

EXECUTIVE SUMMARY



Stress Testing for Resilient Power Systems

The electricity grid is adapting to shifting resource portfolios, increasing electrification, and the growing impact and frequency of extreme weather events. Recent wide-area reliability events, including multi-day winter storms such as Winter Storm Uri (2021), Winter Storm Elliott (2022), as well as major heat events in the West, underscore the need for analytical methods that directly test power-system performance under high-impact, low-probability conditions.

This executive summary highlights results from the ESIG Transmission Resilience Task Force report, *Stress Testing Methods for Evaluating Resilience to Extreme Events*:

Valuing Interregional Transmission. The report sets the stage by describing stress testing and explaining how it offers an approach to measure system resilience and incorporate higher-fidelity modeling of interregional transmission. It outlines a four-step stress testing framework to guide planners in developing their own stress tests for system planning. In addition to the report, a case study was conducted for a future (2029) Southwest Power Pool (SPP) system to implement stress testing principles and evaluate the resilience value of interregional transmission. Extreme events were identified using historical weather data, and stress tests were conducted across extreme heat, extreme cold, and low renewable

**See the full report and accompanying case study—
[Stress Testing Methods for Evaluating Resilience to Extreme Events: Valuing Interregional Transmission](#)**

The SPP case study shows that when power system planning models include higher-fidelity representation of inter-regional transfer capability and weather-correlated external resource availability across a wide-area, this can materially change assessment outcomes, highlight a broader range of mitigation options, and reveal the resilience value of interregional transmission during extreme events.

events. Reliability planning today often simplifies or omits resource availability in neighboring systems and typically limits considerations of neighbors only to immediate neighbors. However, the SPP case study shows that when power system planning models include higher-fidelity representation of interregional transfer capability and weather-correlated external resource availability across a wide-area—beyond a system's immediate neighbors—this can materially change assessment outcomes, highlight a broader range of mitigation options, and reveal the resilience value of interregional transmission during extreme events.

Evaluating Grid Resilience Through Stress Testing

Stress testing is a method for evaluating grid resilience by running detailed “what if” simulations of specific historical or future extreme events on future power systems. It accomplishes this by simulating grid performance across a range of high-risk conditions at hourly resolution. These simulations reveal how underlying event conditions (such as weather) and combinations of stressors (e.g., high demand and correlated outages) drive tail-risk outcomes.

Stress testing contrasts with probabilistic resource adequacy studies by focusing specifically on simulating tail events in detail rather than as part of the thousands of conditions simulated in resource adequacy studies which produce average risk metrics. Assessing a smaller set of critical conditions allows planners to analyze grid risks, mitigations, and operational considerations in detail, including adding greater resolution of neighboring regions and their transmission capabilities. This allows

planners to determine which grid improvements, including interregional transmission, can most cost-effectively support grid reliability during high-impact, low-probability events. It complements resource adequacy analysis by helping planners understand how and why reliability can break down during extreme events and ensure that proposed generation and transmission plans are robust to tail-risk events.

This report builds on previous work by the Energy Systems Integration Group to present a set of guiding principles to support the development of rigorous and consistent stress testing frameworks tailored to regional needs. The approach described here helps establish an analytical process for determining the resilience value provided by interregional transmission during extreme events, by capturing hourly variations in external resource capabilities as a function of weather, that can inform future reliability and economic cost-benefit analyses such as those envisioned by Federal Energy Regulatory Commission (FERC) Order 1920.

Regulatory Drivers for Stress Testing

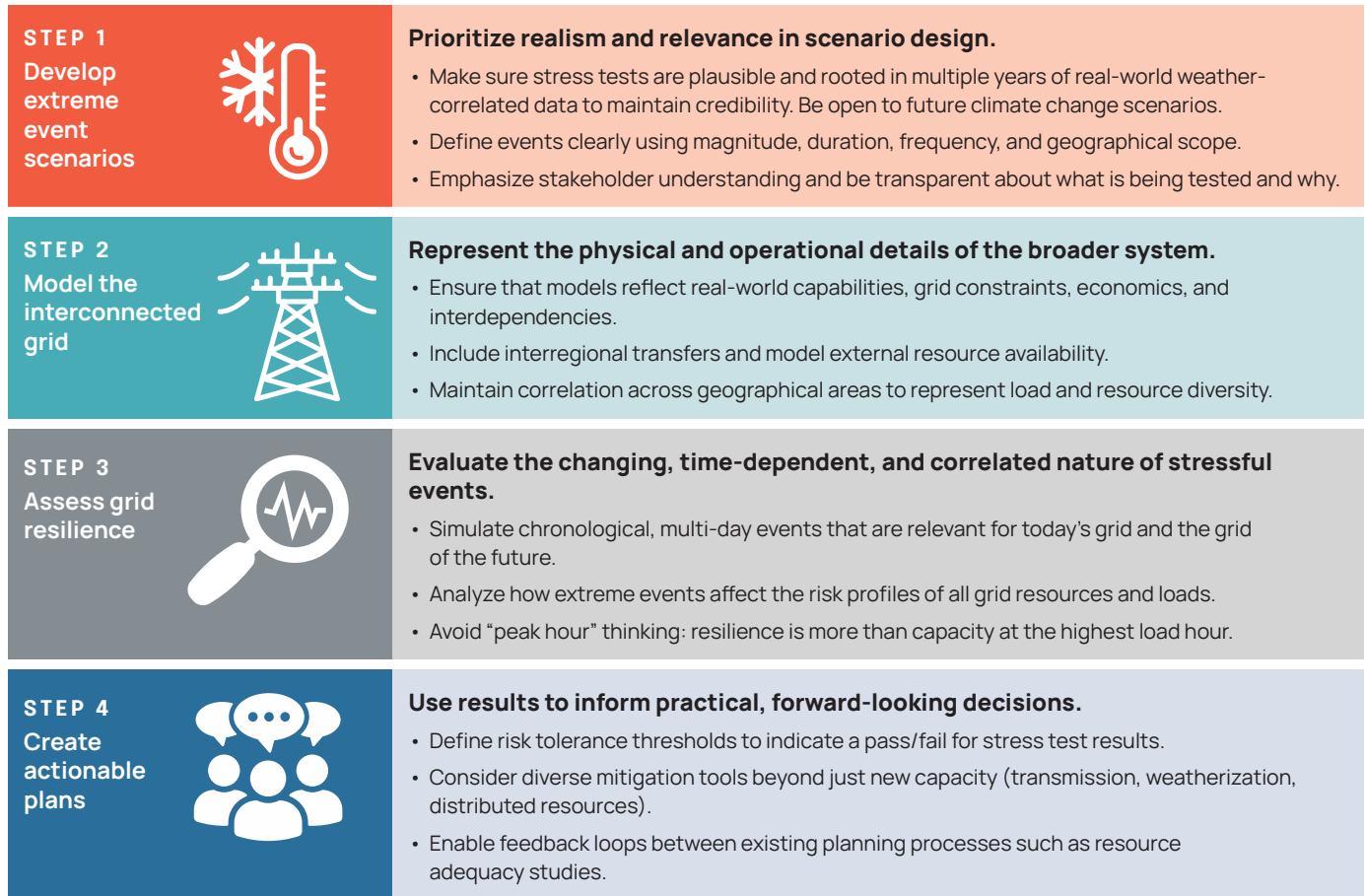
Stress testing is increasingly reflected in planning and compliance requirements. FERC Order 1920 requires transmission providers to evaluate resilience benefits in long-term planning, including the benefit “that a Long-Term Regional Transmission Facility would provide during an extreme weather event and unexpected system



© iStockphoto/jose1983

FIGURE ES-1

Four Steps and Key Principles for Developing Stress Tests



The stress testing process is outlined in four steps along with important principles to consider at each stage. Adhering to these principles ensures that stress testing creates realistic extreme conditions to evaluate grid resilience while enabling feedback loops to inform grid needs.

Source: Energy Systems Integration Group.

conditions that results in multiple concurrent and sustained generation and/or transmission outages.”¹

In addition, the North American Electric Reliability Corporation (NERC) TPL-008-01 standard reinforces the need to assess system performance in extreme temperatures. Meeting these requirements will require methods to identify extreme events, develop models to assess them, and evaluate whether planned investments maintain reliability under conditions well beyond traditional planning cases. This report and case study propose and demonstrate the use of such methods.

¹ Federal Energy Regulatory Commission, "Order No. 1920: Building for the Future Through Electric Regional Transmission Planning and Cost Allocation" (2024), <https://www.ferc.gov/media/e1-rm21-17-000>.

The Stress Testing Process

Figure ES-1 presents the steps for developing stress testing scenarios and using them to evaluate system resilience. Each step is built on underlying principles to ensure that stress testing is effective and realistic. The stress testing process detailed in this report is not meant to be prescriptive but is rather designed to aid planners in representing realistic extreme events in their grid resilience assessments. The remainder of this summary reviews the results of implementing these steps for a case study that stress-tested a future (2029) SPP system produced by the ESIG Transmission Resilience Task Force, with detailed analysis on how interregional transmission representation affects results of a resilience study.

SPP Stress Testing Case Study

The stress testing case study uses data for SPP to demonstrate stress testing modeling, with a particular focus on transmission and interregional transmission for resilience. It implements the four-step process and key principles shown in Figure ES-1 (p. 3), demonstrating for planners a rigorous method to identify, simulate, and analyze extreme events.

Step 1: Develop Extreme Event Scenarios

To develop extreme event scenarios, the first step was to link weather and power system data provided by SPP with available temperature and power system data for the continental United States—to ensure a wide-area,

correlated view of both SPP and all interconnected, neighboring power systems across the continental United States. Figure ES-2 lists the objectives considered when developing the underlying data to screen for extreme events. These objectives ensure that the weather and power system data used to identify and then stress SPP was based on a wide-area weather dataset that covers neighboring region conditions as well as local SPP conditions.

Methods Used to Identify SPP Extreme Events

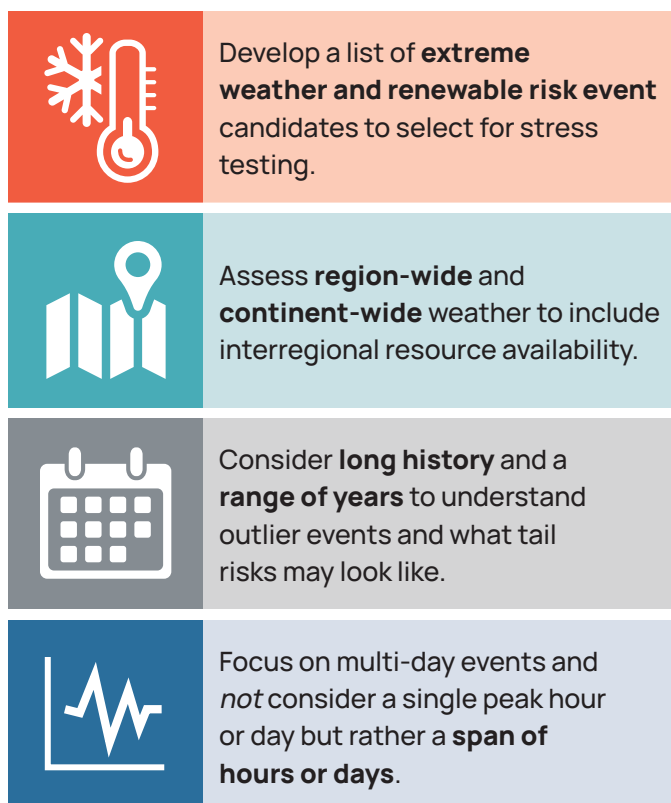
The weather and power system data used for this analyses included:

- 43 weather years (1980–2022) of hourly load, wind, and solar data for a projected 2029 SPP system, provided by SPP
- 43 weather years of hourly temperature data weighted by population (1980–2023), provided by the Pacific Northwest National Laboratory
- 12 weathers years of coincident hourly load, wind, and solar data for the continental United States (2007–2013 and 2019–2023), from the National Laboratory of the Rockies and U.S. Energy Information Administration 930 data
- 8 years of daily maximum outages by generation fuel type (2016–2023) resampled to the 1980–2022 period using temperature-day matching from NERC

After combining these datasets, hourly, daily, and multi-day periods of low resource availability and high loads were statistically screened to determine the most challenging grid conditions expected on the future resource mix. For this study, challenging periods were identified based on a 10th and 90th percentile threshold. Risk days were defined as days where wind, solar, and thermal resource availability were below the 10th percentile and days where load and residual load (load minus renewables) were above the 90th percentile. The set of days was then reduced to only consider evaluating periods where a completed wide-area power and weather dataset was available (2007–2013 and 2019–2022).

FIGURE ES-2

Four Steps and Key Principles for Developing Stress Tests



Integrated system planning opportunity – NERC TPL 008-1 standard on extreme heat and cold weather events presents a collaboration point for planners to link stress testing and transmission planning.

Source: Energy Systems Integration Group.

TABLE ES-1

Stress Periods with Different Risk Drivers Identified for SPP Based on Analyzing Multiple Weather Years of Resource Adequacy Data

| Stress Period Type | Stress Period Dates | Risk Drivers | Event Description |
|--------------------|--------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Extreme cold | Feb. 11–24, WY 2021 | Colder than 99.85% of all days | Freezing temperatures, extremely high load and thermal outage levels, low wind |
| Extreme heat | July 13–Aug. 10, WY 2011 | Hotter than 99.99% of all days | Extreme heat, high summer load |
| Wind drought | Aug. 29–Sep. 18, WY 2011 | Over 33,000 MW of SPP wind resources (on a 56,000 MW peak load system) largely unavailable for multiple days due to weather across the entire region | Low-wind period of five consecutive days where production levels were < 10th percentile for summer/fall; this event had a very low probability of occurrence based on 40 years of data |
| Compound | Jan. 31–Feb. 14, WY 2010 | Worst magnitude compound risk day in consistent U.S. dataset in the study (2007–2013 and 2019–2022) | Multiple low-wind and -solar days compounded by cold weather, high load, and thermal outage risk |

Four stress periods identified by reviewing resource adequacy datasets and potential worst-case weather-correlated thermal resource availability for SPP. Each stress period reflects different combinations of risk drivers, and together this set of time periods can then undergo detailed stress testing analysis on a 2029 future resource mix and demand growth scenario.

Note: WY = weather year.

Source: Energy Systems Integration Group; data from the Southwest Power Pool (resource mix, hourly renewable and load data), Pacific Northwest National Laboratory (hourly temperature data), North American Electric Reliability Corporation (worst-case weather correlated fleetwide outages), and Bracken et al. (2024) (risk screening method and compound event determination).

We selected four event types from the screened data for the stress testing analysis to represent a range of conditions. These events reflected extreme cold, extreme heat, wind drought, and a compound event that reflects an aggregated high-risk period with a combination of high demand, high thermal outage risk, and low renewable production periods (Table ES-1).

Step 2: Modeling the Interconnected Grid

Modeling the interconnected grid may be the most important step in the stress testing process due to the importance of interregional transmission and external resource availability, which make the existing grid resilient to extreme events. For the SPP case study, transfer capabilities for external regions were modeled with layered assumptions including direct region-to-region and simultaneous zonal import limits (Figure ES-3, p. 6, top). Internal SPP transfer limits reflect SPP assumptions and a zonal transfer limit between SPP North and South. To

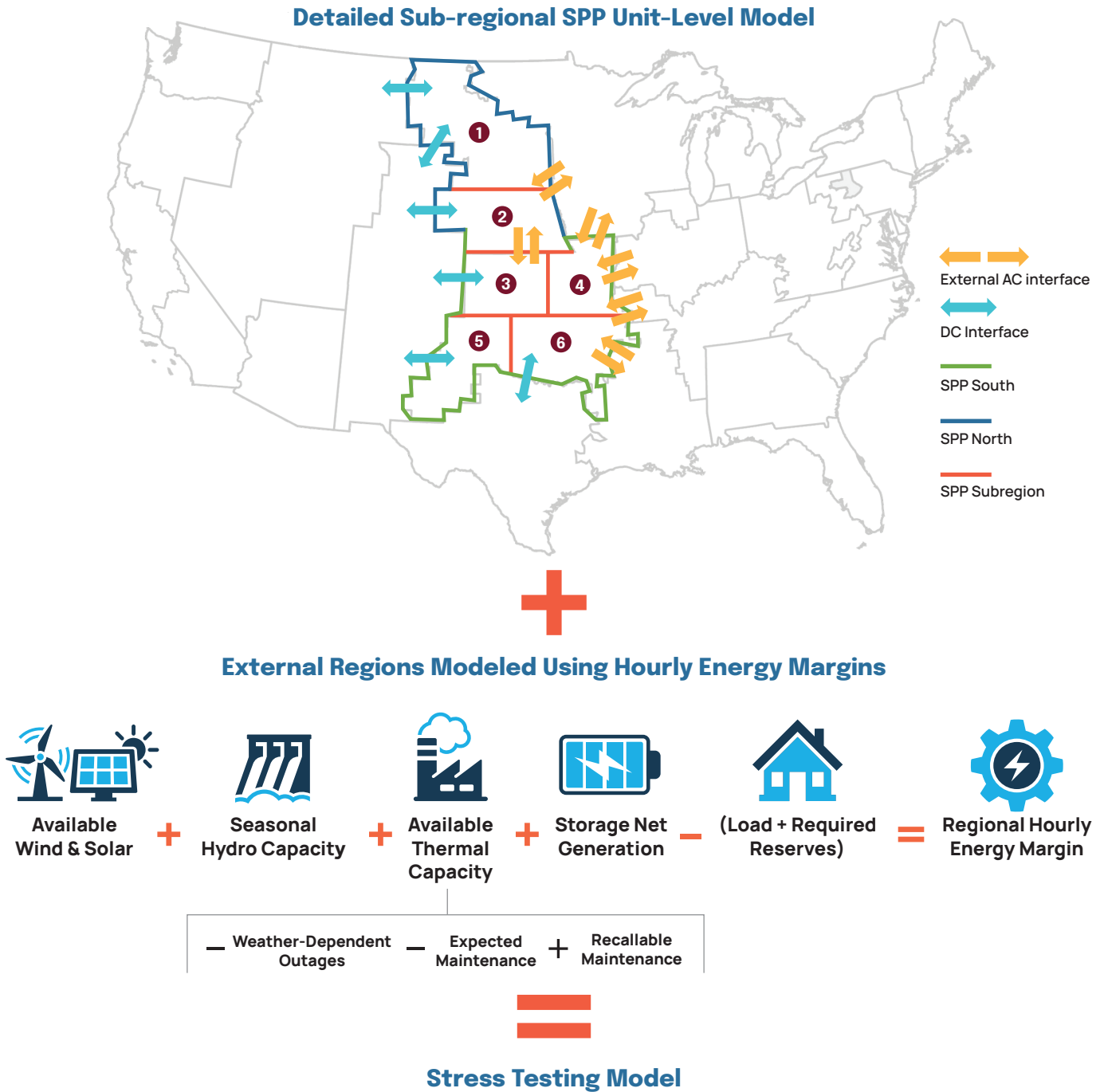
account for fluctuations in external resource availability, we modeled external regions using the hourly energy margin approach outlined in the ESIG report *Interregional Transmission for Resilience: Using Regional Diversity to Prioritize Additional Interregional Transmission*² and used region-specific correlated power system and weather data (Figure ES-3, p. 6, middle). Internal SPP generation and storage resources were modeled at a unit level. To account for forced outages as would be seen in an extreme weather event across all regions modeled, we used daily weather-dependent outages by fuel type (e.g., coal, single fuel gas). Hourly availability profiles were used for wind and solar resources based on historical weather and future system installed capacity. These components were brought together to create a weather-correlated and time-synchronized stress testing model for SPP.

Simulations were performed across three representations of the interconnected, external systems by assuming either (1) no external assistance was available (“island”),

² Energy Systems Integration Group, *Interregional Transmission for Resilience: Using Regional Diversity to Prioritize Additional Interregional Transmission* (2024), <https://www.esig.energy/interregional-transmission-for-resilience>.

FIGURE ES-3

SPP Stress Testing Case Study Zonal Topology with Interregional Transmission Interfaces



Higher-fidelity study region with weather-correlated and time-synchronized national representation to model discrete extreme events.

The model framework merges a detailed sub-regional unit-level model for the Southwest Power Pool with an hourly energy margin representation for external regions. The model topology includes representation of region-specific weather data, time-synchronized renewable profiles, and daily weather-dependent forced outages across all fuel types. Zonal transfer capabilities are adhered to between all regions in the model, and an internal reserve limit is held for every region.

Source: Energy Systems Integration Group.

(2) only firm, contracted assistance was available (“firm only”), or (3) non-firm external market assistance was available provided that neighboring regions had surplus capacity available and respecting interregional transfer capability limits (“modeling neighbors”).

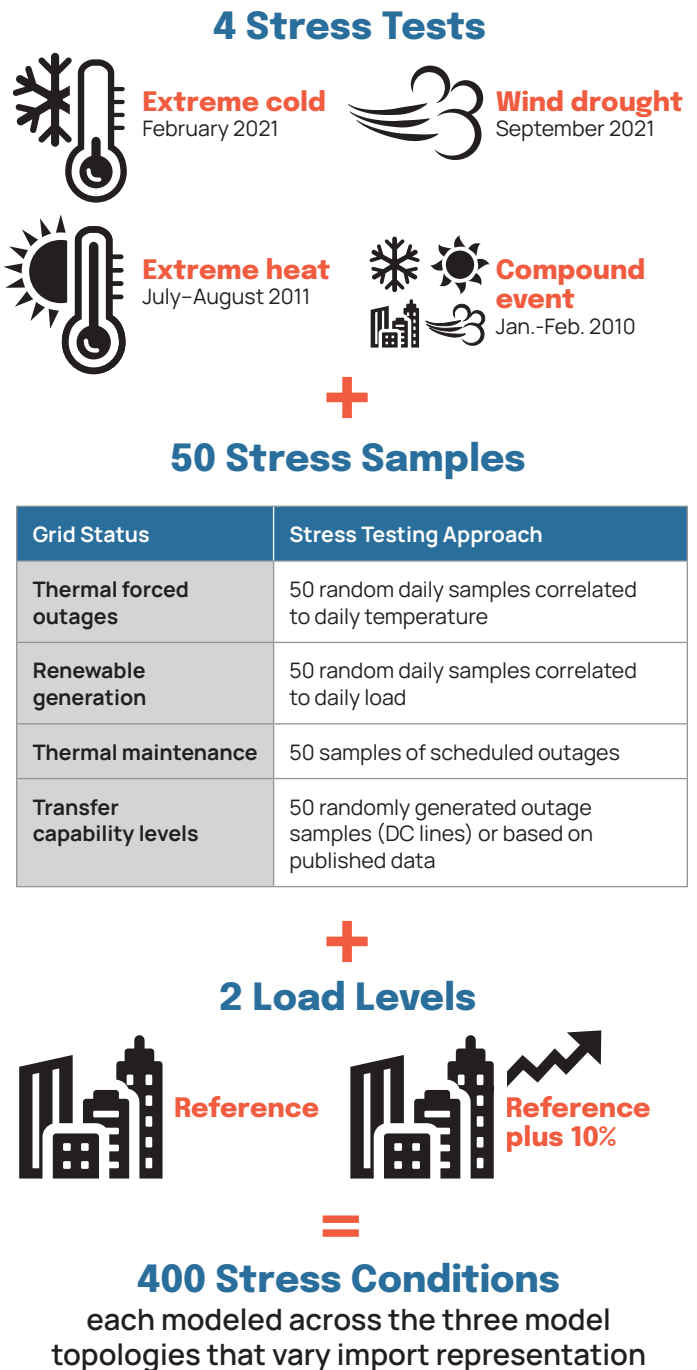
Step 3: Assessing Grid Resilience

To isolate the resilience benefit of interregional transmission during stress testing, three topologies discussed above were used that increase the representation of interregional transmission for SPP.

To assess the SPP region’s resilience during each of the four weather events selected, 50 unique stress samples were simulated in which conditions varied every hour and day of the stress test. Each stress sample had a unique daily thermal outage profile, hourly renewable profile, hourly thermal maintenance profile, and hourly DC intertie availability profile. The weather-informed profiles were synchronized across the entire continental United States. Each of the 50 stress samples per event were simulated at two different load levels: the reference load reflects the projected SPP load, and the +10% load level scales the SPP projection 10% higher to stress the event. The result of this set-up produced four unique stress tests (reflecting the three weather events and the compound event), each evaluated across 50 different combinations of stressors and two load levels, for a total of 400 unique stress cases (Figure ES-4). Each of these cases was also modeled across the three model topologies that vary import representation.

For each of the 400 simulated stress conditions, the key metrics of interest were the hourly energy margins, the magnitude and duration of unserved energy (load shed) events, and the flow of energy imports across the three transmission topologies for SPP. These metrics serve as a source of quantitative information for where expansion of interregional transfer capability may offer the greatest benefits—whether due to the availability of surplus resources or access to greater weather diversity to offset the local weather-induced risks embedded in the modeling data. In addition, when we compare the unserved energy events that occur in stress testing with and without higher-fidelity representation of interregional transmission, it is possible to estimate the specific resilience benefit of this grid asset during tail-risk events.

FIGURE ES-4
Stress Tests and Stress Variables
Considered in the SPP Case Study



Source: Energy Systems Integration Group.

SPP Stress Test Results

The Impact of Interregional Transmission in Reducing or Entirely Avoiding Unserved Energy Events

Our modeling indicated that existing interregional transmission in SPP provides an important buffer to the system during extreme weather events, even when neighboring regions are being affected by similar weather patterns. For the 2029 system modeled, when the full interregional transfer capability for SPP was evaluated, almost no unserved energy was seen across all four stress periods simulated. Interregional transmission brought significant value even in the most extreme event modeled, a recreation of February 2021 Winter Storm Uri as if it occurred on the 2029 SPP system, which exhibited very high demand, low renewable energy availability, and high thermal outages.

Figure ES-5 shows the contrast in unserved energy events for each stress test assuming different transmission

topologies. Results for the compound event, which exhibited low renewable and high outage risks but had more moderate electricity demand, are not shown since no unserved energy events occurred in the simulations of this event.

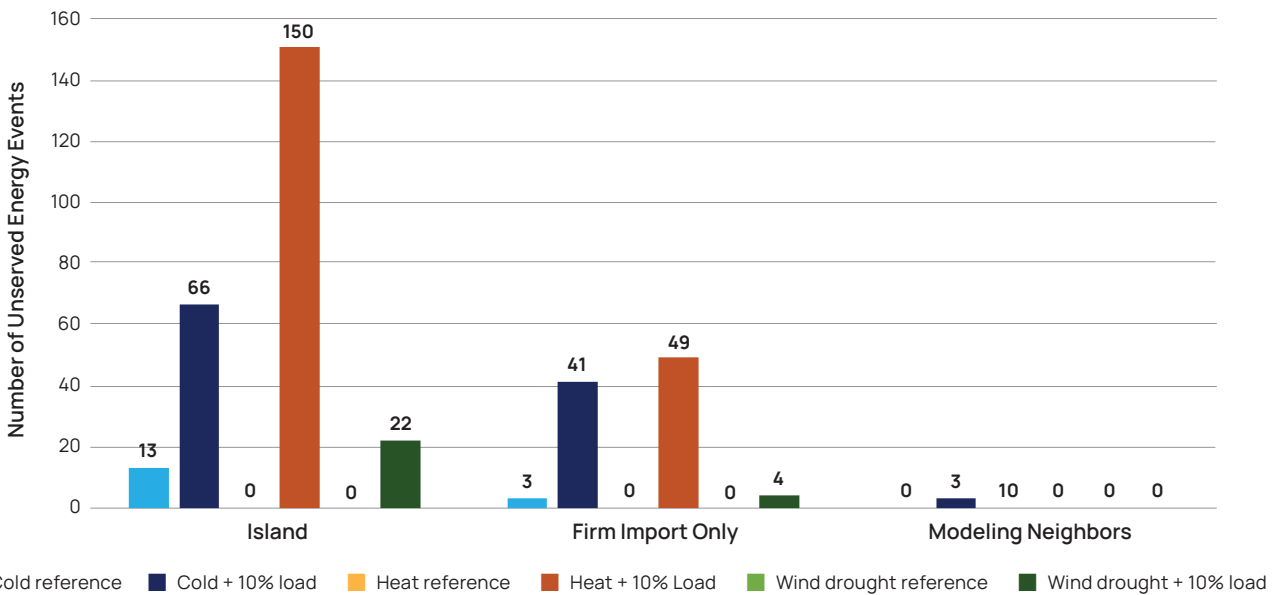
The contrast in stress testing results based on the transmission topology illustrates the resilience value of transmission for the tail-risk events modeled. When interregional transmission is included in the modeling, we see SPP's ability to absorb more risk, and, when the system limits are exceeded, the risk of load shedding is reduced in both magnitude and duration.

Hourly Imports into SPP During the Extreme Cold Stress Test

Figure ES-6 (p. 9) further illustrates how detailed interregional transmission modeling reveals a more resilient system during critical periods. The two top panels in the figure show the energy margin in SPP for several days in

FIGURE ES-5

Number of Unserved Energy Events Observed per Stress Test for the 2029 SPP System Using Three Interregional Transmission Topologies



The total count of unserved energy events that occurred for each stress test and transmission topology are shown in the chart. From left to right, the representation of interregional transmission and external resource availability improves in fidelity. Consequently, the number of unserved energy events observed in the stress test decreases as representation of weather-correlated external resource availability and existing transfer capabilities improves.

Source: Energy Systems Integration Group; data from the Southwest Power Pool, North American Electric Reliability Corporation, and Pacific Northwest National Laboratory.

February—how much surplus energy the system had hour by hour—for the reference load and load 10% higher than the reference load. The two bottom panels show exchanges of power between SPP and its neighbors, with the largest net imports corresponding to low energy margins. These panels show that there were many hours when net imports from neighbors exceeded SPP’s assumption for firm imports (i.e., assuming only firm imports underestimates net imports in many hours during critical periods)—as seen where the net interchange lines drop below -2,230 MW. If stress testing were to cap import capability to firm imports only and not reflect the

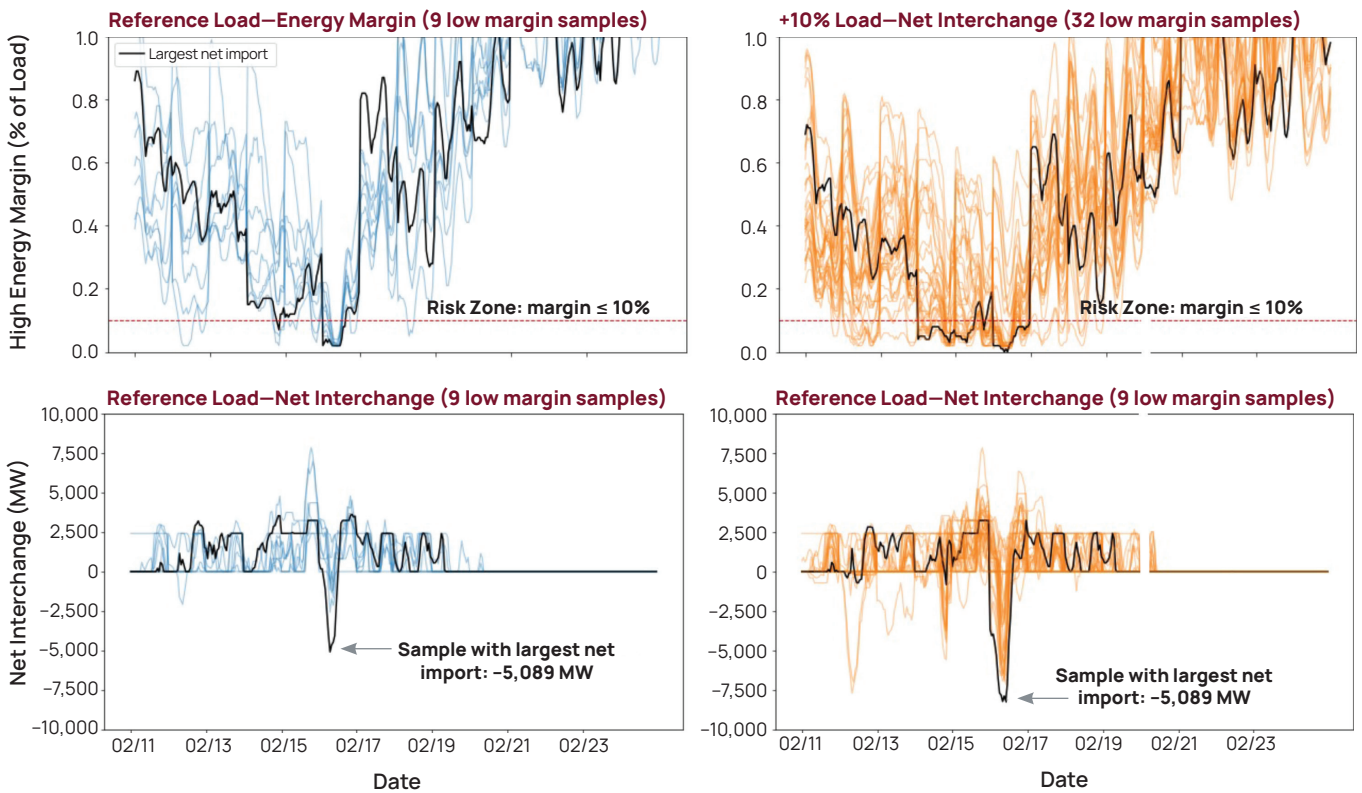
availability of additional external resources and inter-regional transfer capabilities, every hour when imports exceed the firm import assumption would be identified as a load shed event and omit the significant resilience value of interregional transmission.³

Import Contributions from External Regions During Different Weather Events

The results also provide insight into how different regions support SPP across different events, reflecting differences in correlated weather impacts, load, outages, and

FIGURE ES-6

Simulated SPP Hourly Energy Margin and Net Interchange with Neighbors in Extreme Cold Stress Testing Samples Where Margins Drop below 2% in at Least One Hour



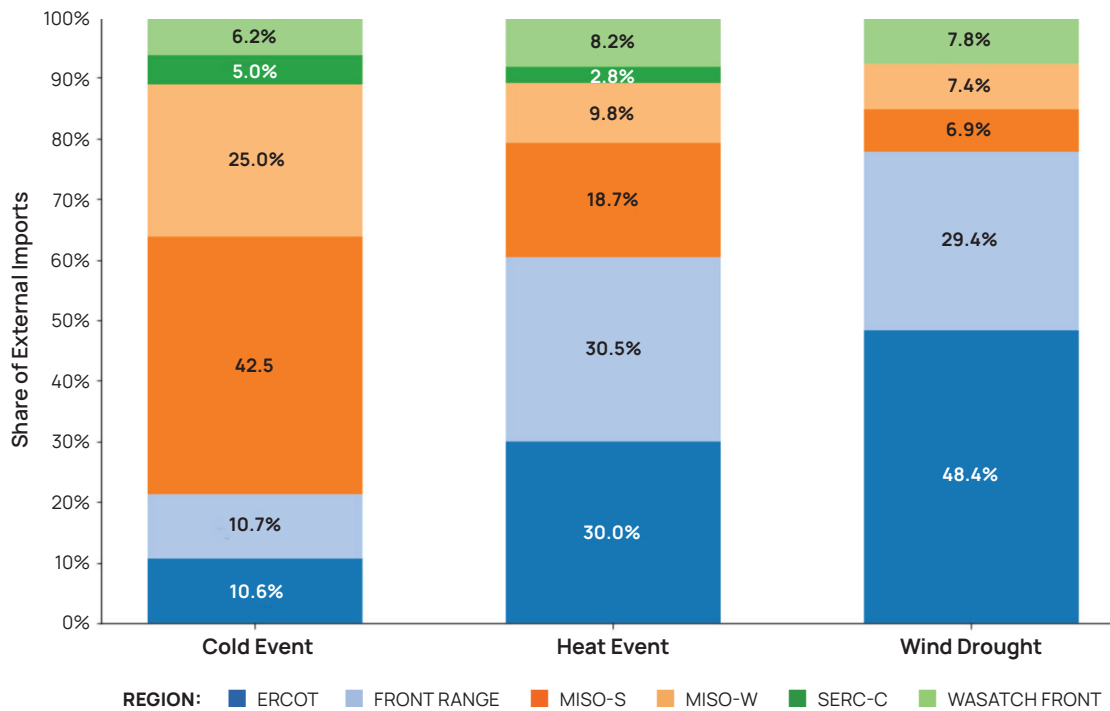
The SPP hourly energy margin as a percentage of load (top figures) is shown for stress testing samples for the extreme cold event. Only samples that had at least one hour when the energy margin dropped below 2% are shown. A line at the 10% threshold is included to show where samples have higher risks due to tighter hourly energy margins. The net interchange (positive = exports, negative = imports) for the reference load (left) and +10% load (right) shows how flows between SPP and its neighbors vary by stress sample and by hour. Notably, during some of the highest-risk hours, imports into SPP can exceed the SPP firm import assumption of 2,230 MW even when accounting for weather-correlated load and resource availability in external regions.

Source: Energy Systems Integration Group; data from the Southwest Power Pool, North American Electric Reliability Corporation, and Pacific Northwest National Laboratory.

3 SPP 2029 net firm import assumptions are 2,230 MW. Total interregional transfer capability modeled is 7,108 MW (AC) and 1,380 MW (DC) for a total of 8,488 MW across SPP-N and SPP-S regions.

FIGURE ES-7

Share of Total External Imports Received by SPP by Sending Region Across the 50 Stress Samples Simulated for the +10% Load Scenario



This chart demonstrates that neighbors’ ability to support a region during extreme weather is event-specific due to correlated weather patterns and different resource mixes and load conditions. During the winter storm, SPP leveraged weather and risk diversity with the Midcontinent Independent System Operator (MISO), which offers a path to the larger Eastern Interconnection. Conversely, during the heat wave and wind drought, to mitigate energy scarcity risks SPP relied more on the diversity between the Electric Reliability Council of Texas (ERCOT) and the Western Interconnection (Front Range and Wasatch Front).

Source: Energy Systems Integration Group; data based on simulations leveraging data from the Southwest Power Pool, North American Electric Reliability Corporation, and Pacific Northwest National Laboratory.

renewable availability across neighboring regions. Figure ES-7 shows the share of total external imports to SPP during the stress tests for the cold event, heat event, and wind drought.

These results underscore that not every neighbor can provide the same assistance during every event and that planning for expanded interregional transfer capability should consider which interfaces provide the greatest resilience value under specific stress conditions.

Step 4: Creating Actionable Plans

By identifying critical risk periods stemming from different types of weather events and modeling inter-regional transmission and external resource availability in higher fidelity, the analysis reveals the resilience value of interregional transmission for SPP. These results

provide quantitative backing to recognize the benefits of existing interregional transmission capabilities and build on them to unlock potentially greater resilience value and mitigate extreme events.

Existing Interregional Transmission Is Critical to SPP Resilience

Across the severe stress events modeled, including extreme cold, extreme heat, and wind drought conditions, SPP resilience remained high when neighboring regions were represented with weather-correlated resource availability. However, simplified “firm import only” assumptions can understate the resilience value of existing interregional transmission by artificially capping energy transfers from neighbors that are available during stress events and potentially overstating unserved energy risks, or at the very least, understating the resilience value of

interregional transmission. In the case study, modeling interregional transfer capability substantially reduced the frequency and severity of load shedding, and it reduced the magnitude and duration of the events that remained when interregional resources were exhausted or interregional transfer capabilities limited additional imports along specific transmission corridors.

Recommendations for Interregional Transmission Planning for Resilience

The need for robust extreme weather modeling is no longer optional; it is being driven by regulatory mandates. FERC Order 1920 specifically requires transmission providers to measure the benefits of interregional transfer capability during extreme weather events and unexpected system conditions. The stress testing framework presented in this report offers a robust methodology for meeting these requirements and justifying investments based on improving system resilience to the most extreme events. To this end, three recommendations are provided stemming from the report and the accompanying stress testing case study to both improve planning for resilient systems and improve how the value of interregional transmission is represented.

Improve Interregional Representations of Extreme-Event Modeling

Isolated modeling of power systems, without including the neighboring interconnected systems or capping interregional support, fails to accurately capture the available support and flexibility provided by the broader grid during extreme events. As a result, potential mitigations or investments may ignore a valuable asset to improve resilience.

Instead, planners can leverage wide-area weather-correlated datasets and aggregation methods, such as the hourly energy margin approach, to dynamically

FERC Order 1920 specifically requires transmission providers to measure the benefits of interregional transfer capability during extreme weather events and unexpected system conditions. The stress testing framework presented in this report offers a robust methodology for meeting these requirements and justifying investments based on improving system resilience to the most extreme events.

model the availability of external resources and transfer capabilities during specific extreme events when stress testing their system.

Establish a Resilience Threshold to Guide Investment Needs

Planners need to establish explicit resilience thresholds to determine when stress test results necessitate new investments. The growing interest in multimetric resource adequacy criteria may provide a beneficial framework for establishing maximum acceptable tail-risk events based on stress testing.

Value and Expand Interregional Transmission

Existing interregional transmission is already critical for maintaining grid resilience today. By developing more robust methods to value this infrastructure, such as those demonstrated in this report, the industry can build a stronger business case for expanding interregional transfer capability and look beyond strictly incremental local reliability-driven upgrades. Doing so will both improve resilience against the extreme weather of today as well as prepare the grid for the challenges of the future.

Stress Testing Methods for Evaluating Resilience to Extreme Events: Valuing Interregional Transmission and the accompanying case study, by the Energy Systems Integration Group's Transmission Resilience Task Force, are available at <https://www.esig.energy/reports-briefs/stress-testing/>.

To learn more about the topics discussed here, please send an email to info@esig.energy.

The Energy Systems Integration Group is a nonprofit organization that marshals the expertise of the electricity industry's technical community to support grid transformation and energy systems integration and operation. <https://www.esig.energy>.

© 2026 Energy Systems Integration Group