet age of the existing equipment determines cost and feasibility of this conversion. [13]

- **Series Compensation:** Improves transfer capability, voltage support, and network impedance; however, they may introduce subsynchronous oscillation risks and do not provide a flexible energy source.
- **Grid Enhancing Technologies:** Enables uprating of equipment based on real-time ambient conditions (i.e., dynamic line rating (DLR)); improves transmission system flows and controllability (i.e., topology optimization); minimal dynamic support for active and reactive power and system strength. [14]
- **Reconductoring/Advanced Conductors:** Improves limiting ratings and can improve network impedance which has some effects on local stability; no flexibility attributes. [15], [16]
- **Raising Towers:** Can increase circuit ratings and transfer capability; may allow for increases in voltage level of existing line(s), and potential for new underbuilt transmission or distribution lines; limited changes to network stability attributes. [17]
- **New Transmission Infrastructure (Lines, Substations, etc.):** Enables increased power flow, network stability, system strength, etc.; supports protective relaying; does not provide dynamic active or reactive power support compared with other solutions unless those solutions are directly included into the new transmission projects.

Multi-Pronged Approach to Grid Reliability

Many options can provide multiple grid reliability services and thus can support a broad range of issues, working in tandem with other solutions. Exploring a multi-pronged approach rather than one unique solution can create a diversified portfolio of solutions, which can result in a more reliable and resilient grid across all expected operating points while minimizing costs to ratepayers.

For example, a large synchronous generator retiring in a load pocket could have multiple impacts on transmission system reliability – thermal overloads into the pocket, voltage collapse risks, lack of system strength, negative impacts on protection systems, etc. While the conventional approach may be to build transmission circuits and run the generator as an RMR until the new facilities are commissioned, there may be alternative solutions that can be deployed at lower cost. GFM BESS could help stabilize the local network, series compensation could help enable higher transfer capability, GETs could provide operational relief during a wide range of operating conditions, advanced reconductors could improve operating restrictions and thermal limits, and raising transmission towers in areas where new infrastructure is challenging to build may be a viable option.

In addition to cost savings, many of these solutions can also be implemented much faster than new greenfield transmission or new synchronous generation. While new transmission and generation is likely needed in many cases in the long-term, these alternatives provide intermediate solutions at lower cost and greater reliability than paying for aging, uneconomic plants to remain online.

Considerations for Deploying Solution Options

Several considerations are factored into evaluating the feasibility of potential solutions to mitigate transmission reliability risks associated with generator retirements. These may include, but are not limited to, the following (see Table 2):

- **CapEx Costs:** Capital costs necessary to deploy the solution.
- **OpEx Costs:** Ongoing operations and maintenance (O&M) costs including staffing and technology.
- **Supply Chain:** Availability and readiness of equipment and manufacturing constraints.
- **Timeline:** Estimated time required to procure, install, and commission the solution.
- **Grid Impact:** The extent of the solution's impact on local, regional, and wide-area reliability.
- **Scalability:** The ability of a solution to scale to address the more significant reliability issues.
- **Operational Flexibility:** Ability to adjust functionality based on real-time grid conditions.
- **Trust:** Transmission provider and ISO/RTO familiarity and experience deploying the solution.
- **Lifespan:** Expected useful life of the asset before major upgrades or replacement are needed.

TABLE 2: Considerations for Deploying Various Solution Options

Solution	CapEx Costs	OpEx Costs	Supply Chain	Timeline	Grid Impact	Scalability	Op. Flex.	Trust	Lifespan
BESS	High	Med.	Med.	1-3 yrs	Local, Regional	High	High	Med-High	10-20 yrs
GFM BESS	High	Med.	Med.	1-3 yrs	Local, Regional	High	High	Low-Med	10-20 yrs
Shunt Capacitor	Low	Low	Low-Med	1-2 yrs	Local	High	Low	High	20-30 yrs
STATCOM/SVC	Med.	Low	High	2-4 yrs	Local, Regional	Med.	Med.	Med.	20-30 yrs
Synchronous Condenser	High	Med.	High	2-4 yrs	Local, Regional	Low	Med.	High	30+ yrs
Series Compensation	Med.	Low	High	1-3 yrs	Regional	Med.	Low	Med.	30+ yrs
GETs	Low	Low	Med.	1-3 yrs	Regional	High	High	Low	10-15 yrs
Reconducto / Advanced Conductor	Med.	Low	Med.	2-4 yrs	Local, Regional	High	Low	Med.	30+ yrs
Raising Towers	Med.	Low	Med.	1-3 yrs	Local, Regional	Med.	Low	Low	30+ yrs
New TX Infrastructure	Very High	Low	High	4-10+ yrs	Local, Regional, Wide-Area	Low	Low	Very High	40+ yrs

Rankings are relative to each other and intended for illustrative purposes only. [16,18,19,20,21,22,23]

Conclusion

This report emphasizes the importance of considering transmission system reliability risks posed by the retirement of synchronous generators and examines how transmission planners may assess these impacts through studies. These studies span a wide range of simulation domains and platforms: powerflow, transient and voltage stability, EMT, short-circuit, etc. The studies identify the likely reliability risks posed by the generator retirement and explore potential mitigating measures and solution options to address these risks. In situations where solutions are not attainable or within the timeline of retirement, then the generating resource may need to remain operational under an RMR agreement. However, to bolster grid reliability while minimizing costs to ratepayers, all possible solutions should be considered in this process in addition to conventional new transmission infrastructure. Evaluating all solution options can be a time consuming process; utilities are burdened to complete these assessments within a relatively short period of time (e.g., 60-90 days upon notice). Thus, innovations in system reliability studies, studies approaches, automation, etc., can help utilities with these evaluations.

By understanding these risks, the analytical approaches used by transmission planners, and the available solutions, stakeholders and decisionmakers can make informed decisions that result in the best solutions for their constituents, and customers, and ratepayers.

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Dr. Ryan Quint is the President and Chief Executive Officer of Elevate Energy Consulting. Ryan founded Elevate in 2024 and is responsible for the strategic direction and execution of Elevate projects across all verticals. He is focused on building a world-class team of experts that partner with industry to tackle emerging challenges facing our grid today and into the future. Prior to launching Elevate, Ryan spent nearly nine years at the North American Electric Reliability Corporation (NERC), most recently as the Director of Engineering and Security Integration where he led numerous strategic initiatives focused on emerging reliability risk mitigation involving inverter-based resources, distributed energy resources, security integration, and leveraging emerging technologies. Ryan also has industry experience at Dominion Energy Virginia and the Bonneville Power Administration. He received his PhD from Virginia Tech, is a registered Professional Engineer in Virginia, and was the recipient of the 2024 IEEE Power and Energy Society Outstanding Young Engineer of the Year Award.

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