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Grid Transformation at a Crossroads:

THE IMPERATIVE FOR INTEGRATED SYSTEM PLANNING

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EXECUTIVE SUMMARY

The electric grid is undergoing an unprecedented transformation. Driven by global decarbonization goals, sector-wide electrification, and the exponential rise of AI-powered data centers, energy systems are now working to accommodate rapid demand growth while balancing dispatchable fossil fuels to weather-dependent, inverter-based renewable resources. This convergence of trends is creating a new planning imperative—one that challenges the reliability, adequacy, and physical behavior of the grid.

Historically, grid planning has relied on a linear, siloed approach, where each domain—resource adequacy, capacity expansion, production cost, and power flow—was analyzed in isolation using disconnected datasets and static assumptions. This model is no longer sufficient. The energy transition now demands a more comprehensive strategy that recognizes and responds to the system-wide impacts of three simultaneous shifts:

- An operations transformation: from dispatchable to variable generation;
- An adequacy transformation: from predictable to uncertain availability;
- A physics transformation: from synchronous machines to inverter-based resources.

This paper makes the case for Integrated System Planning (ISP) as the critical framework to address these interconnected challenges. ISP moves beyond traditional methods by unifying planning tools and enabling iterative, data-consistent analyses across all core domains. With ISP, planners can evaluate grid reliability and economic performance holistically—identifying the true high-risk hours, coordinating resource and transmission decisions, and planning around the operational realities of a deeply decarbonized system.

Regulatory bodies are recognizing the urgency of this shift. Recent U.S. FERC Orders 2023, 901, and 1920 explicitly call for more advanced planning methods to address the complexities of inverter-based resources, growing interconnection backlogs, and long-term transmission needs. These mandates signal a new era of regulatory expectations—one where ISP is not just best practice, but a necessity.

Drawing on GE Vernova's global experience with utilities and system operators, this paper outlines the technical rationale, systemic benefits, and regulatory alignment of integrated system planning. The path to a reliable, affordable, and decarbonized power grid lies in breaking down silos and planning the system as a system.

THE SITUATION

We are in a time of dramatic change with respect to our electric system. New mandates are continuously emerging promoting deeper and deeper levels of decarbonization. At the same time, demands on the electric grid are growing. Fuel-dependent sectors such as transportation, heating and industrial processing are increasingly transitioning to electric usage or "electrifying" in order to decarbonize energy demands. Meanwhile, the artificial intelligence revolution is driving unprecedented growth in new data centers. Energy demands associated with artificial intelligence applications is significantly greater than traditional data center applications thus challenging electric system's delivery capacity.

Given these three megatrends challenging the electric system, the key question for planners is: **How to enable electric demand growth while decarbonizing … without compromising reliability and cost?**

Figure 1 illustrates the nature of this electric system planning challenge. In 2023 the world depended on fossil fuels for ~60% of its electric generation. In order to decarbonize, this fossil-based generation needs to be transitioned to zero-emission sources such as hydro, nuclear, or variable renewables such as wind or solar. Across every continent, the growth of wind and solar has outpaced the growth of nuclear and hydro given cost advantages and ease of siting. **Thus planners are challenged to plan an electric grid increasingly dependent on variable renewables.**

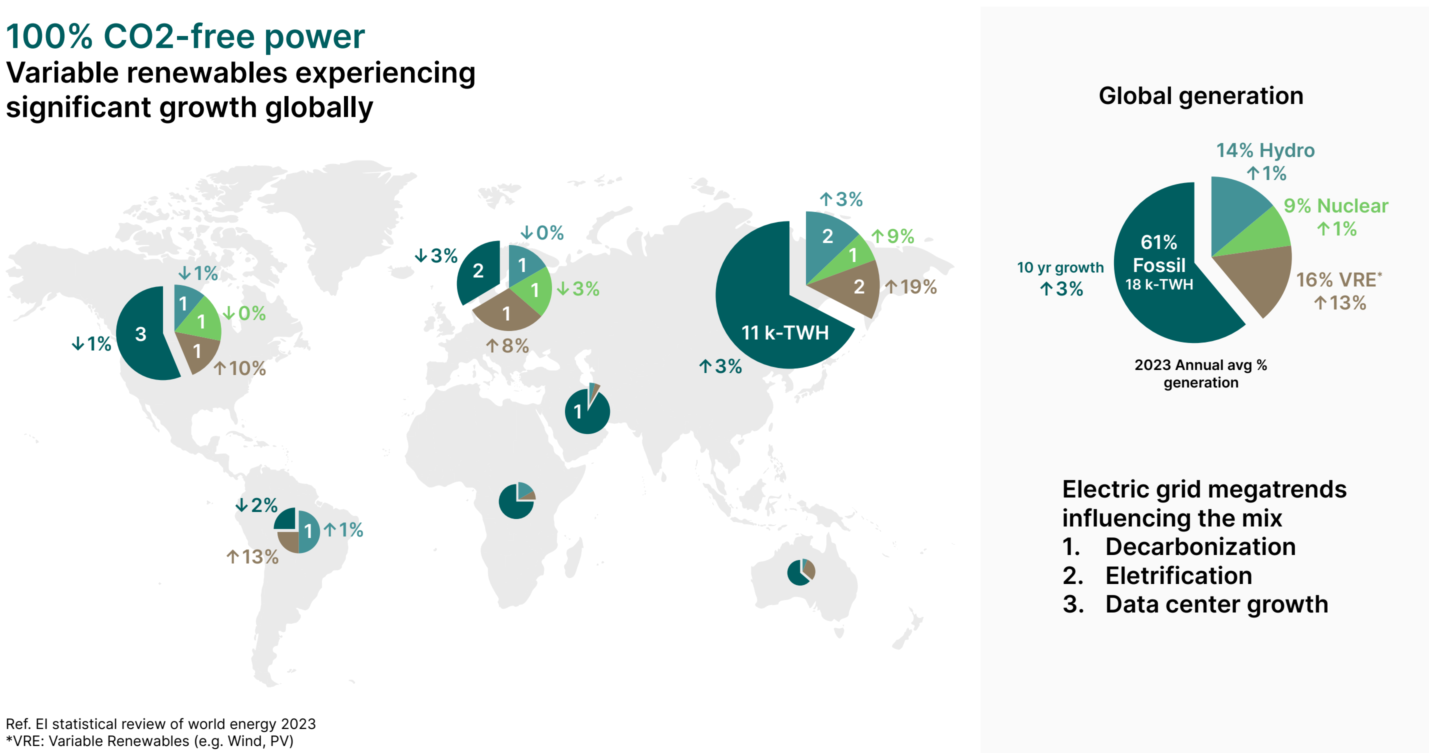


Figure 1: 2023 electric generation mix by fuel type and continent illustrating the world's dependence on fossil fuels while variable renewables growth outpaces all other fuel types.

The energy transition from fossil sources to variable renewables is more than just an emissions change. A successful energy transition requires planning for three types of transformations:

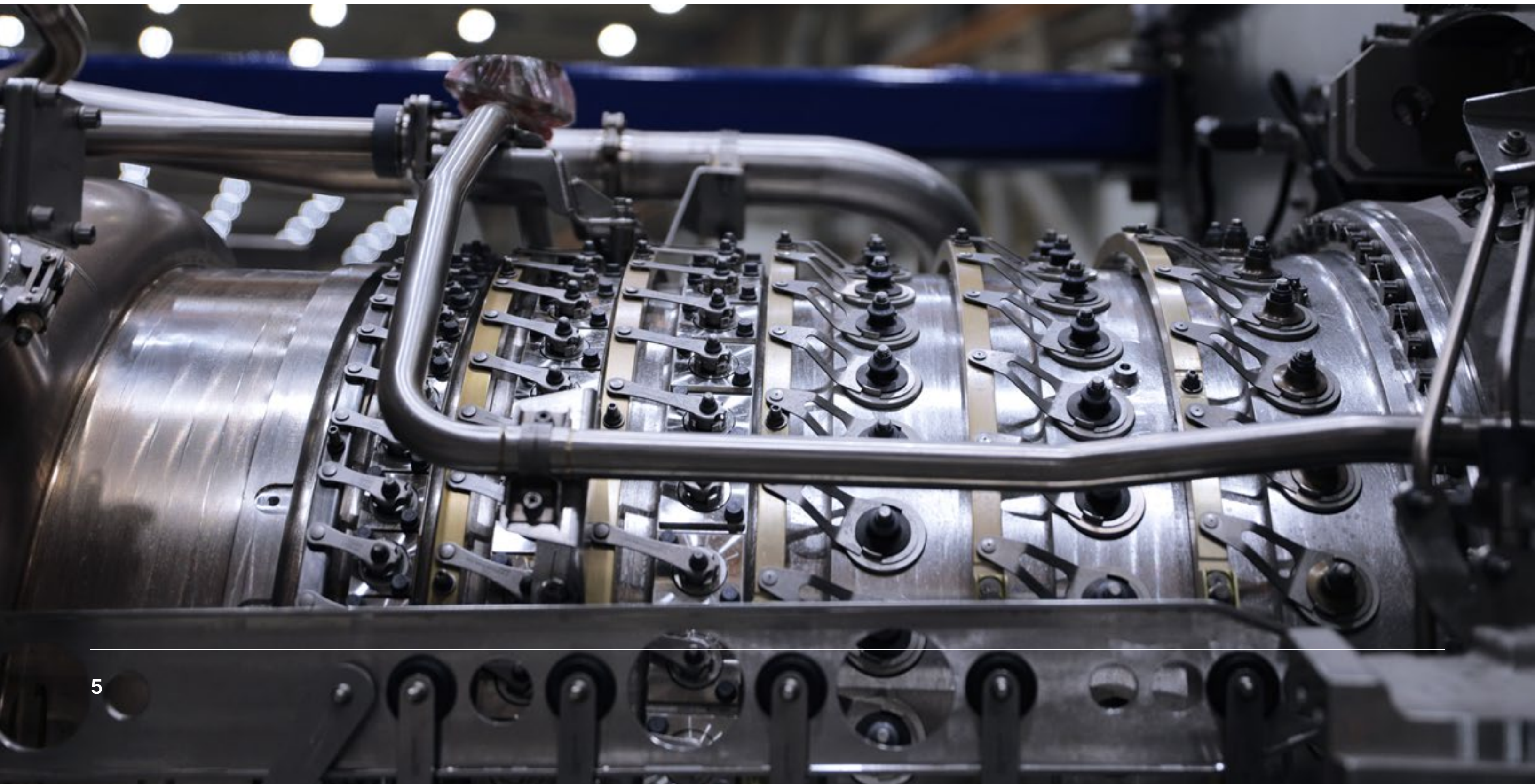
1. **An operations transformation: From constant to variable fuel sources.** Operators are used to generators with fuel sources that can be dispatched at virtually any level within its technical capability at any time. The availability of wind and solar, however, vary with the weather. The most infamous example is the California "duck curve" during which solar resources rapidly decline every day at sunset such that other resources need to rapidly ramp up in its place to serve load. At the same time, wind resources can drop to near-zero levels for days in events known as "wind lulls." The challenge is how to serve during such events in a carbon-free manner.

2. **An adequacy transformation: from certain to uncertain generation.** Operators are used to generators with fuel sources that are available almost any time they are needed. The availability of wind and solar resources is uncertain given dependence on weather. Wind levels may appear at levels below their forecast. Unforecasted cloud cover may impact solar levels. What resources can serve load under such forms of uncertainty? Operators need to plan their overall energy mix such that they can serve load despite such uncertainty of wind and solar resources.

3. **A physics transformation: from synchronous machines to inverter-based resources.** For the last 100 years of our electric system, frequency and voltage has been maintained by synchronous machines: rotating turbines that mechanically drive an electrical generator to create electricity. Planners have experience being able to plan how disturbances on the system (e.g. lightening) may impact frequency and voltage. Wind turbines, solar panels, and batteries all drive power electronic, inverter-based electrical generators which maintain frequency and voltage in a fundamentally different manner. Given the relative inexperience of planners with such inverter-based resources (IBRs), being able to plan for reliable voltage and frequency in given expected disturbances is a new challenge.

All three of these transformations are currently underway simultaneously. In our experience, however, the departments responsible for planning each of these transformations rarely collaborate and their planning tools are disconnected and siloed. Herein lies the real decarbonization challenge.

Planning a reliable and economic system with significant load growth and weather-dependent, inverter-based resources is the real energy transition challenge.



THE TRADITIONAL PLANNING PROCESS

The traditional planning process generally overlooks these transformations since historically, none of these changes were factors to consider. However, given that many regions are currently in the middle of all three of these transformations at the same time, our planning practices must transform accordingly. In our experience with system operators around the world, before the growth of variable renewables, this traditional planning process has often looked quite linear as shown in Figure 2.

Though this process has worked well for the last 20-30 years of our industry, the main challenge with this approach is that **planning steps and models are typically siloed.** As you can see from Figure 2, the output from each planning step (i.e. adequacy, capacity expansion, power flows) feeds the next planning step. Each step is often performed in relative isolation with modeling tools that are disconnected from each other. Common pitfalls are as follows:

1. **Modeling assumptions are disconnected.** For example, adequacy models used for capacity planning may rely on assumptions that are very different from those assumed in a power flow model of the system: the same generators may have different names, and the solutions are solving for a different set of constraints, which makes modeling data portability quite challenging. Another example of this challenge is getting the AC power flow that determines stability to solve based on the commitment and dispatch of the DC power flow used in production cost. The DC power flow calculates the commitment, dispatch and resulting power flows to optimize the production cost, but does not account for the voltage or reactive constraints. The AC power flow used for steady state stability solves network voltage, real and reactive flows and other power system quantities. These simulations have historically been done independently with separate data sets but in today's power system, that is not sufficient to identify the riskiest system conditions.

2. **Limited hourly analysis is performed.** The traditional planning approach also centers around the assumption that the most risky period of time for grid reliability is the hour of peak load. Reserve margins are typically determined based on load forecast uncertainty and resource availability during peak load hours. Generation plans have historically focused on the lowest cost resources to meet peak load. Network plans are based on a range of technical models that represent various aspects of power flows during peak hours. Again, this planning practice was adequate in the past because the riskiest hour for the grid was indeed during peak. However, with a system transitioning towards higher reliance on weather-dependent generators whose output varies hour-to-hour, the riskiest hour may no longer be during peak. The traditional planning approach depicted in Figure 2 rarely includes hourly analysis to help identify other non-peak hours of high risk—a major flaw going forward.

3. **Solutions are siloed.** Figure 2 depicts how the output from each planning step (i.e. adequacy, capacity expansion, power flows) feeds the next planning step. Each step is often performed in relative isolation. For example, generation planners generally assume that the network reliability of the system is not a consideration in resource decisions. At the same time, network planners typically do not consider resource expansion alternatives to mitigate network reliability needs they identify. The challenge if grid planning processes are siloed in this way, is that each department assumes their decisions do not affect and are unaffected by the others. While this has been a fair assumption in the past, with a system in the middle of three simultaneous transformations, this assumption is no longer suitable.

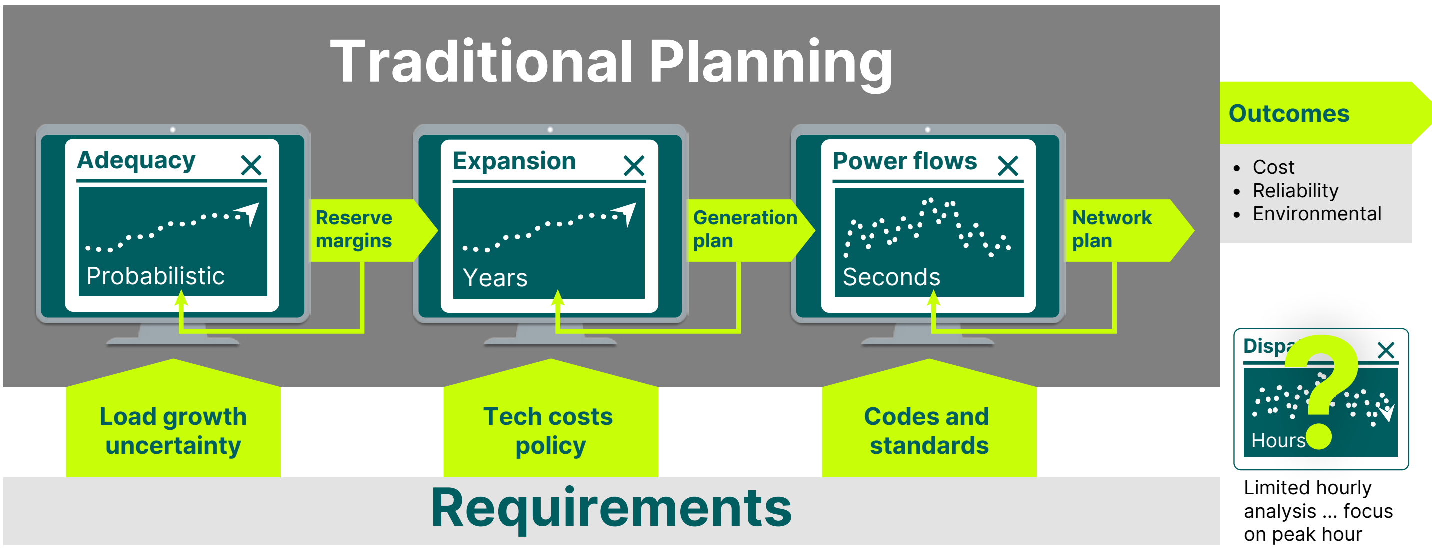


Figure 2: Typical traditional planning process ... a linear approach.

THE INTEGRATED SYSTEM PLANNING PROCESS

In a decarbonizing system undergoing three simultaneous grid transformations, system operators are transitioning away from this traditional linear approach toward a more integrated system planning approach as shown in Figure 3. Such an approach allows for an iterative assessment where the output of each planning step (i.e. adequacy, capacity expansion, production cost, power flows) is considered as an input to the next. Benefits are as follows:

1. **One source of data:** With the integrated system planning approach, each simulation step pulls from a common source of data. Generator names are consistent, system assumptions are consistent. Time spent on data clean-up is saved.

2. **Holistic solutions optimization:** In this way the impacts of the three simultaneous grid transformations can be evaluated together and upgrades to system performance can be defined holistically. For example, a generation plan may now reflect benefits to network reliability. At the same time, network planners may consider resource expansion alternatives to mitigate the network reliability needs they identify.

3. **Hourly risk analysis:** One of the most significant benefits to the integrated system planning approach is the focus on hourly analysis to identify the conditions of greatest risk. In our new world with high renewables penetration typical high-risk hours may include:

   - Peak net load (Load minus variable renewables)
   - Peak variable renewables / IBRs
   - Peak net load ramping
   - Low synchronous machine headroom/footroom
   - Peak energy exchanges with neighboring systems
   - Peak renewables curtailment
   - Peak transmission congestion
   - Peak load + storage charging

These high-risk hours can be identified via adequacy and/or production cost analysis and then can be simulated in the power flow step to assess reliability risks across both operations and stability.

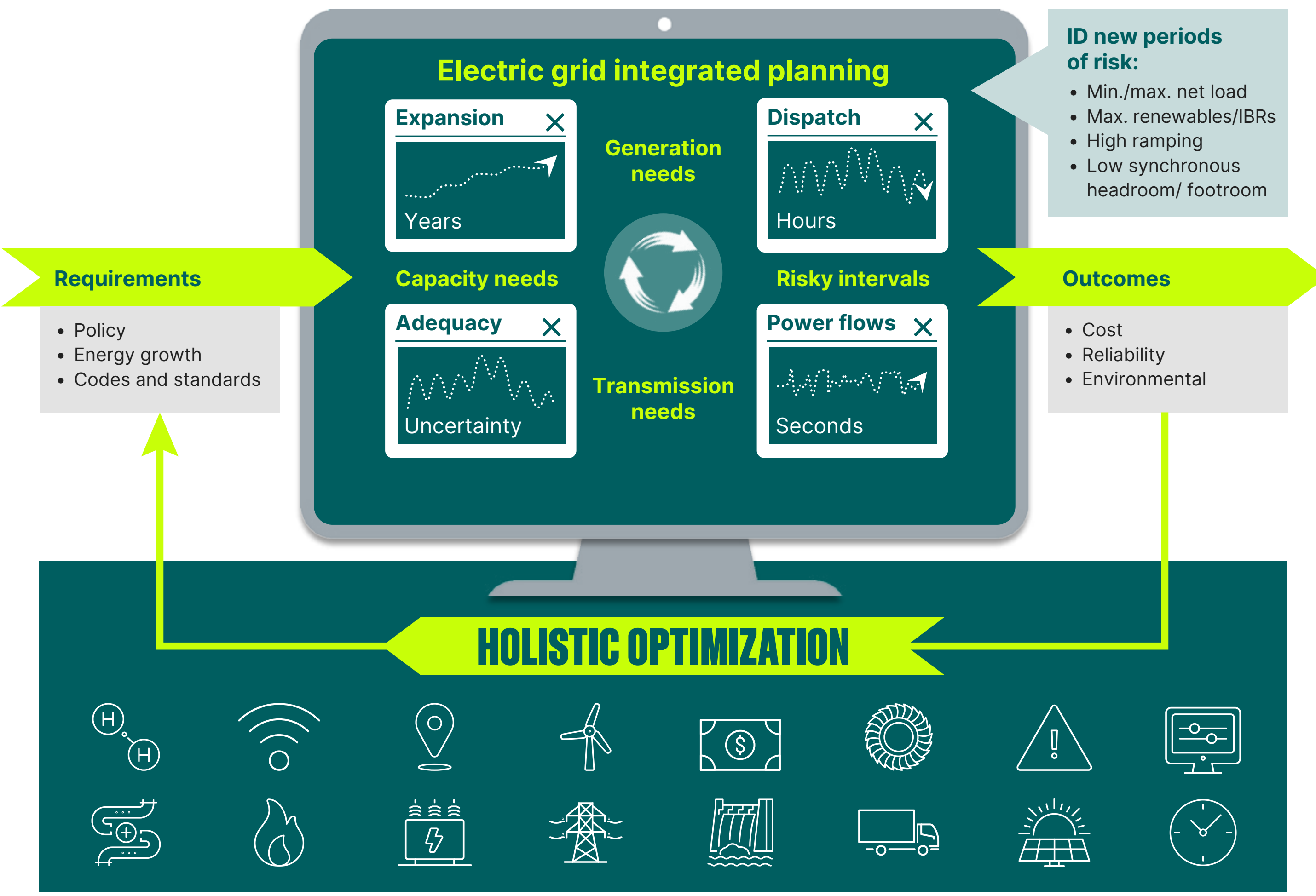


Figure 3: Integrated system planning process for deep decarbonized grid systems with high penetrations of variable, inverter-based renewables.

REGULATORS RECOGNIZING THE NEED FOR INTEGRATED SYSTEM PLANNING

While the team at GE Vernova recognized the advantages of an integrated system planning approach given the team's experience supporting global system operators and utilities, often change requires more than a recognition of the advantages. Given the bottlenecks associated with new resources being interconnected and the occurrence of reliability events associated with high levels of inverter-based resources, regulators are beginning to recognize the importance of an integrated system planning approach to facilitate the three transformations.

For example, a number of regulations have emerged in the United States that are leading to the need to adopt a more integrated systems planning approach:

1. **FERC Order 2023:** In this order, FERC recognizes that gaps in stability criteria related to IBR integration has left gaps in the interconnection process. Thus FERC is requiring that more detailed modeling must be performed. The system impact assessment analyzes overloads, steady state voltage constraints and dynamic stability constraints, using pre-determined system conditions typically under peak and light load. While analyzing congestion using peak and light load will test some of the necessary system conditions that may drive transmission upgrades, but it's not sufficient only to investigate peak load alone. Other system conditions representing peak inverter-based renewables, weakest grid scenarios, lightest inertia conditions need to be investigated to determine if any there are any stability constraints or reliability risks during the interconnection process. More detailed models and studies, including dynamic analysis using user-written equipment models and electromagnetic transients (EMT) analysis and models are required in Order 2023. Performing deeper analysis with these types of models is necessary in grids that are integrating more inverter-based resources and/or large data center loads to identify risks and constraints, but only if solving the risks of the most constraining system conditions using integrated system planning processes.

2. **FERC Order 901:** According to NERC, the rapid integration of IBRs is "the most significant driver of grid transformation" on the Bulk Power System. NERC's Reliability Standards first approved in 2007 were developed to apply nearly exclusively to synchronous generation resources. As a result, these NERC Reliability Standards may not account for the material technological differences between the response of synchronous generators (i.e. rotating generators) and the response of inverter-based resources to the same disturbances (i.e. faults, trips) on the Bulk Power System. In this order, FERC is directing NERC to develop new or modified Reliability Standards that address reliability gaps related to inverter-based resources in the following areas:

   a. Data sharing

   b. Model validation

   c. Planning and operational studies

   d. Performance requirements

FERC is taking action finding that current NERC Reliability Standards do not ensure that system operators have the necessary tools to plan and interconnect IBRs into the bulk power system. NERC's new or modified Reliability Standards are to be submitted to FERC by November 2026.

3. **FERC 1920:** FERC indicates that there are gaps and needs to reform the transmission planning process to account for the impact and risks with integrating higher penetration of variable inverter-based generation. This order addresses transmission planning reform by:

   - Requiring to conduct and periodically update long-term transmission planning to anticipate future needs.
   - Requiring to consider a broad set of benefits when planning new facilities.
   - Requirement to identify opportunities to modify in-kind replacement of existing transmission facilities to increase their transfer capability, known as "right-sizing."
   - Customers pay only for projects from which they benefit.
   - Expands states' pivotal role throughout the process of planning, selecting, and determining how to pay for transmission facilities.

   Integrated system planning is needed to completely analyze risks and transmission system needs in future scenarios that have higher penetration of inverter-based resources and large data center loads. As mentioned above, picking out the most stressful conditions representing weakest grid conditions, lightest synchronous inertia, areas with high penetrations of IBR where instabilities and interactions are most likely to occur is necessary in transmission planning. Using integrated system planning processes more completely evaluates critical upgrades and mitigations in the planning process. This order also requires more comprehensive processes that span operational, physical and cost analysis where integrated system planning is critical, including:

   - Avoided or deferred transmission upgrades
   - Reduced LOL/Planning Reserve
   - Production Cost Savings
   - Reduced transmission Losses
   - Reduced congestion
   - Extreme weather mitigation
   - Capacity cost benefits from reduced peak energy losses
   - Combined Generator Interconnection and Transmission Planning processes
   - Probabilistic/Stochastic planning approach
   - Interregional TP methods and data sharing

CONCLUSION

Overall, integrated system planning is critical to address generator interconnection, inverter-based resource integration and transmission planning requirements outlined in the FERC orders above. Evaluating resource adequacy, operational and production cost needs and grid stability separately and independently is insufficient to plan for grids diversifying in generation mix and adding large complex data center loads. Holistic evaluation across these analyses is the only way to identify and mitigate the new risks in our transitioning power system.

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