Stress Testing the Southwest Power Pool

Evaluating the Role of Interregional Transmission in Supporting SPP Resilience to Extreme Events

February 2026

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Stress Testing the Southwest Power Pool Case Study

1. Case Study Motivations and Modeling Set-up
2. Developing Extreme Event Scenarios
3. Modeling the Extreme Events
4. Stress Testing Results
    - February 2021 Cold Event
    - July – August 2011 Heat Event
    - August – September 2011 Wind Drought
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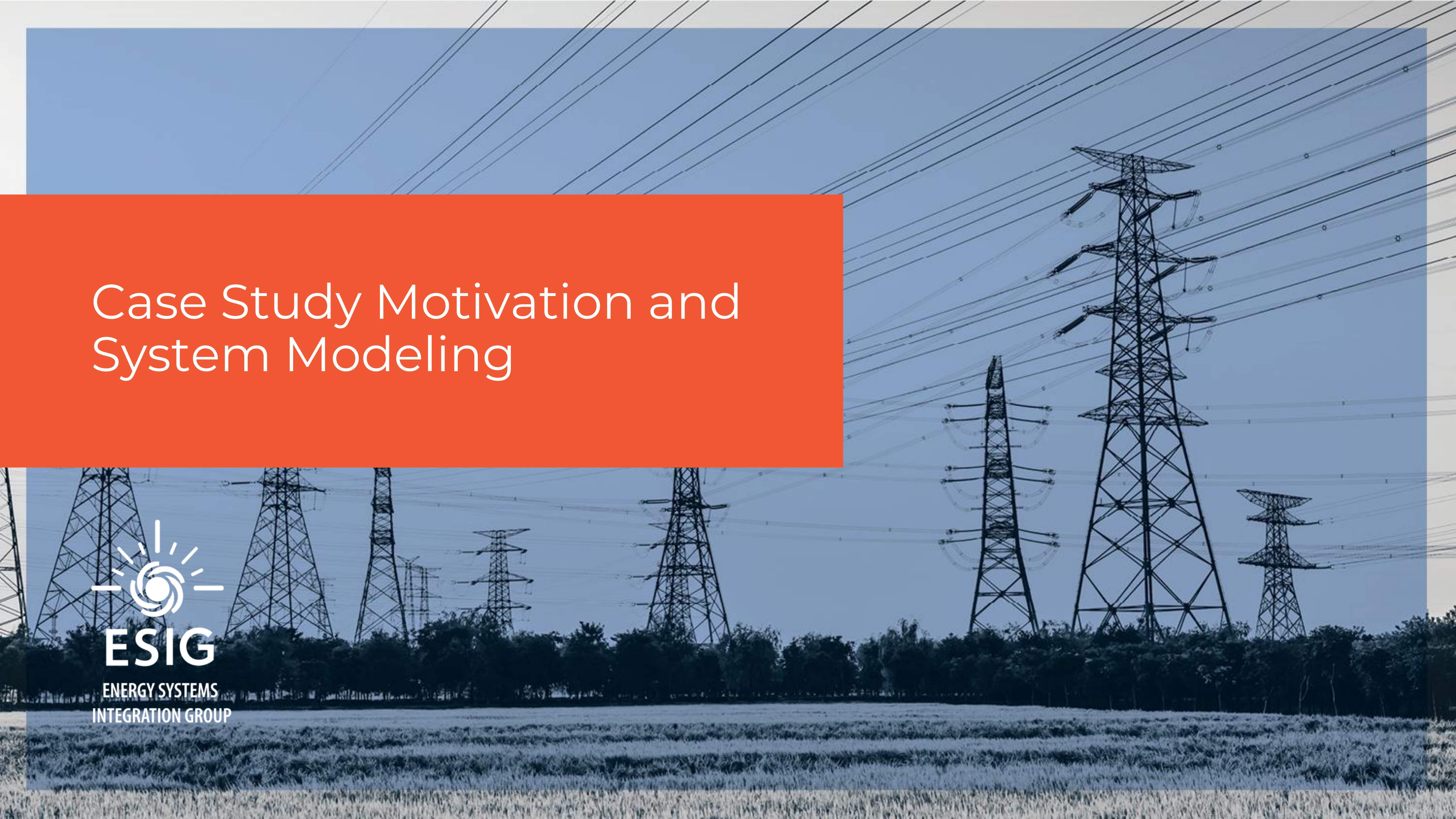
5. Stress Testing Key Findings and Recommendations

This case study and the report it accompanies, *Stress Testing Methods for Evaluating Resilience to Extreme Events: Valuing Interregional Transmission*, can be found at https://www.esig.energy/reports-briefs/stress-testing/.

Case Study Motivation and System Modeling



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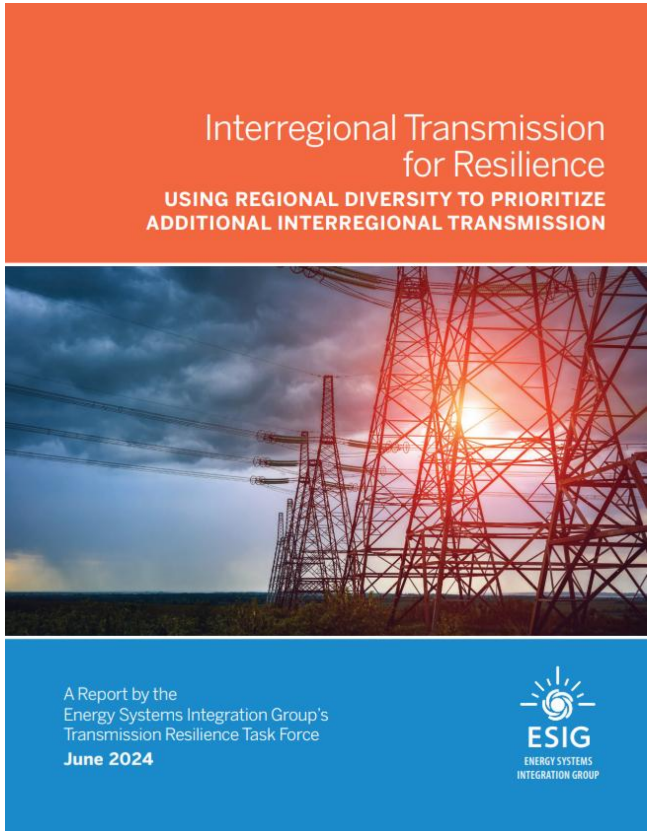
Study Motivation

Motivation 1: Develop an approach for stress testing to analyze system resilience to discrete extreme events and incorporate interregional transmission

Motivation 2: Use the stress testing approach on an actual system to evaluate interregional transmission resilience benefits

Study Outcomes:

1. Stress Testing Methods for Evaluating Resilience to Extreme Events
2. Stress Testing the Southwest Power Pool Case Study [this work]



Transmission Resilience Task Force:

The task force's goal was to develop new methodologies for resilience assessments that outline the role of interregional transmission in providing resilience benefits

Prior Task Force Work (Phase I):

Interregional Transmission for Resilience: Using Regional Diversity to Prioritize Additional Interregional Transmission

A four-step stress testing process turns extreme events into planning conclusions.

The method connects scenario selection, interconnected-grid representation, chronological simulation, and result interpretation for planning decisions.

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Step 1: Develop Extreme Event Scenarios	Prioritize realism and relevance in scenario design. • Stress tests should be plausible and rooted in multiple years of real-world weather correlated data to maintain credibility. Be open to future climate change scenarios. • Events should be defined clearly using magnitude, duration, frequency, and geographic scope. • Emphasize stakeholder understanding. Be transparent about what is being tested and why.
Step 2: Model the Interconnected Grid	Represent the physical and operational details of the broader system. • Models should seek to reflect real-world capabilities, grid constraints, economics, and interdependencies. • Include interregional transfers and model external resource availability. • Maintain correlation across geographic areas to represent load and resource diversity.
Step 3: Assess Grid Resilience	Evaluate the changing, time-dependent, and correlated nature of stressful events. • Simulate chronological, multi-day events that are relevant for today's grid and the grid of the future. • Analyze risks for all resources and load for how the extreme event affects their risk profiles. • Avoid “peak hour” thinking – resilience is more than capacity at the highest load hour.
Step 4: Create Actionable Plans	Use results to inform practical, forward-looking decisions. • Define risk tolerance thresholds to indicate a pass/fail for stress test results. • Consider diverse mitigation tools beyond just new capacity (transmission, weatherization, distributed resources). • Enable feedback loops between existing planning processes like resource adequacy studies.

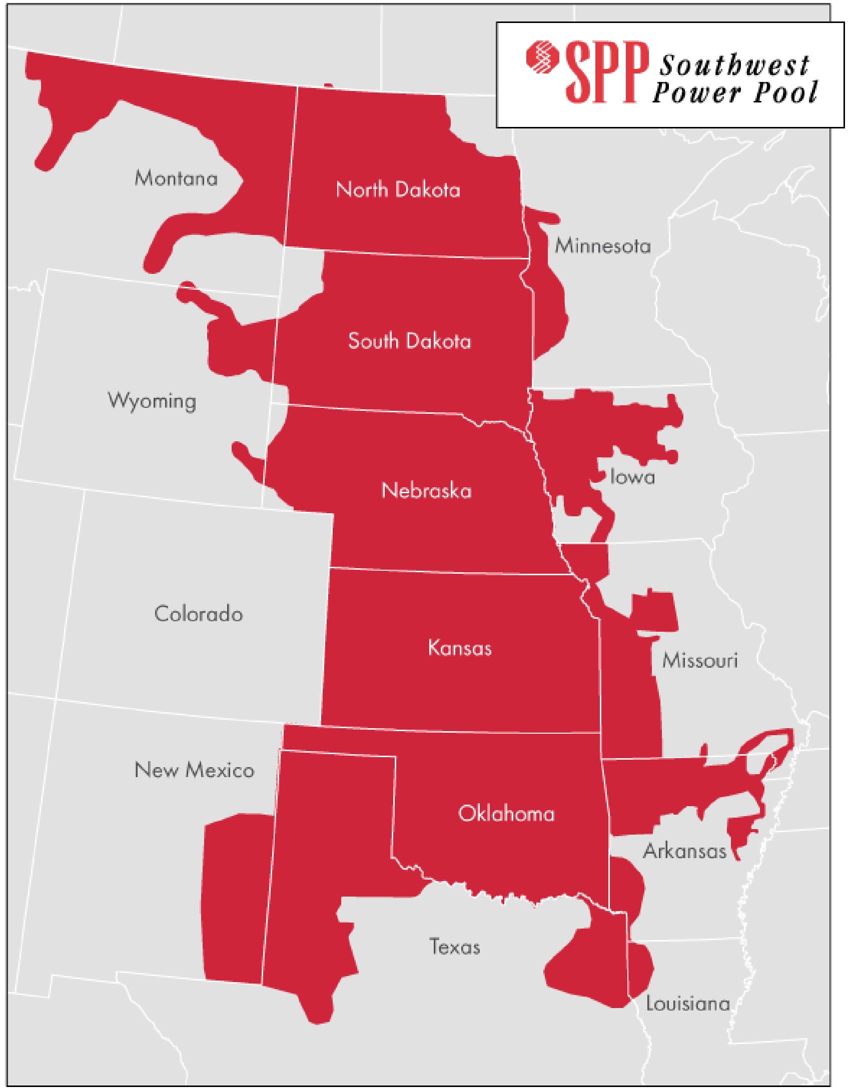
SPP Stress Testing Case Study
Motivations

Motivation 1: Develop an approach for stress testing to analyze system resilience to discrete extreme events and incorporate interregional transmission

Motivation 2: Use the stress testing process on an actual system to evaluate interregional transmission resilience benefits

Additional Goals:

- Develop methods to generate combinations of stress variables for specific extreme weather events
- Further enhance the hourly energy margin approach from Phase 1 of the project for use in a study to improve interregional transmission modeling
- Analyze extreme weather events using a geographically consistent, hourly, time-synchronized wind, solar, outages, and load dataset



Source: Southwest Power Pool

A hybrid stress test model links unit-level operations in SPP with hourly external energy margins.

This approach preserves chronology and weather correlation so that transfer capability and external support are evaluated realistically.

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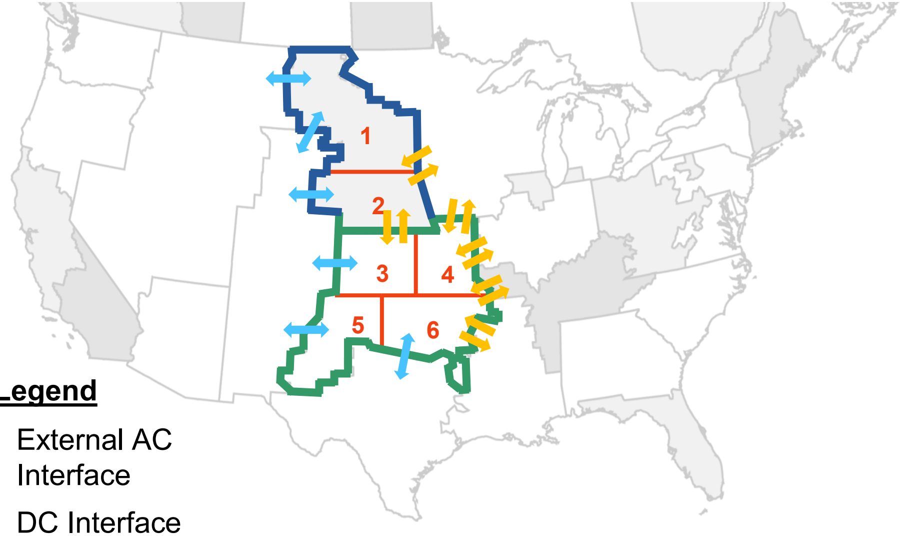
Combine a **detailed representation of SPP**, with a simplified representation of the U.S. system.

1 Detailed Sub-regional SPP Unit Level Model



Legend

- External AC Interface
- DC Interface
- SPP South
- SPP North
- SPP Subregion

*All region boundaries are approximate and do not show overlapping territory
**All internal SPP interfaces connect to a central "SPP System" node for DR and respective SPP-S and SPP-N nodes for internal transfers
***Canadian regions depicted are not included in the model

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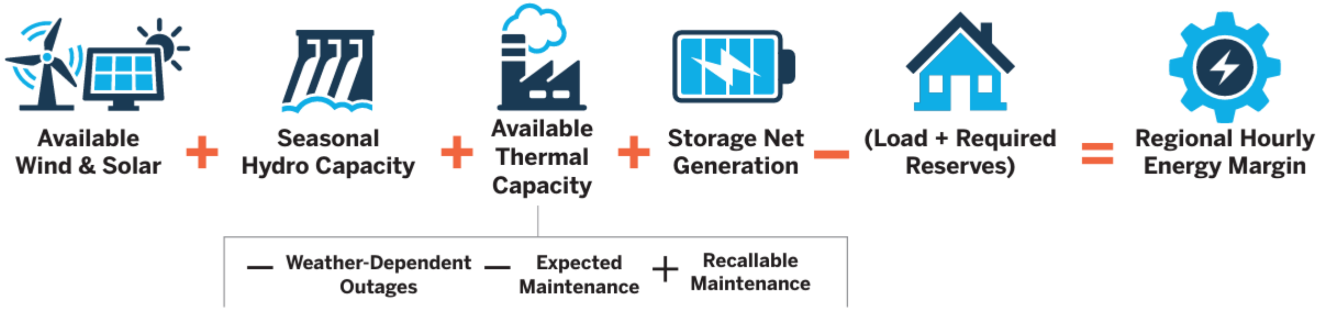
2 External Regions Modeled using Hourly Energy Margins



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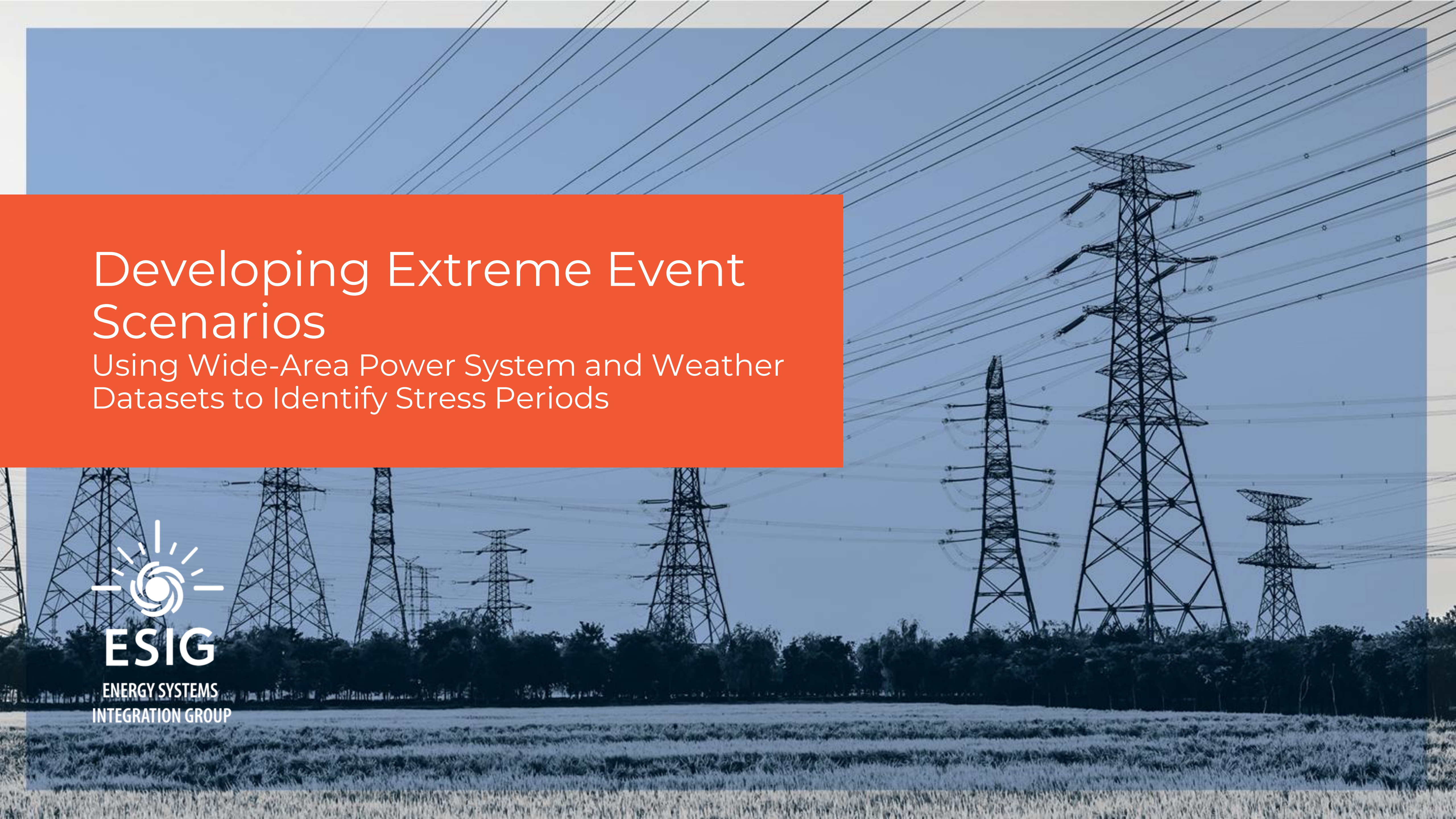
Stress Testing Model

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

Source: Energy Systems Integration Group.



Developing Extreme Event Scenarios

Using Wide-Area Power System and Weather Datasets to Identify Stress Periods

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Wide-area, multi-day screening captures interregional dependence during extreme events.

The screening criteria enforce correlated weather, coincident stressors, and sustained conditions that drive tail risk

Develop a list of **extreme weather and renewable risk event** candidates to select for stress testing.

Assess **region-wide** and **continent-wide** weather to include interregional resource availability.

Consider long history and a range of years to understand outlier stress what tail risks may look like.

Focus on multi-day events and *not* consider a single peak hour or day but rather a **span of hours or days**.

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

Extreme events can be identified by screening linked power system and weather datasets for high-risk periods.

Using hourly, chronological, weather-correlated data from a consistent dataset ensures that stress testing results preserve wide-area correlations in risk.

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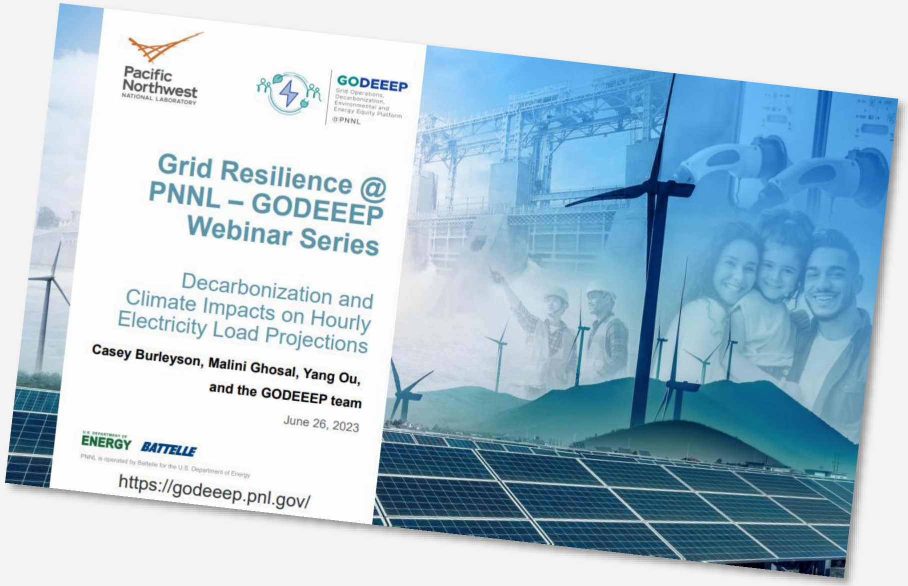
National Temperature Dataset

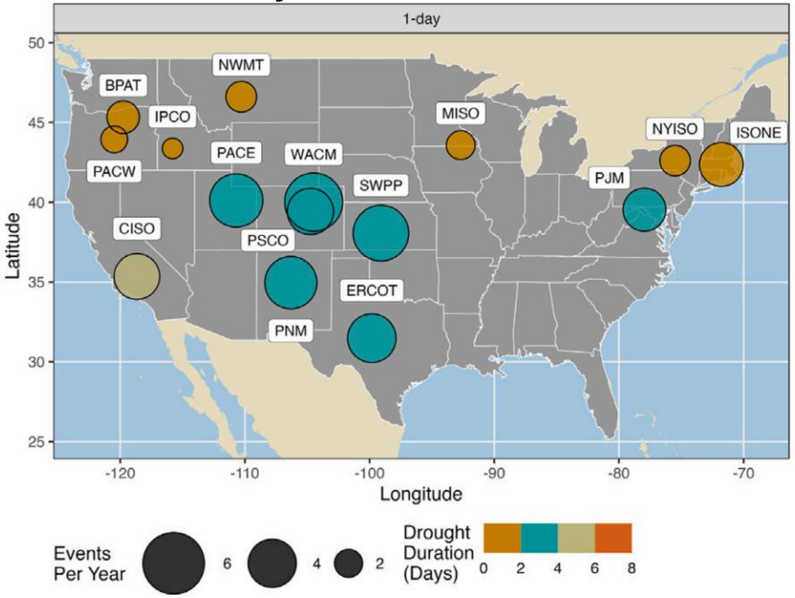
- National-scale temperature dataset is synchronized with power system data to map weather-dependent variables and screen for temperature-based risks.
- Temperature relationships across regions are maintained by drawing from the same dataset for identifying events.



Source: https://www.pnnl.gov/events/godeeep-webinar-series-deep-dive-one

SPP Resource Adequacy Dataset

- 43 weather years of load, wind, and solar capacity factors were used to screen for energy shortfall risks.
- A standardized energy drought analysis developed by Bracken et al. was used to identify multi-factor risks such as renewable droughts and thermal availability risks.



Source: https://www.sciencedirect.com/science/article/pii/S0960148123014659

Energy availability to meet daily or hourly demand can be screened to identify potential shortfalls.

Identified energy droughts or shortfall risks can be examined for the cause (e.g., extreme cold weather) and selected for detailed stress testing.

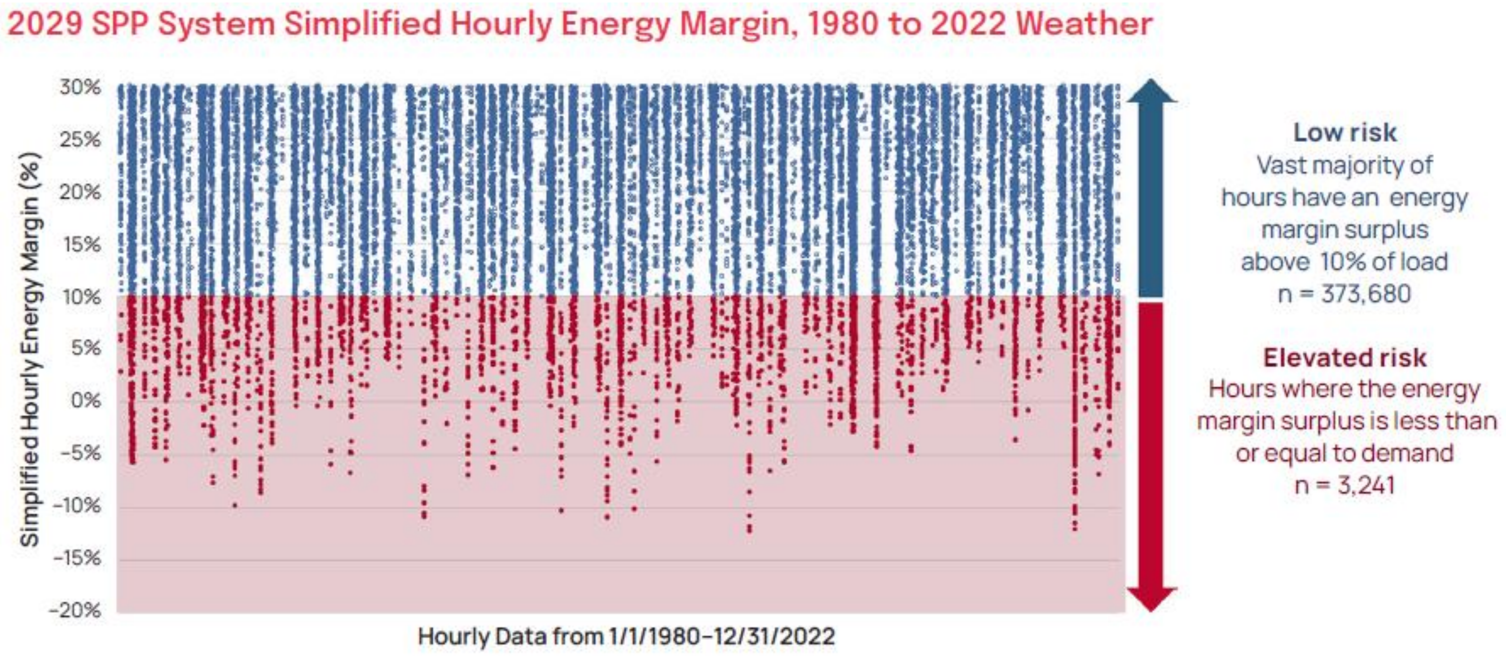
43 years of hourly load and renewable data were screened and analyzed to identify “energy droughts.”

Using historical data, temperature-correlated thermal fleet outages were randomly generated for past daily temperatures.

The worst-case daily availability was used based on binning historical temperatures and outage days.

The chart shows days where energy availability is above or below a 10% surplus of daily demand.

Simplified Daily Energy Surplus for SPP Using Resource Adequacy and Historical Temperature Data



Note, this screening method does not account for energy storage, demand response, or transfer capabilities. It only reveals days in which total energy availability to serve demand with some buffer may be at risk in the 2029 SPP system.

Source: Energy System Integration Group; data from SPP and North American Electric Reliability Corporation (NERC).

Multiple unique extreme events are identified based on risk factors relevant to SPP.

Most regions will need to examine extreme cold and heat events, but given the high levels of wind in SPP, a wind drought event was also included.

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The stress periods used for testing are not exhaustive, but reflect both extreme single-factor and compound-factor events:

- Two periods are characterized mainly by their temperature extremes.
- One event represents a multi-day wind "energy drought" relevant to SPP.
- All events have some level of compound risks. The compound risk event identified has a high compound weighting where factors such as demand, solar, wind, and thermal availability are all moderately severe but not the most severe.

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

After selecting periods for stress testing, examining where the conditions land in a historical sense is valuable.

Stress testing inherently focuses on the most extreme conditions, so stress events analyzed from screening methods should exhibit tail-risk conditions.

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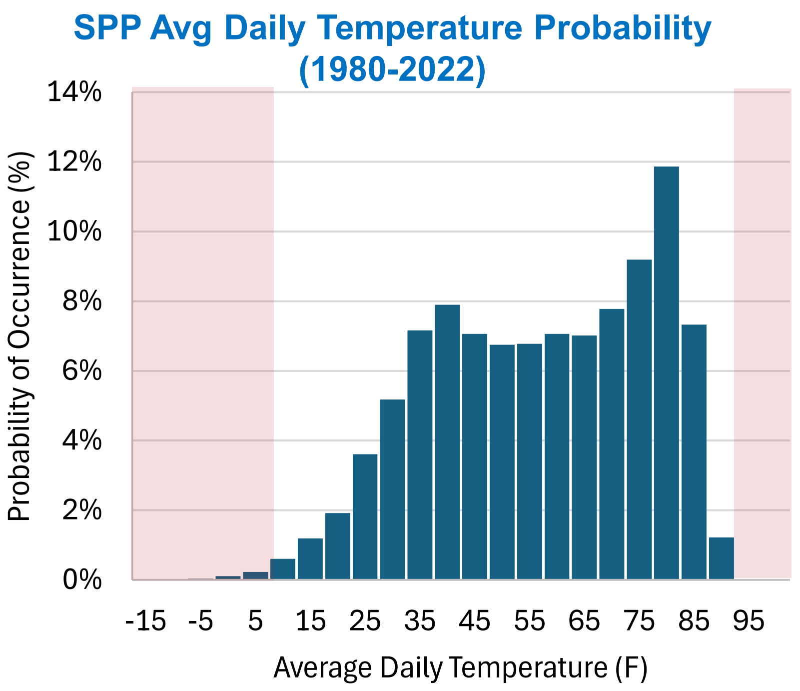
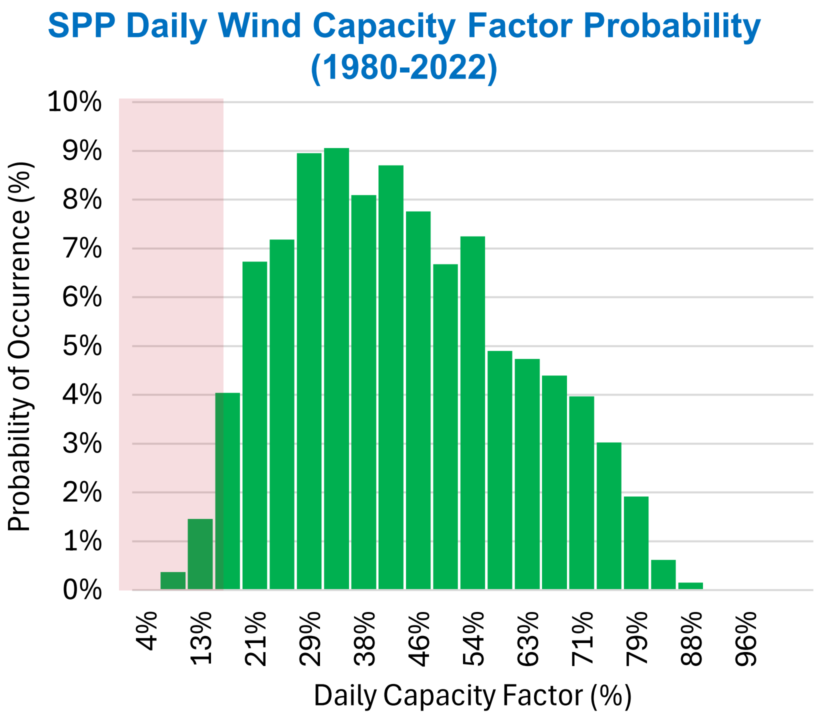
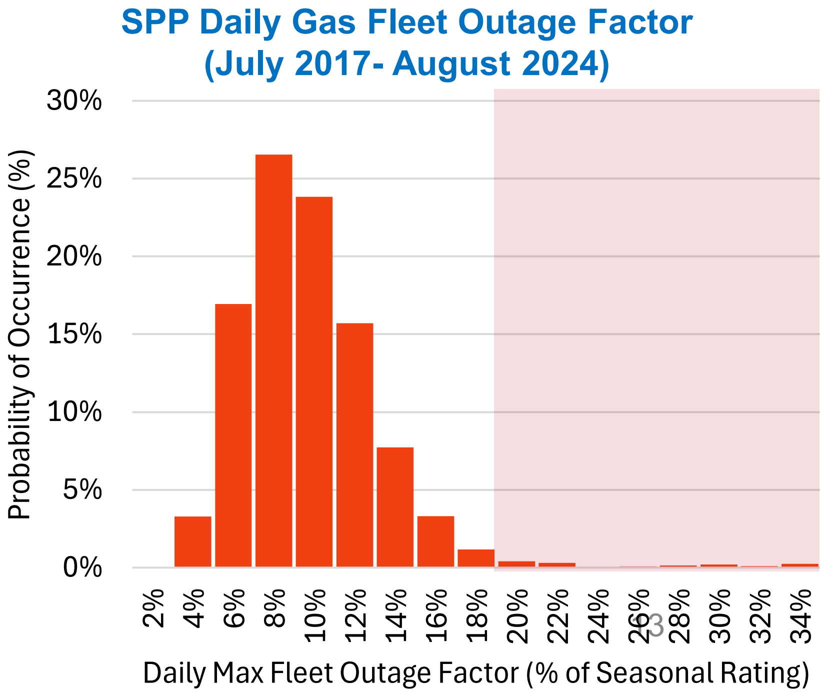
All four events selected have grid conditions at the tail ends of major risk drivers like temperature, wind generation, and thermal fleet outages.

The red shaded areas on each plot indicate conditions present in the chosen stress periods.



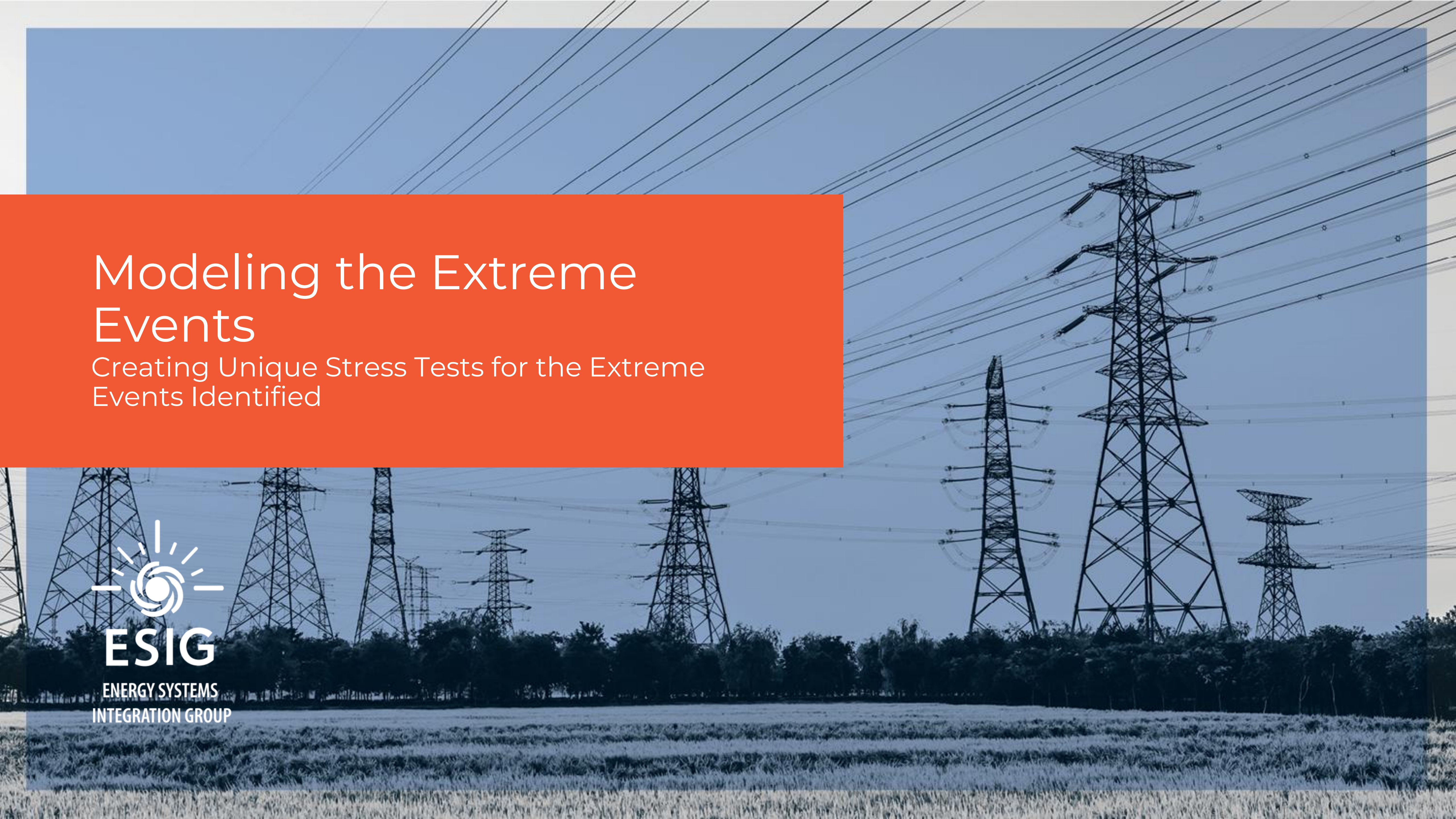




Source: Energy System Integration Group; data from SPP, NERC, and Pacific Northwest National Laboratory (PNNL).

Modeling the Extreme Events

Creating Unique Stress Tests for the Extreme Events Identified



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Four event types and 100 chronological runs per event probe high-risk conditions.

The study varies outages, renewables, and load across 50 stress samples and two load levels for each event.

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4 Stress Tests

Extreme cold
February 2021

Wind drought
September 202

Extreme heat
July–August 2011

Compound event
Jan.-Feb. 2010

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50 Stress Samples

Grid Status	Stress Testing Approach
Thermal forced outages	50 random daily samples correlated to daily temperature
Renewable generation	50 random daily samples correlated to daily load
Thermal maintenance	50 samples of scheduled outages
Transfer capability levels	50 randomly generated outage samples (DC lines) or based on published data

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2 Load Levels

Reference

Reference plus 10%

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400 Stress Conditions

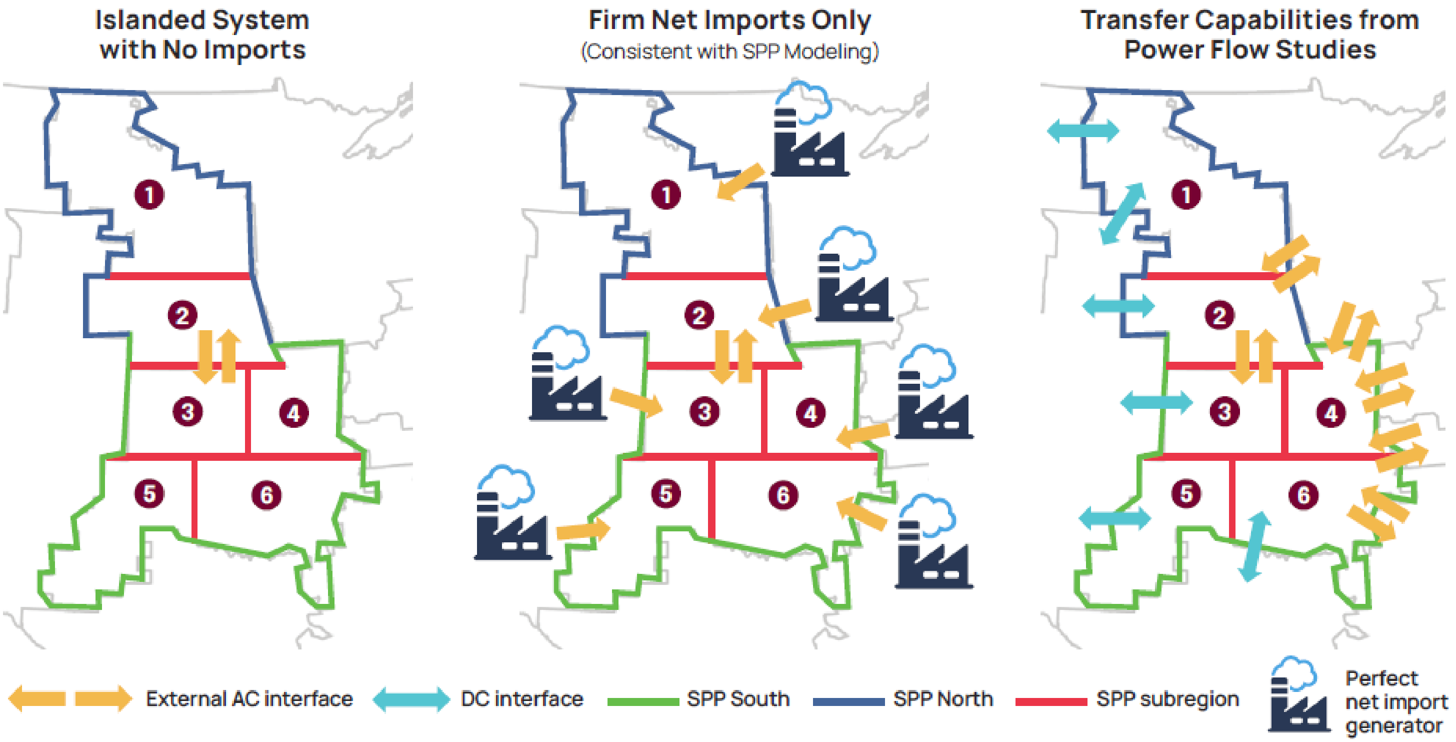
each modeled across the three model topologies that vary import representation

Source: Energy Systems Integration Group.

Three import representations are used to assess interregional transmissions value.

These cases isolate the impact of modeling decisions on stress testing results which affect the perceived resilience value of transmission.

Modeling the same stress test across three import representations was done to assess the impact of higher-fidelity interregional modeling on system risk.



Source: Energy Systems Integration Group.

There are different regulatory, risk tolerance, and methodological reasons for different modeling choices. But stress testing should seek to represent the available resources and transfer capability of the external system.

Stress Testing Results

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Stress Testing Results Setup

All four cases were simulated using the three import representations.

Each case was modeled across 50 unique combinations of each stress variable.

For each case, the following metrics were compared between import representations:

- SPP hourly energy margin
- Statistics on hours where margins <10% and <3%
- System-wide net imports and tight margin hours
- Magnitude and duration of unserved energy events
- Proportion of load served by imports across stress samples

February 2021 Cold Weather Event Stress Test

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Cold event: Compounding stressors make imports decisive for limiting load shed.

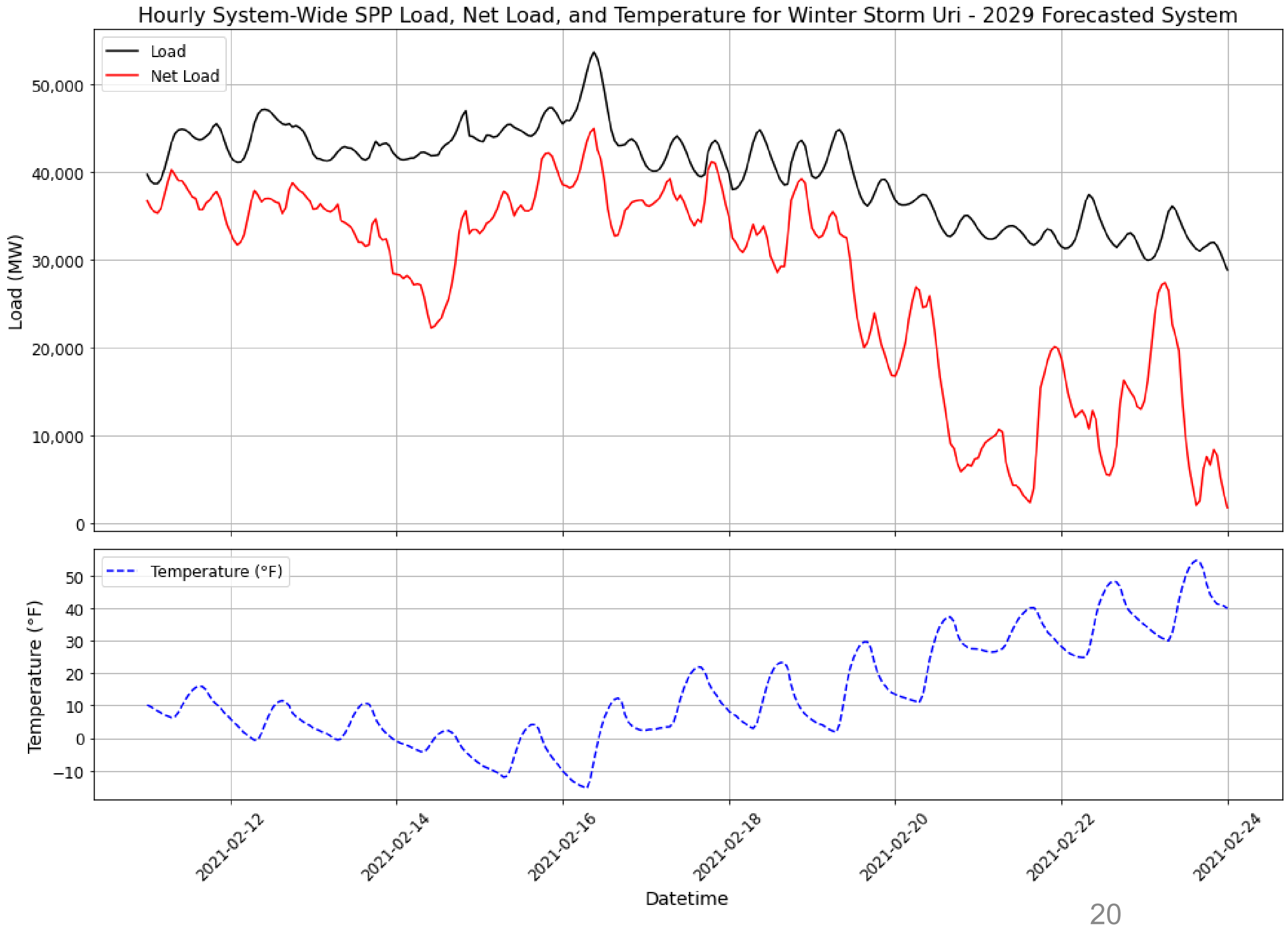
The Uri-like event aligns high load, low renewable output, and elevated outage risk over many hours.

Re-simulated Winter Storm Uri weather, applied to a future power system.

The event consists of a multi-day period with declining temperatures and high net load across SPP and neighboring regions.

Periods of high net load plus low renewable generation truly stress the system. Imports were critical to maintain reliability.

SPP shed load on February 15 and 16 during the actual Uri event.



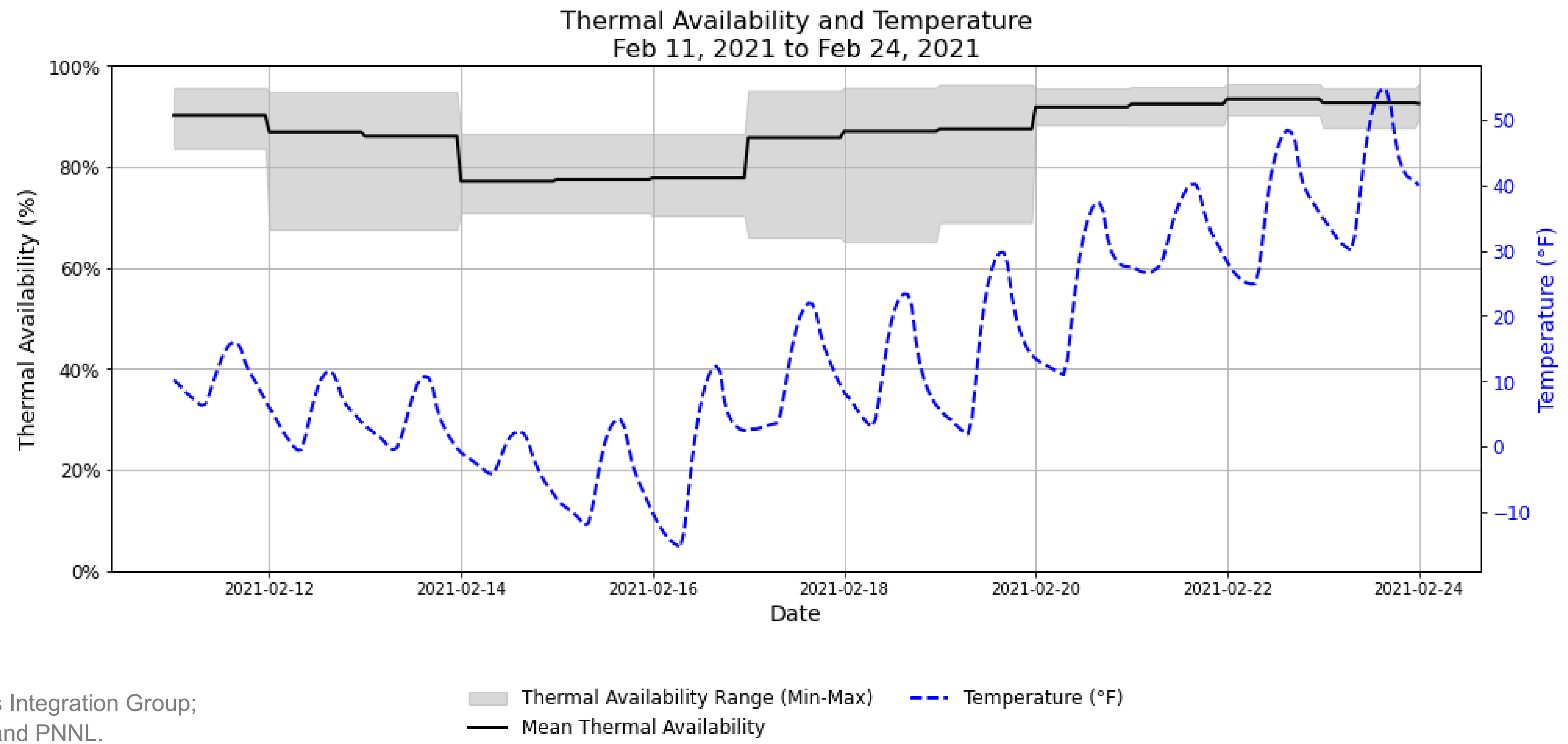
Source: Energy Systems Integration Group; data from SPP and PNNL.

To stress the system, thermal availability is varied for each day based on temperature-outage relationships.

Like Uri, weather-dependent availability for the thermal fleet can drop close to 60%

The gray shaded area represents the range of thermal availability simulated.

Conditions resemble Uri, which had some of the worst-case thermal outage levels. It should be noted that while cold weather affects thermal outages, not every extreme cold event has extreme Uri-like outages when reviewing temperature alone.



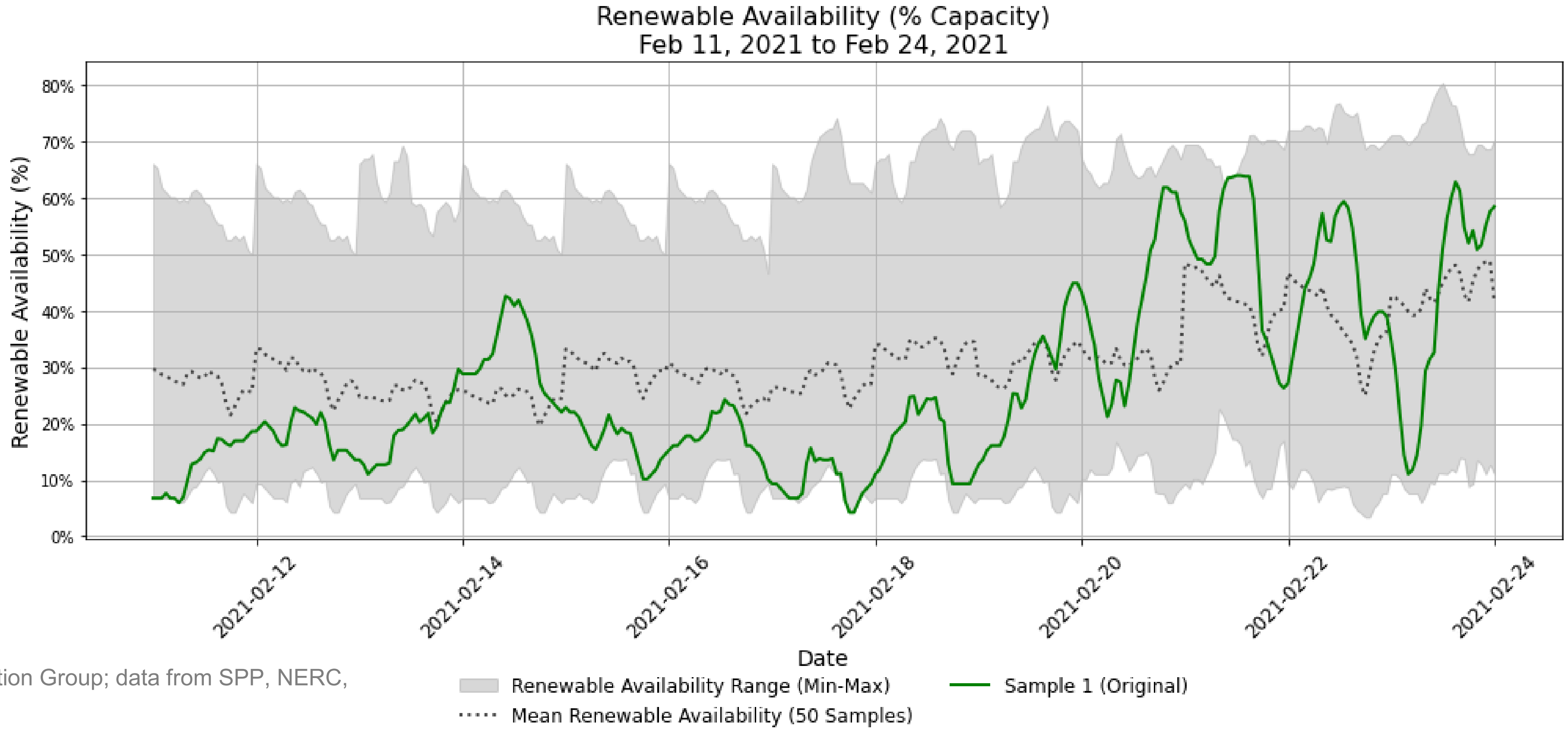
Source: Energy Systems Integration Group; data from SPP, NERC, and PNNL.

Unique renewable profiles were created to stress the event if different plausible renewable conditions occurred.

Variability in renewable generation is high, even when days with similar load levels are re-sampled.

50 combinations of variations hourly profiles were generated based on days where load levels were similar in February across the weather years available.

Not all extreme cold weather events have the same renewable availability, as exhibited by the mean line. However, several samples produce events with worse renewable availability for testing.



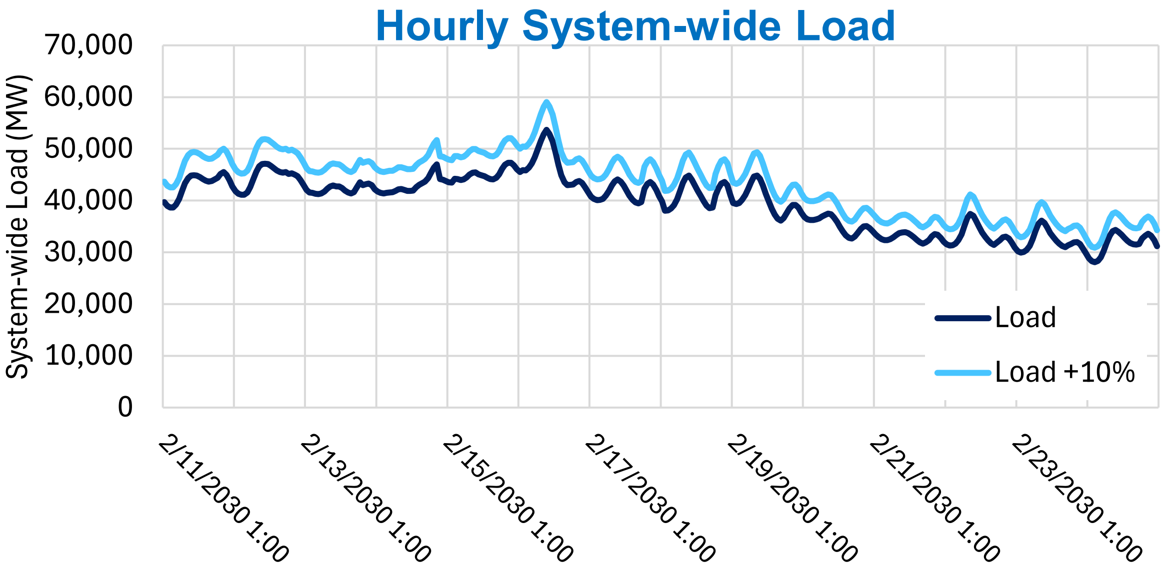
Source: Energy Systems Integration Group; data from SPP, NERC, NREL, EIA, and PNNL.

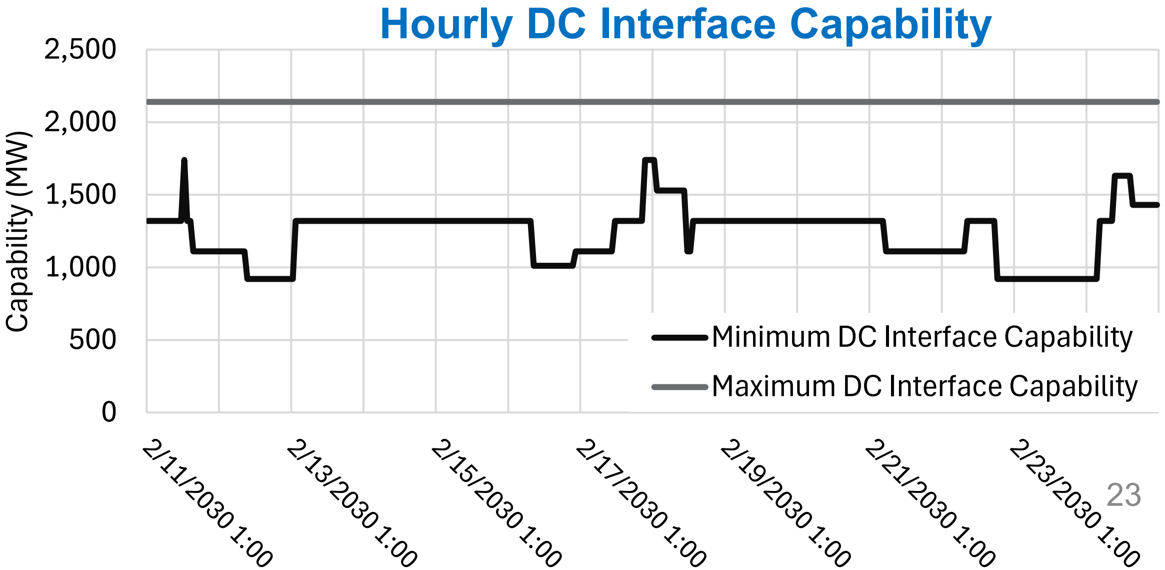
Load, generator maintenance, and DC interface capability for SPP were also stressed to increase risks and evaluate resilience.

The February event was modeled for the reference forecasted load and a high load case where every hour was scaled by 10%.

Randomized forced and maintenance outages were modeled on SPP DC interfaces with capabilities ranging from 100% available to less than 50%.

Increasing the load resulted in greater system stress due to the compound effects of low renewables and increased thermal outages.





Source: Energy Systems Integration Group; data from SPP

During the cold event, higher load increases scarcity hours, and imports are more essential to maintaining service.

Modeling neighbors shows imports rising as margins tighten, and unserved energy appears only under higher load when imports are exhausted.

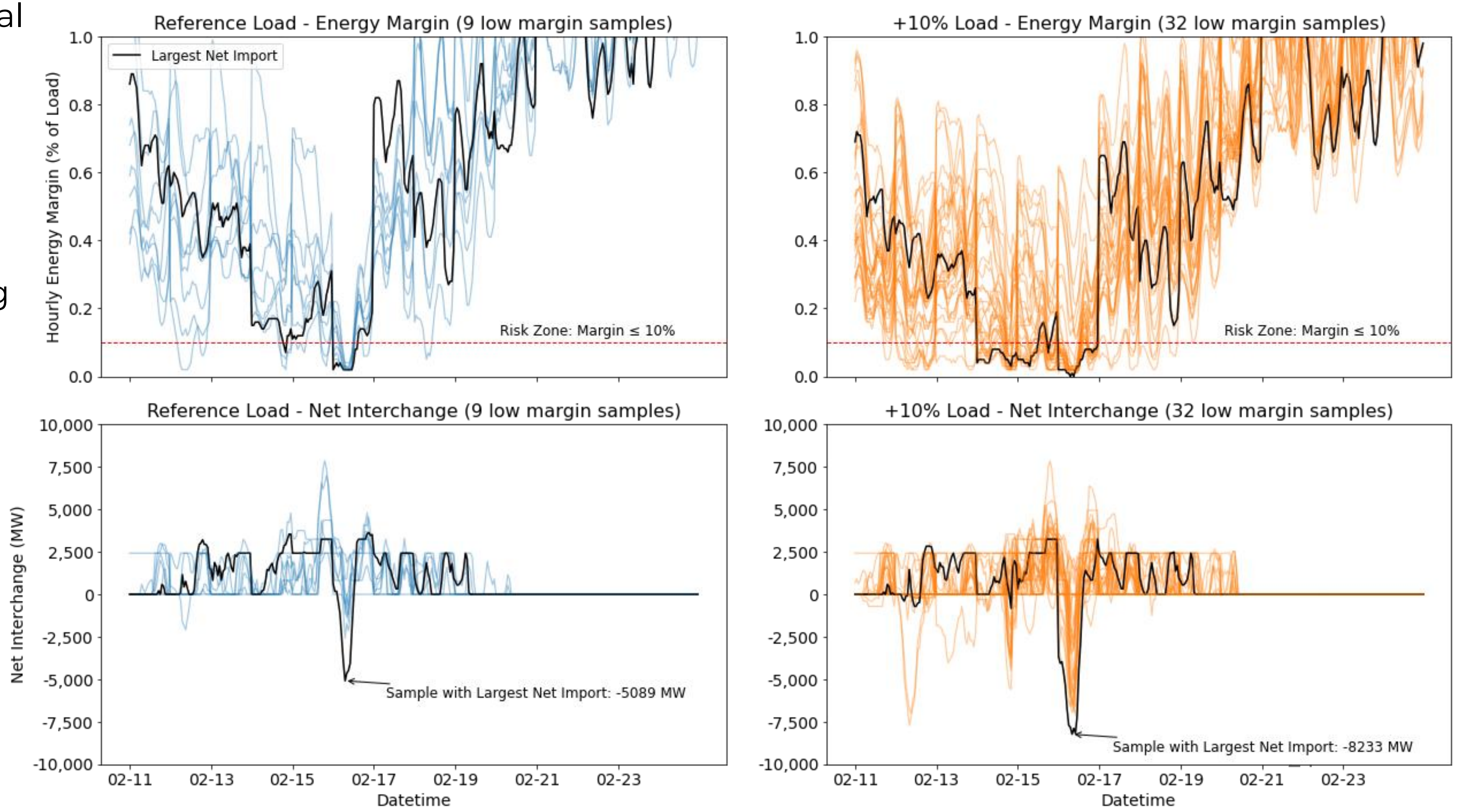
Across the 50 samples, several hours of net imports (negative values) exceed net firm import assumptions of ~2,200 MW.

Several samples have hours with very low margins hitting SPP operating reserve limits.

Result	Reference Load	+10% Load
Hours Margin <10%	419	1,458
Hours Margin <3%	66	322
Max Net Imports (MW)	5,089	8,233
Longest Duration Net Imports (hours)	10	24
Max Unserved Energy (MW)	0	1,315

Source: Energy Systems Integration Group

February 11 – February 24, 2021 Cold Event Samples with Hours <2% Energy Margin



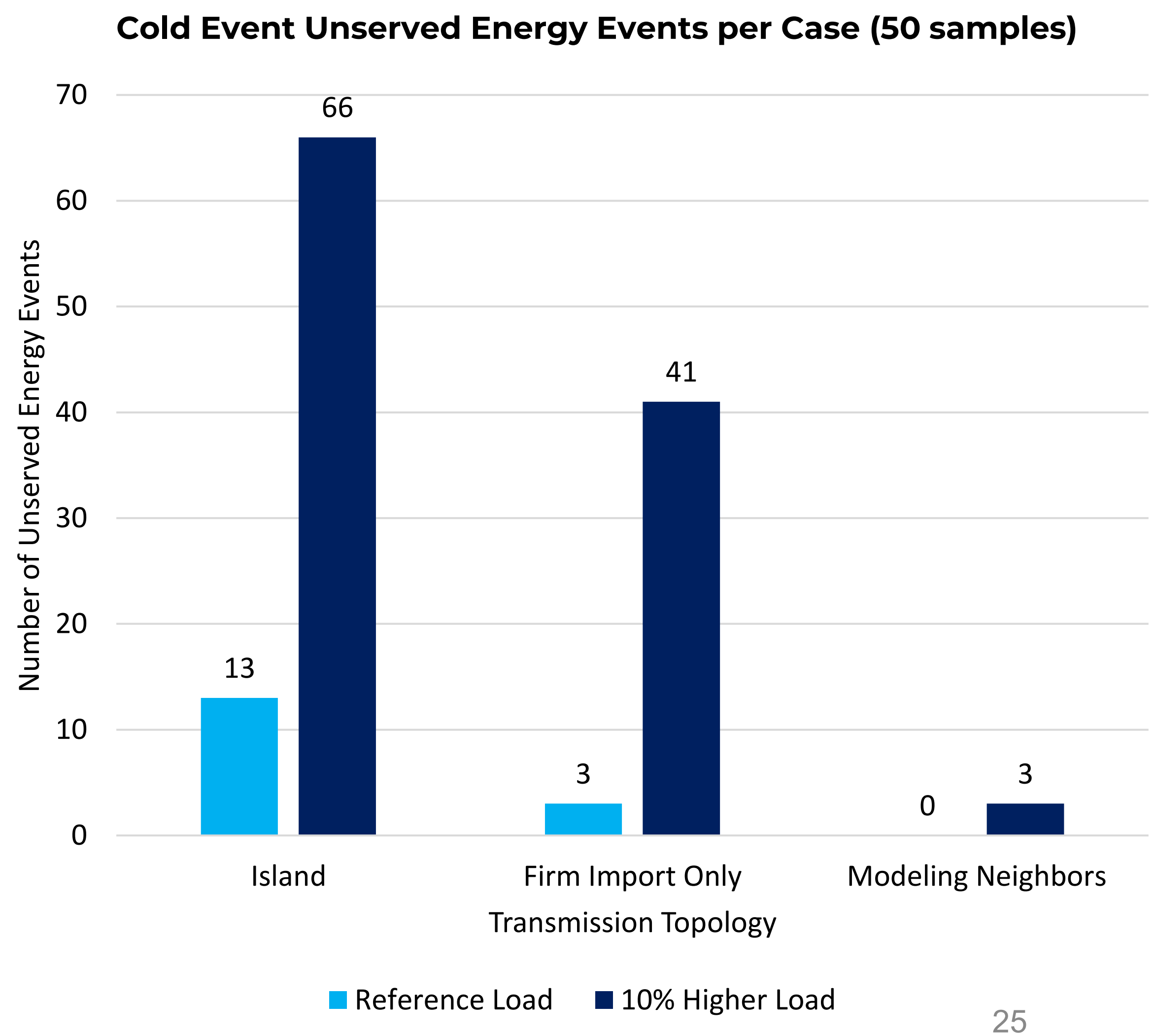
Cold event: Representing transfer limits reduces unserved energy magnitude and duration.

Comparing topologies shows reduced occurrence of shortfall events when the model represents interregional transfer capability.

Across the three system representations, modeling neighboring resource availability and existing transfer capability shows the system is resilient to the extreme cold event.

Pushing the system to high load levels for winter (59 GW) just begins to exceed interregional support.

Whether and how external assistance and interregional transmission is modeled has a large influence on determining how resilient a system is.



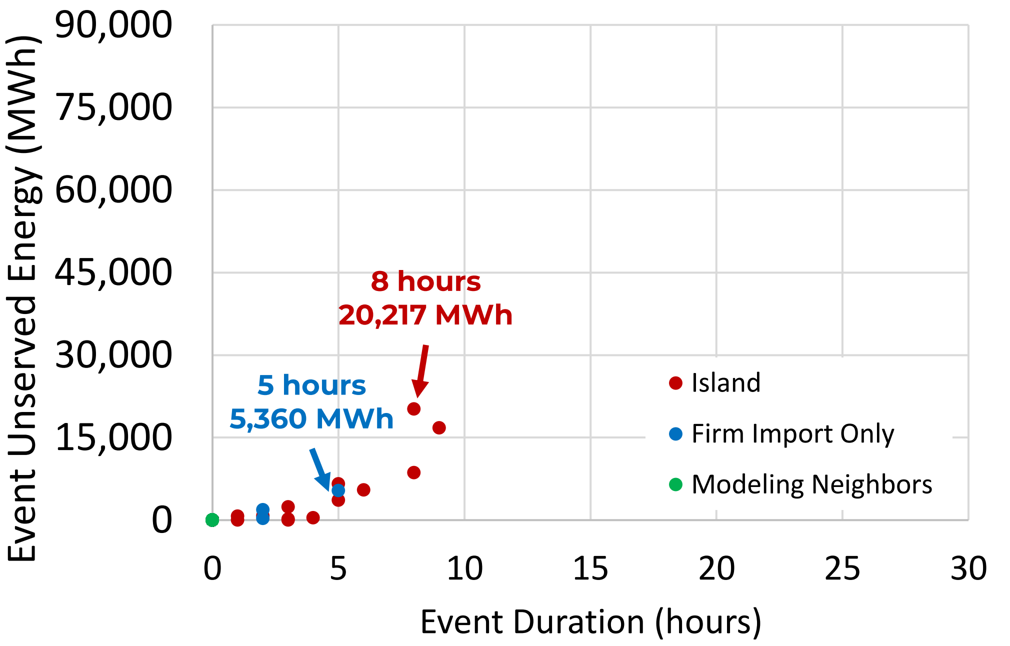
Source: Energy Systems Integration Group

Cold event: Interregional transfers limit unserved energy under high load and elevated outage risk.

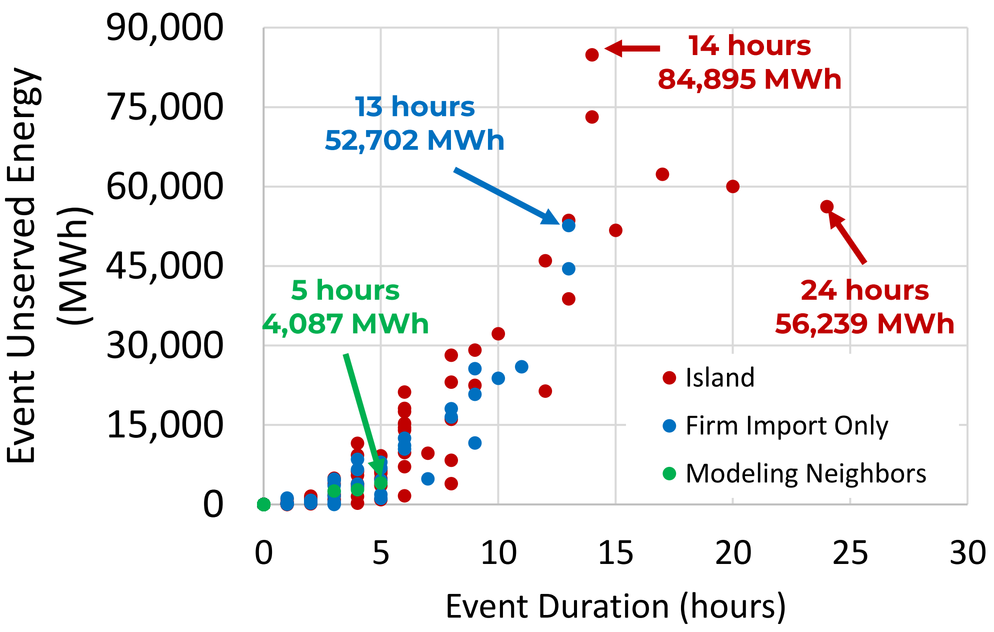
Tracking import availability using transfer capability and weather-correlated external resource availability ensures that imports reflect capabilities.

- High thermal outage risks and low renewable generation coupled with high load drive unserved energy risks across all three interregional transmission topologies.
- The SPP system is shown as much more resilient to unserved energy events when modeling full interregional transfer capabilities.

USE Magnitude and Duration – Reference Load



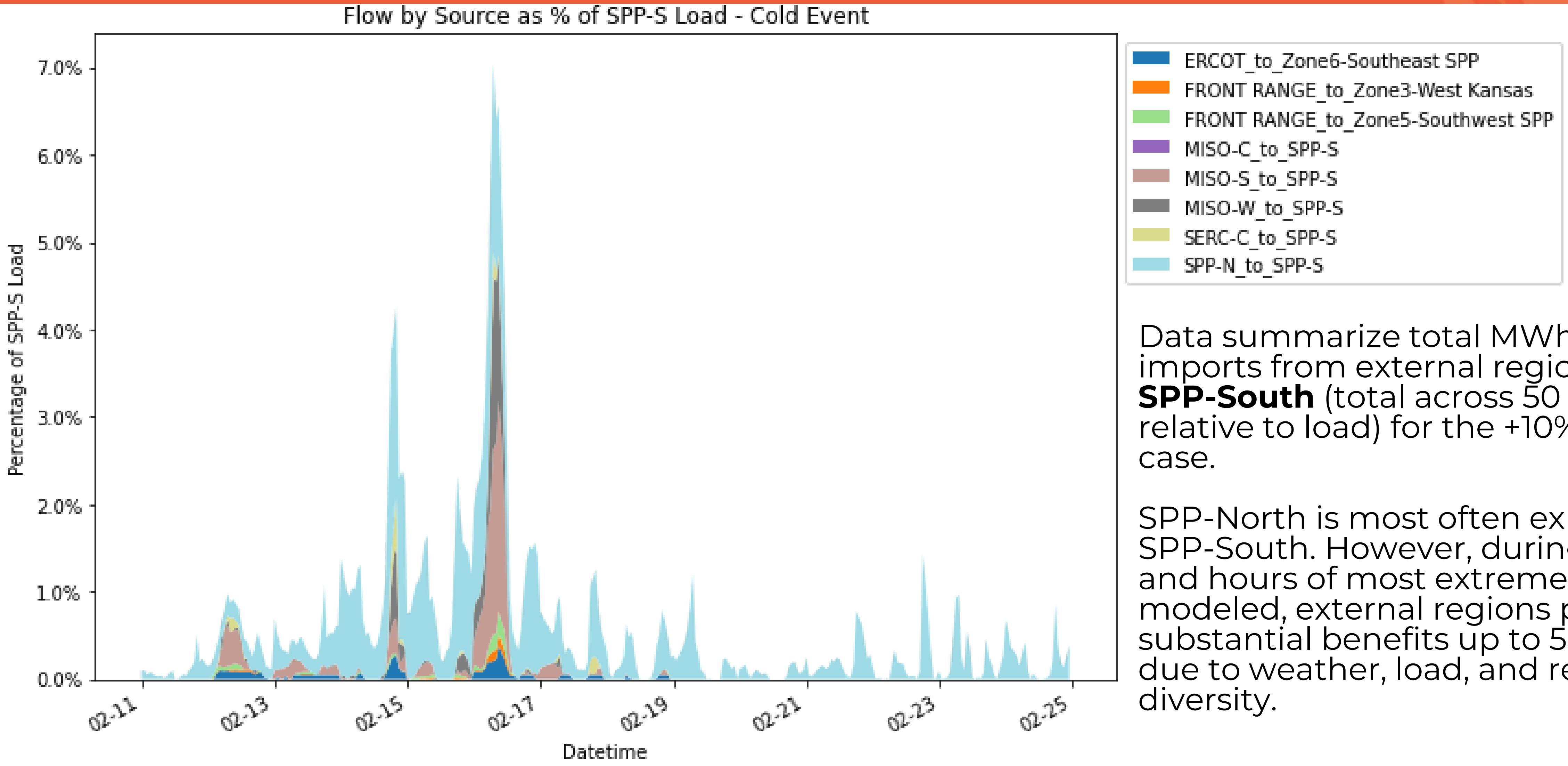
USE Magnitude and Duration - +10% Load



Source: Energy Systems Integration Group; data from SPP.

Cold event: External imports support SPP-South during the most critical hours up to ~5% of SPP-South's load.

Tracking the direction (sending) end of imports enables stress testing results to inform prioritization of which regions have potential surpluses.



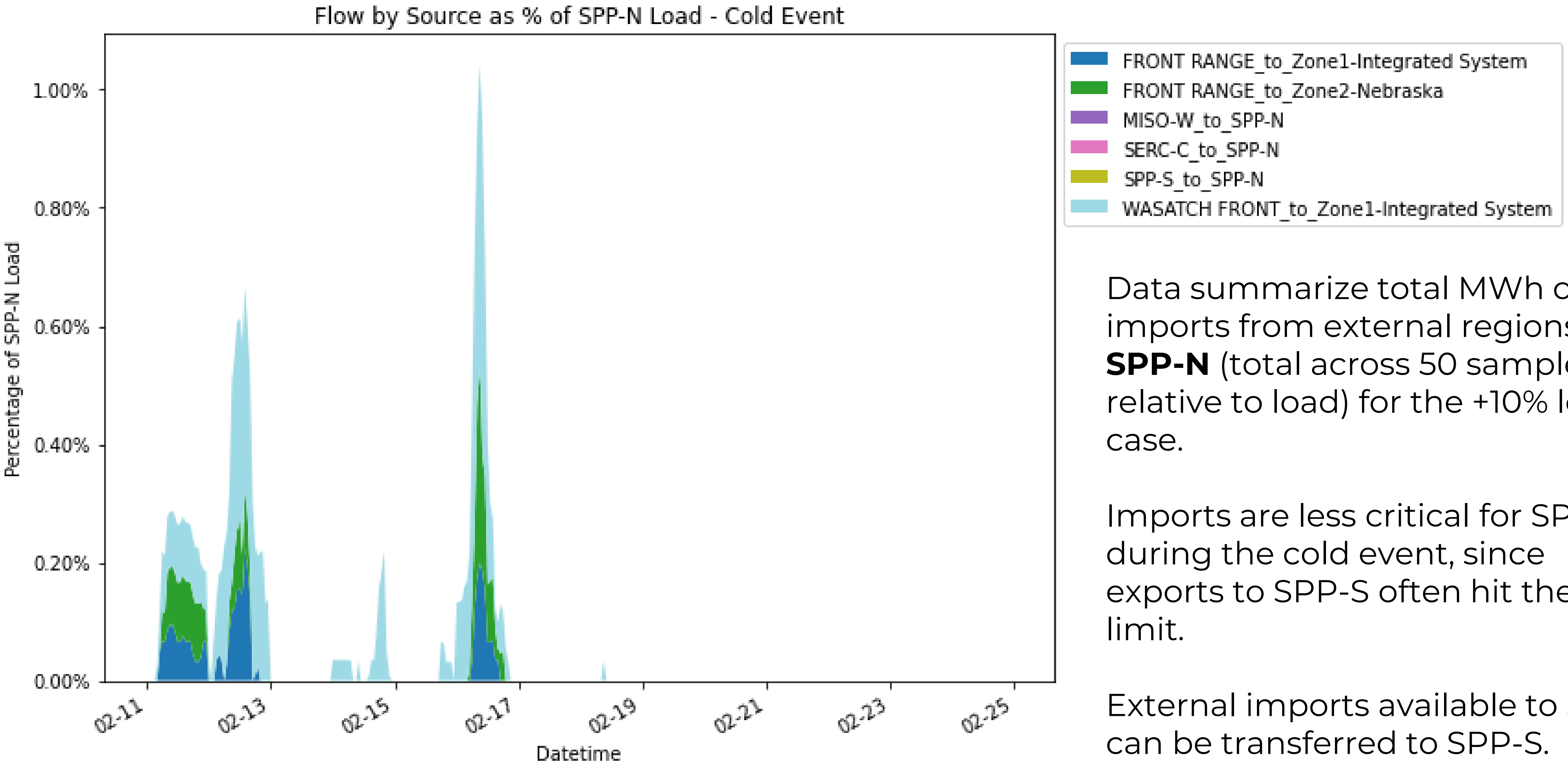
Data summarize total MWh of imports from external regions **into SPP-South** (total across 50 samples relative to load) for the +10% load case.

SPP-North is most often exporting to SPP-South. However, during days and hours of most extreme risk modeled, external regions provide substantial benefits up to 5% of load due to weather, load, and resource diversity.

Source: Energy Systems Integration Group; data from SPP

Cold event: External imports allow SPP-N to support SPP-S to a greater degree by increasing resource diversity

SPP-S faces the greatest stress during this event, even though SPP-N is also stressed, its import capability facilitates greater resilience in the system.



Data summarize total MWh of imports from external regions **into SPP-N** (total across 50 samples relative to load) for the +10% load case.

Imports are less critical for SPP-N during the cold event, since exports to SPP-S often hit the N-S limit.

External imports available to SPP-N can be transferred to SPP-S.

Source: Energy Systems Integration Group; data from SPP

Heat Event Summary

Based on Period from July 13 to August 10, 2011

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Heat event: Extreme temperatures drive sustained high net load and elevate loss-of-load risk.

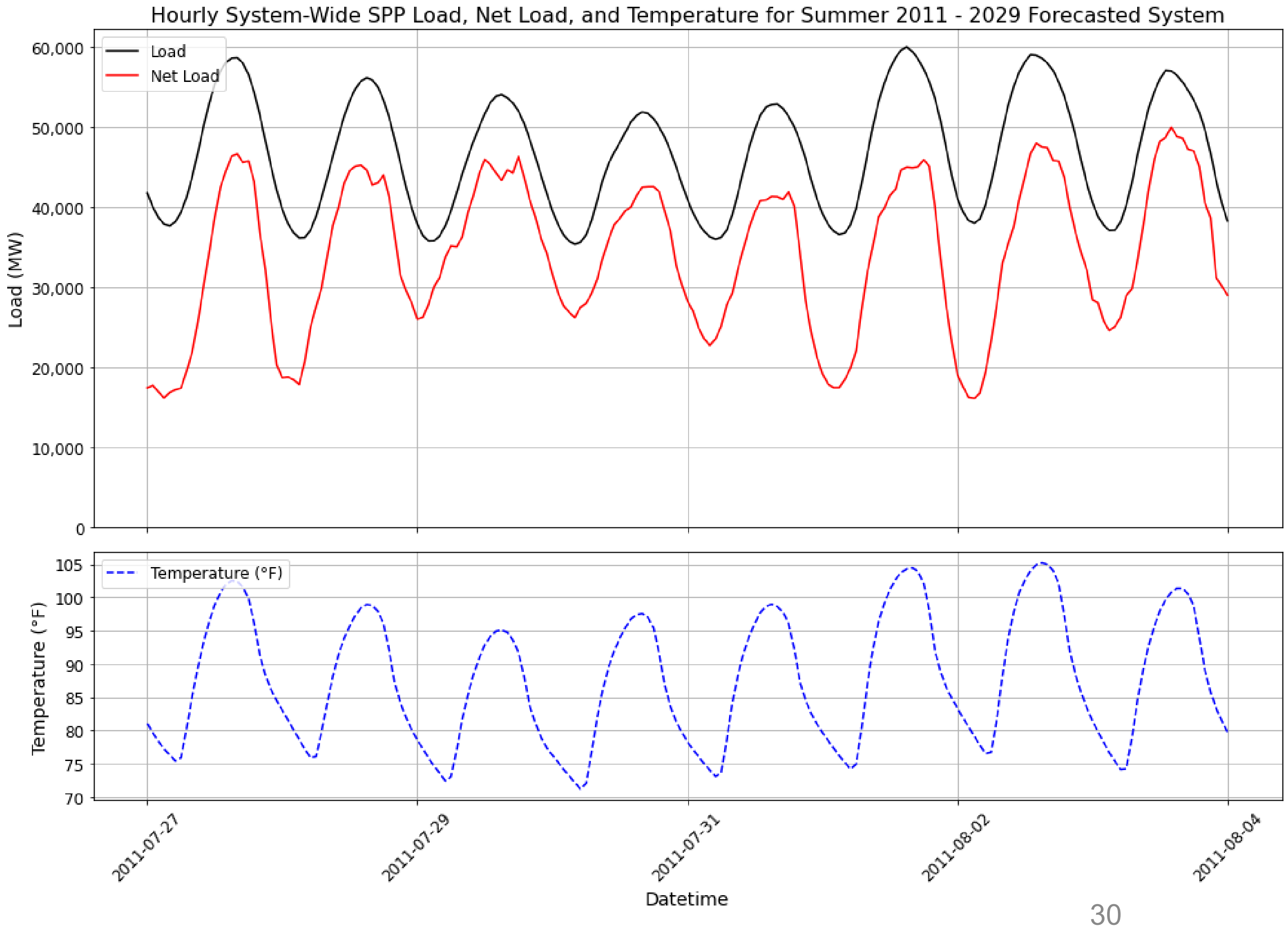
Low summer wind and uncertainty in thermal availability compound high-load conditions across multi-day heat periods.

Re-simulated summer 2011 heat events across SPP. July 27 – August 4 are shown, but multiple heat events occurred.

Several days where system-wide average temperature exceeded 100 degrees F.

High load conditions due to extreme heat, low summer wind generation, and uncertainty in thermal generation contribute to high loss-of-load risks during this period.

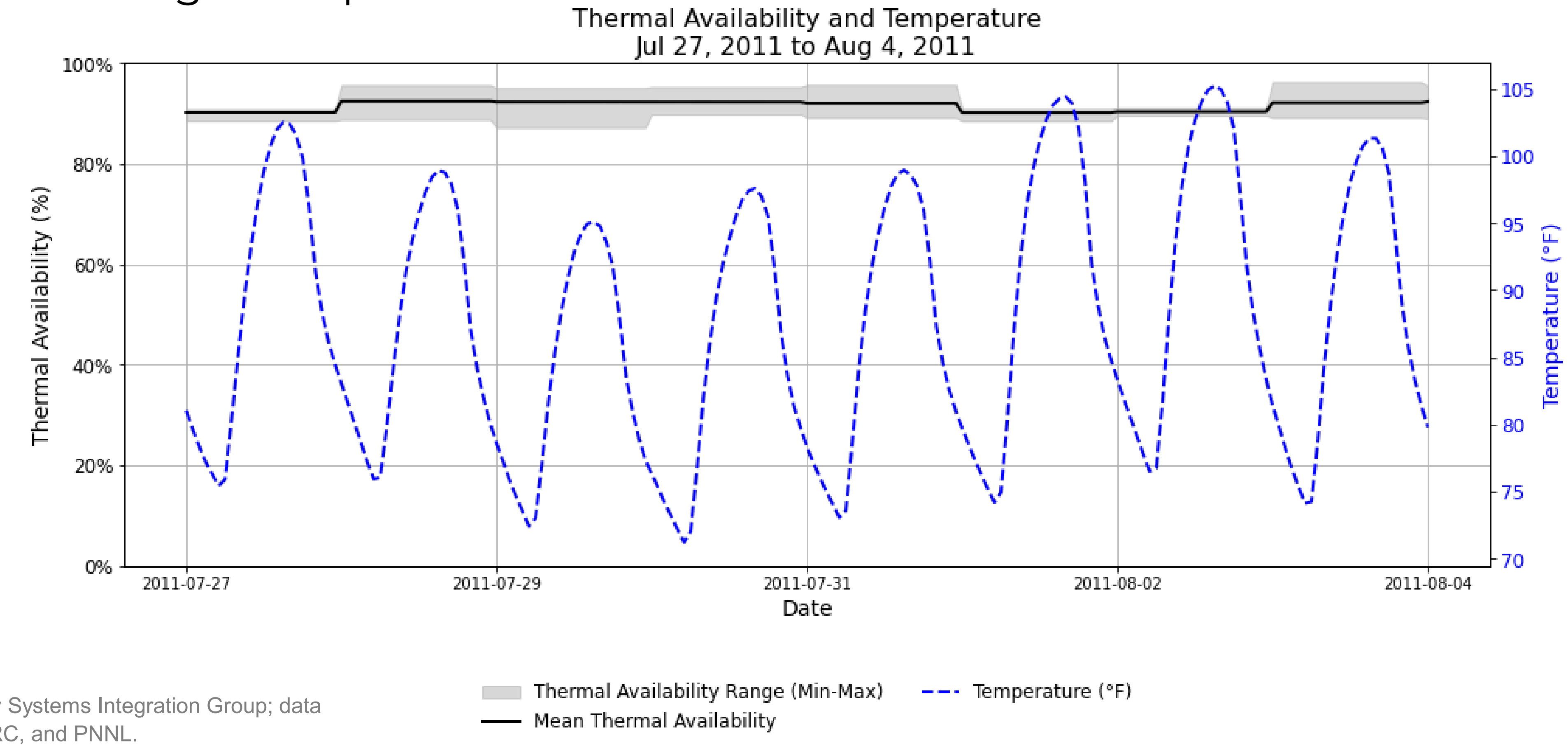
The 2023 SPP LOLE Study found 41% of summer LOLE risk in 2011.



Thermal availability is varied for each day based on temperature-outage relationships for summer.

Unlike winter, outage levels based on similar temperature days show less deviation in summer.

50 combinations of variations in temperature-correlated thermal availability for the summer event showed a tighter band of availability levels. This is due in part to the small sample size of high-temperature events.

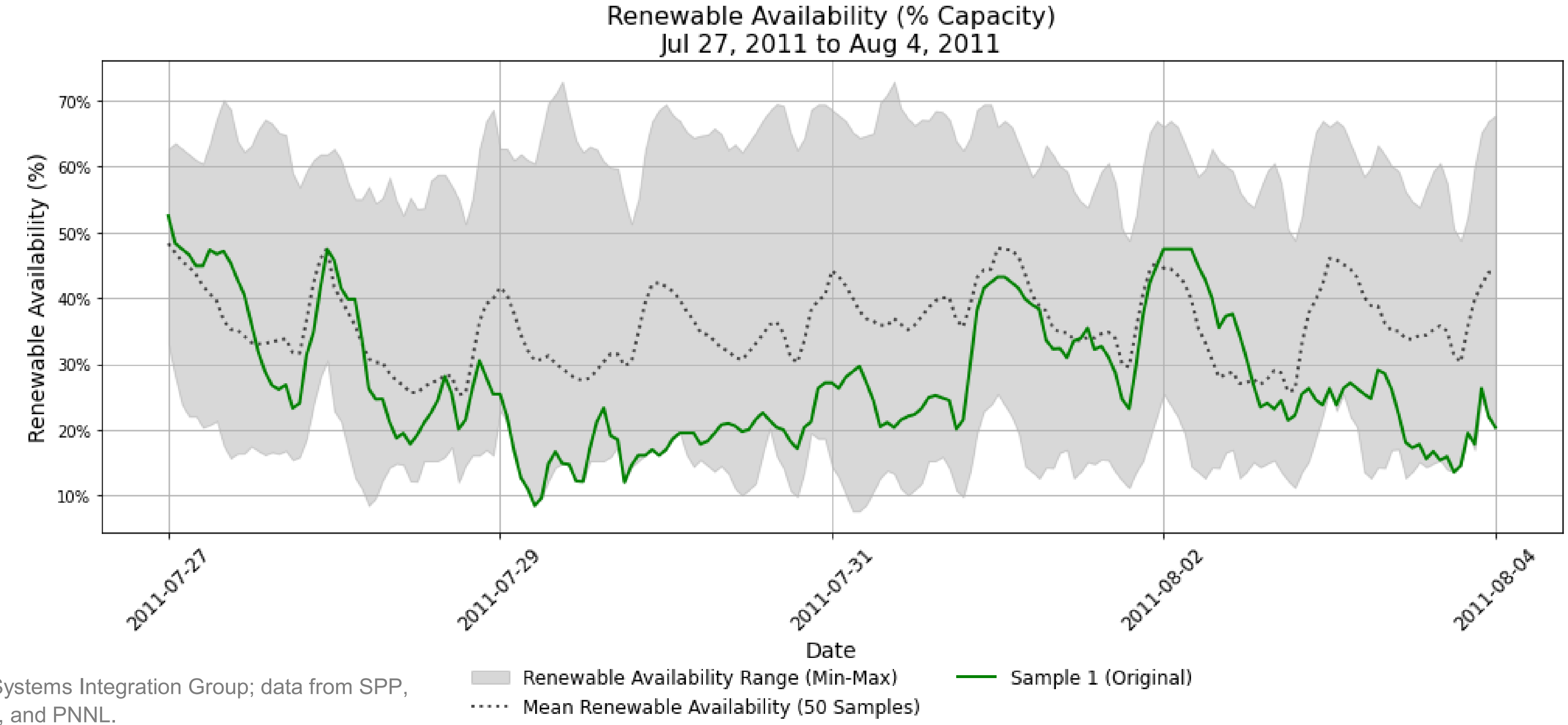


Source: Energy Systems Integration Group; data from SPP, NERC, and PNNL.

Unique renewable profiles were created to stress the event if different plausible renewable conditions occurred.

Variability in renewable generation is high, even when days with similar load levels are re-sampled.

50 combinations of variations hourly profiles were generated based on days where load levels were similar in July and August. Compared to the original profile, some periods with extremely high temperatures on August 1 and 2 have chances for lower renewable generation, increasing risks.



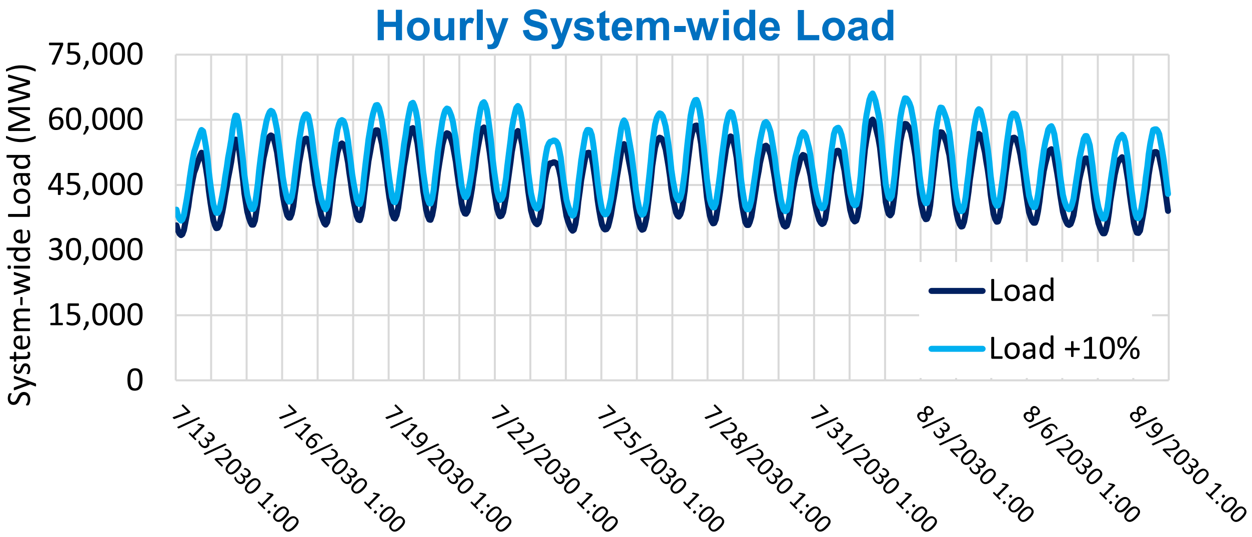
Source: Energy Systems Integration Group; data from SPP, NERC, NLR, EIA, and PNNL.

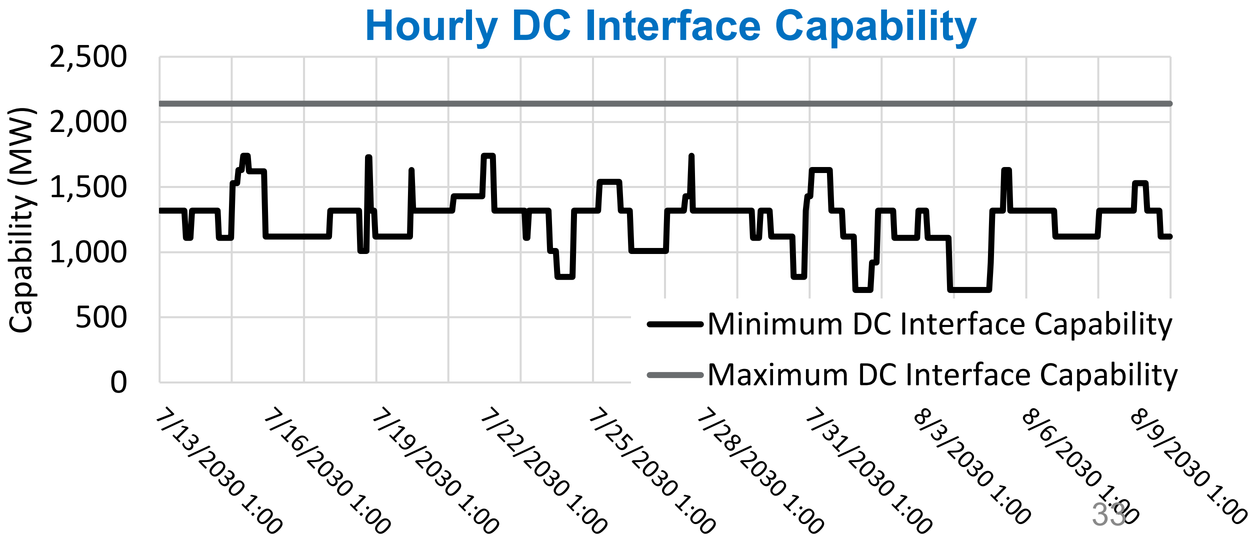
Load, generator maintenance, and DC interface capability for SPP were also stressed to increase risks and evaluate resilience.

Summer 2011 loads are extremely high compared to the set of weather years available.

Increasing load by 10% brought the system to a 66 GW peak load.

Randomized forced and maintenance outages were modeled on SPP DC interfaces with capabilities ranging from 100% available to <50%.





Source: Energy Systems Integration Group; data from SPP

During the heat event, high temperatures drive high load and margins are tight.

When load is increased in the +10% scenario, SPP requires imports above net firm import levels and avoids load shedding.

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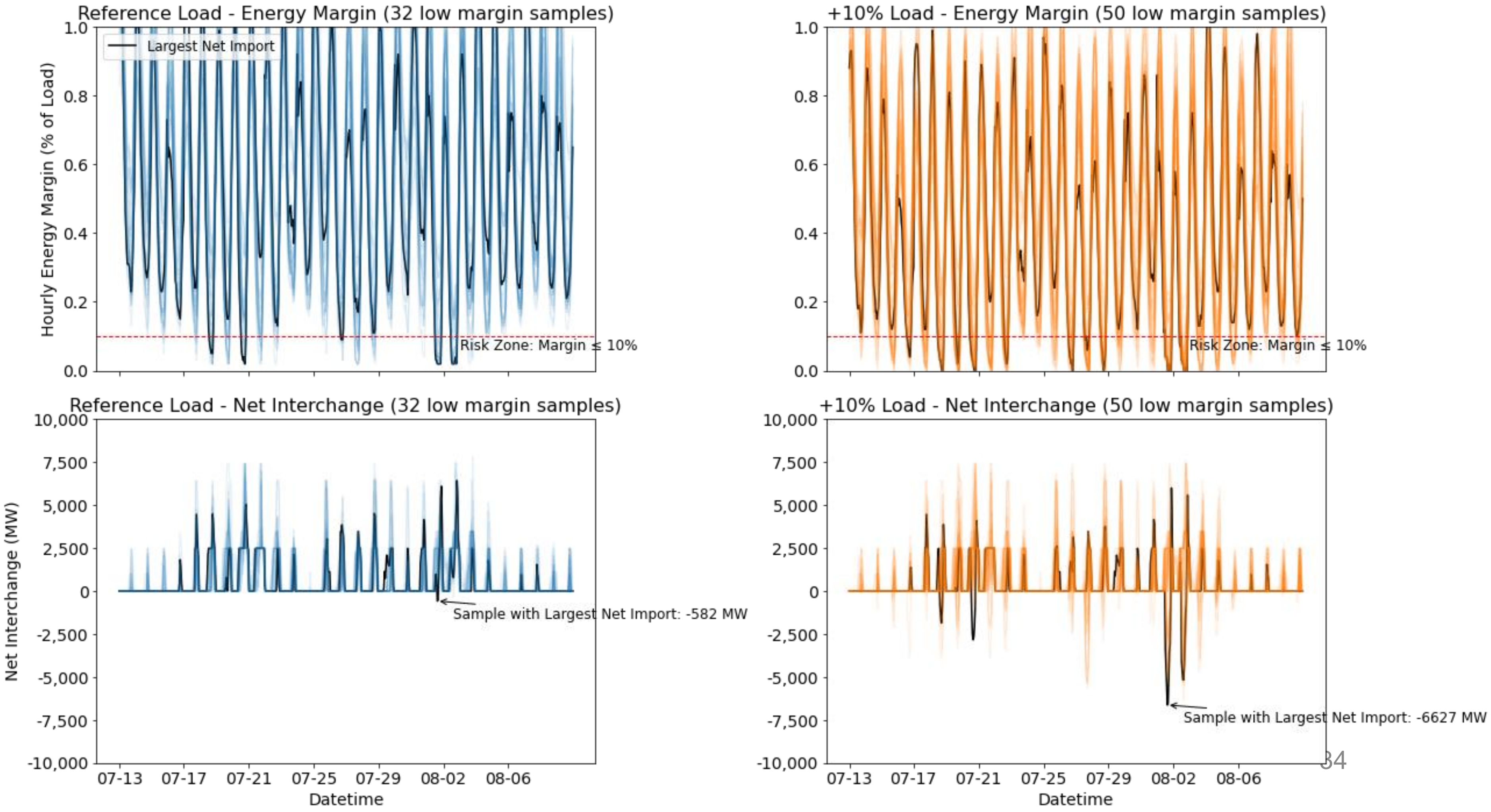
Across the 50 samples, for both cases, the future SPP system is often exporting to neighbors, reducing margins to the minimum allowed.

In the higher load scenario, several periods have net imports >2,200 MW.

Result	Reference Load	+10% Load
Hours Margin <10%	991 (3%)	4236 (13%)
Hours Margin <3%	233 (0.7%)	1355 (4%)
Max Net Imports (MW)	582 MW	6,627
Longest Duration Net Imports (hours)	2	10
Max Unserved Energy (MW)	0	0

Source: Energy Systems Integration Group

July 13th – August 10th, 2011, Heat Event Samples with Hours <2% Energy Margin



Heat event: Modeling neighbors reduces shortfalls identified under simplified imports.

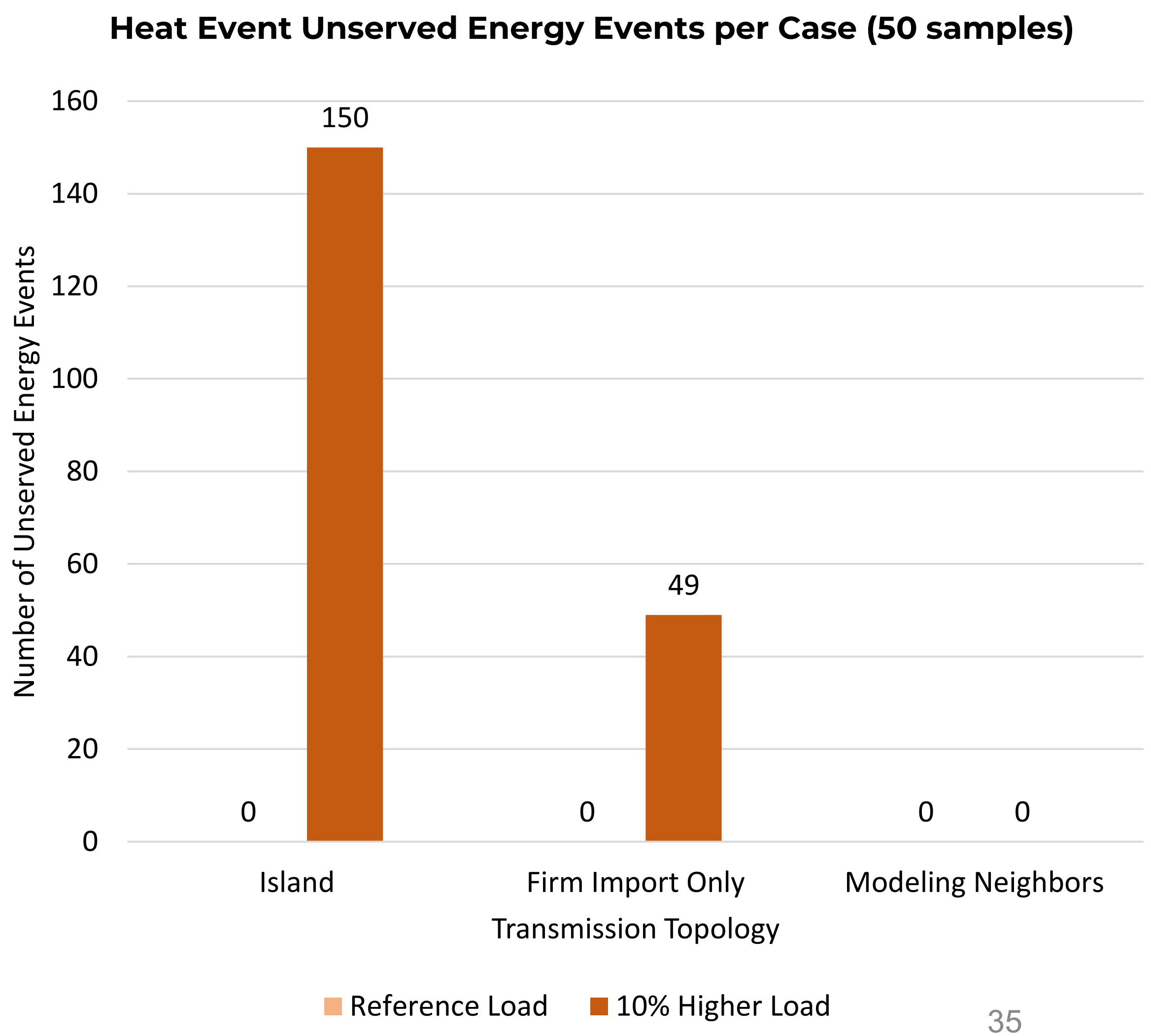
Comparing topologies shows reduced occurrence of shortfall events when the model represents interregional transfer capability.

Across the three system representations, modeling neighboring resource availability and existing transfer capability shows the system is resilient to the extreme heat event modeled.

Pushing the system to high load levels was required to see unserved energy in the limited transmission cases.

However, even summer peak loads of 66 GW do not result in unserved energy when modeling neighbors.

The extreme heat event modeled in summer does not have as extreme of outages relative to extreme cold (minimum modeled 80% availability).



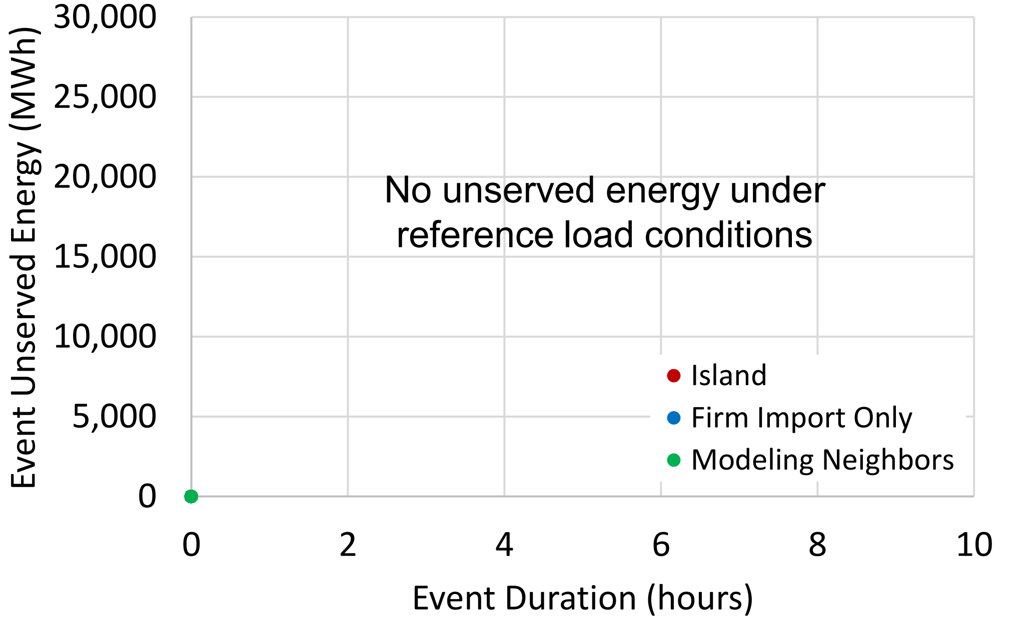
Source: Energy Systems Integration Group

Heat event: Higher load exposes how interregional transfers support reliability.

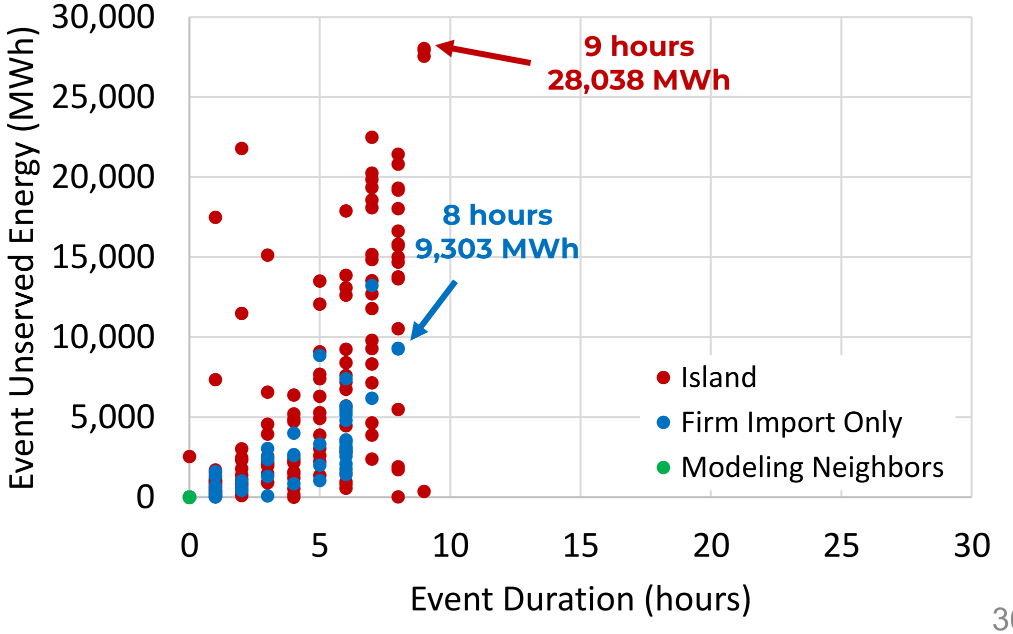
Interregional transfer capability and external resource availability can support SPP even during the most extreme +10% load case.

- Extreme heat under reference load conditions is manageable for the conditions modeled. This is driven in part by +6 GW of solar in the 2029 system relative to the 2025 system.
- Modeling higher load reveals that interregional transmission provides a critical buffer to higher load conditions. The reference system shows now risk in these results but substantial risk when load is raised and interregional transmission is not accounted for.

USE Magnitude and Duration – Reference Load



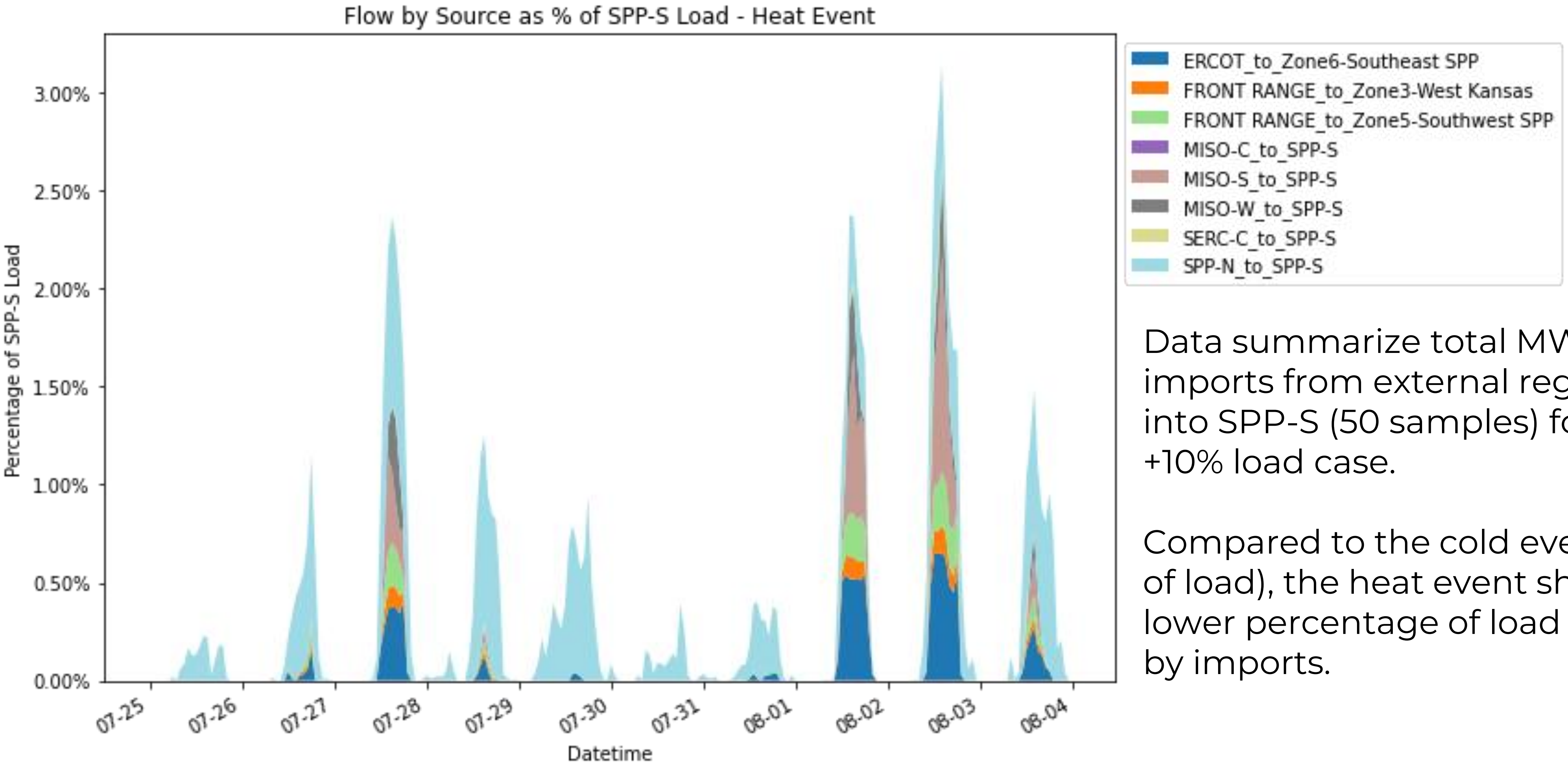
USE Magnitude and Duration – +10% Load



Source: Energy Systems Integration Group; data from SPP.

Heat event: External imports support SPP-S when load is higher than projected in the +10% load case.

Tracking the direction (sending) end of imports enables stress testing results to inform prioritization of which regions have potential surpluses.



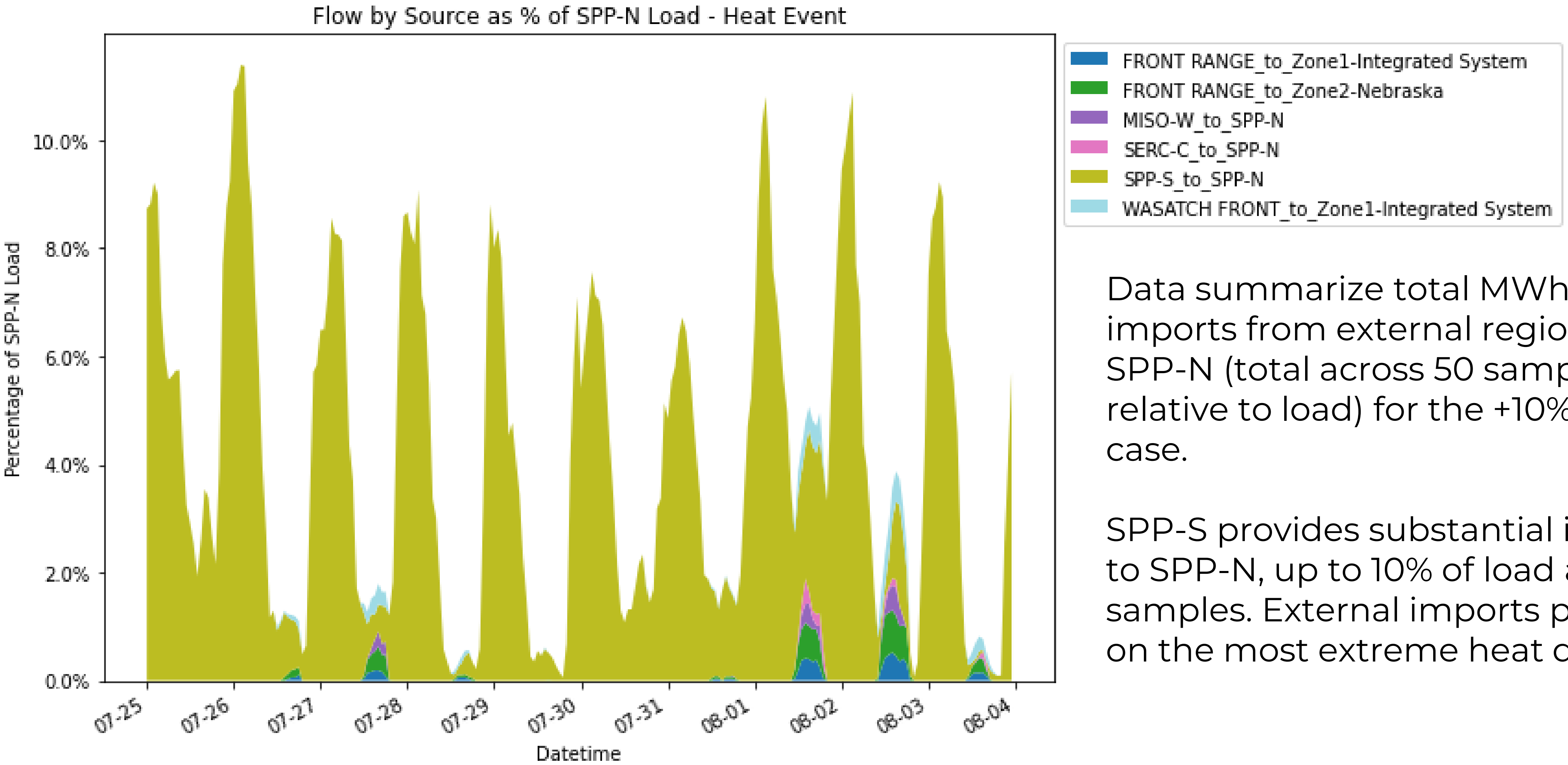
Data summarize total MWh of imports from external regions into SPP-S (50 samples) for the +10% load case.

Compared to the cold event (~7% of load), the heat event shows a lower percentage of load served by imports.

Source: Energy Systems Integration Group; data from SPP

Heat event: SPP-S supports SPP-N through a combination of exporting solar generation and passing through imports.

High summer load risk is offset in SPP-N overwhelming via benefits from transfer capability between SPP-N and SPP-S.



Data summarize total MWh of imports from external regions into SPP-N (total across 50 samples relative to load) for the +10% load case.

SPP-S provides substantial imports to SPP-N, up to 10% of load across the samples. External imports play a role on the most extreme heat days.

Source: Energy Systems Integration Group; data from SPP

Wind Drought Event Summary

Based on Period from August 29 to September 18, 2011

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Wind drought event: Prolonged low wind increases net-load stress, especially under higher load conditions.

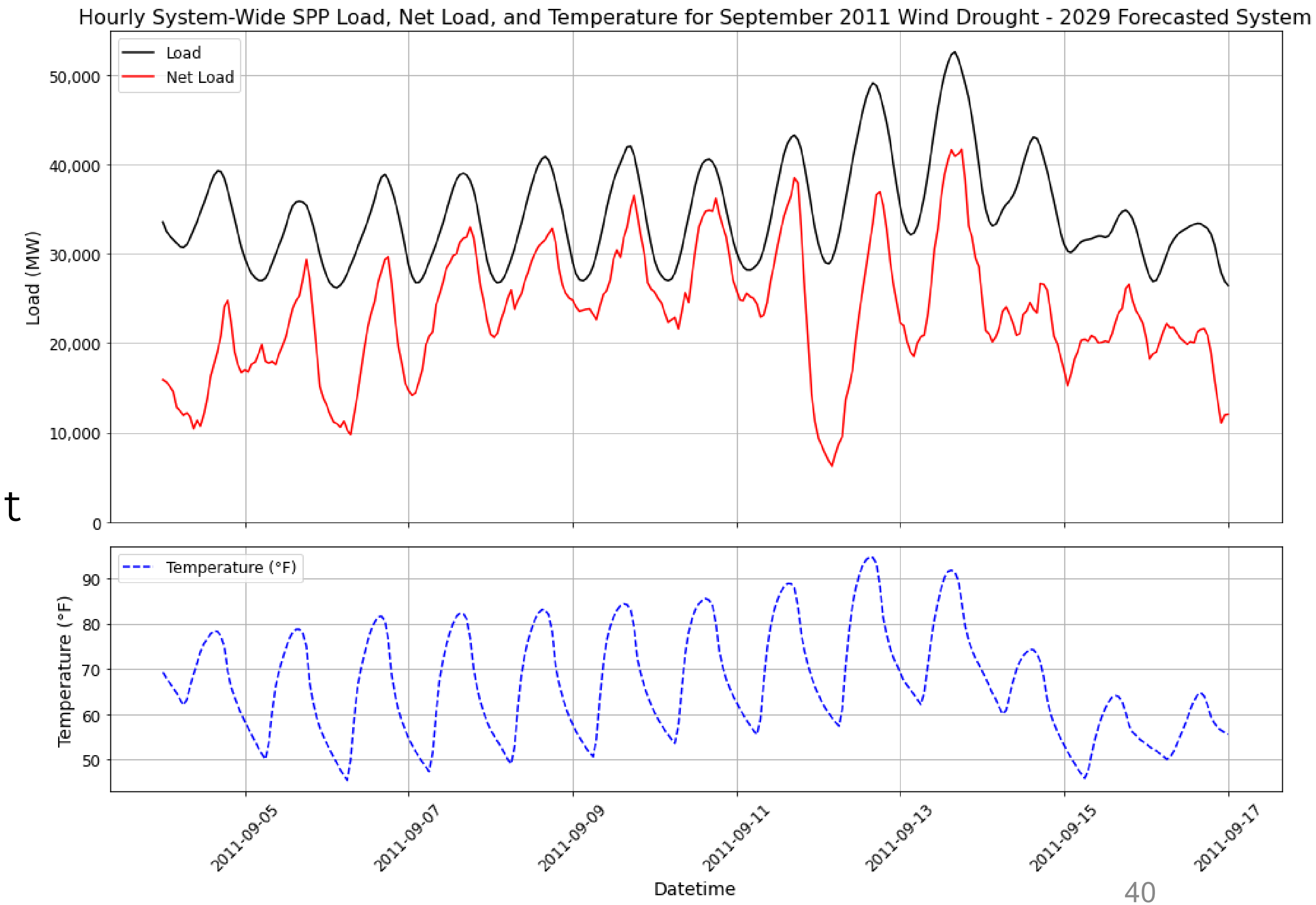
Extended low-wind availability becomes consequential when higher demand and other stressors coincide.

Re-simulated a five-day wind drought period across SPP. Only September 4 – 17 are shown here.

Temperatures are milder in September, but low wind conditions generate periods of higher net-load risk.

Risks from lower renewable generation or higher outages could make this event stressful.

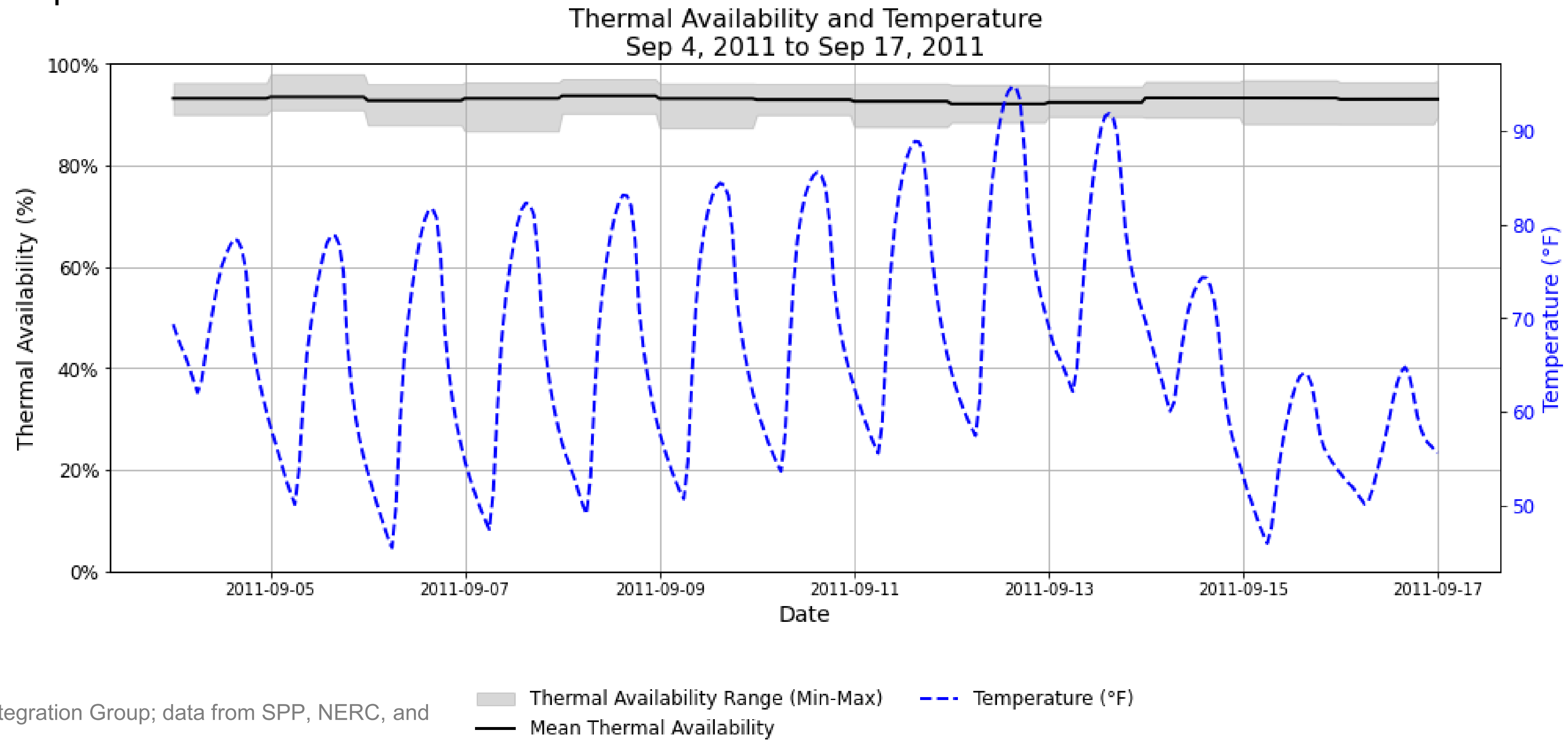
Multi-day wind droughts may be a source of increased SPP risk in a higher-renewables system.



Thermal availability is varied for each day based on temperature-outage relationships for fall.

Similar to summer, the range in availability levels is more consistent in fall, although more variation is seen due to more moderate temperature ranges.

Like the summer event, the wind drought shows a tighter band of thermal availability with lower range values of 85%. Samples with lower availability plus lower renewable generation pose risk of load shed in the stress test.

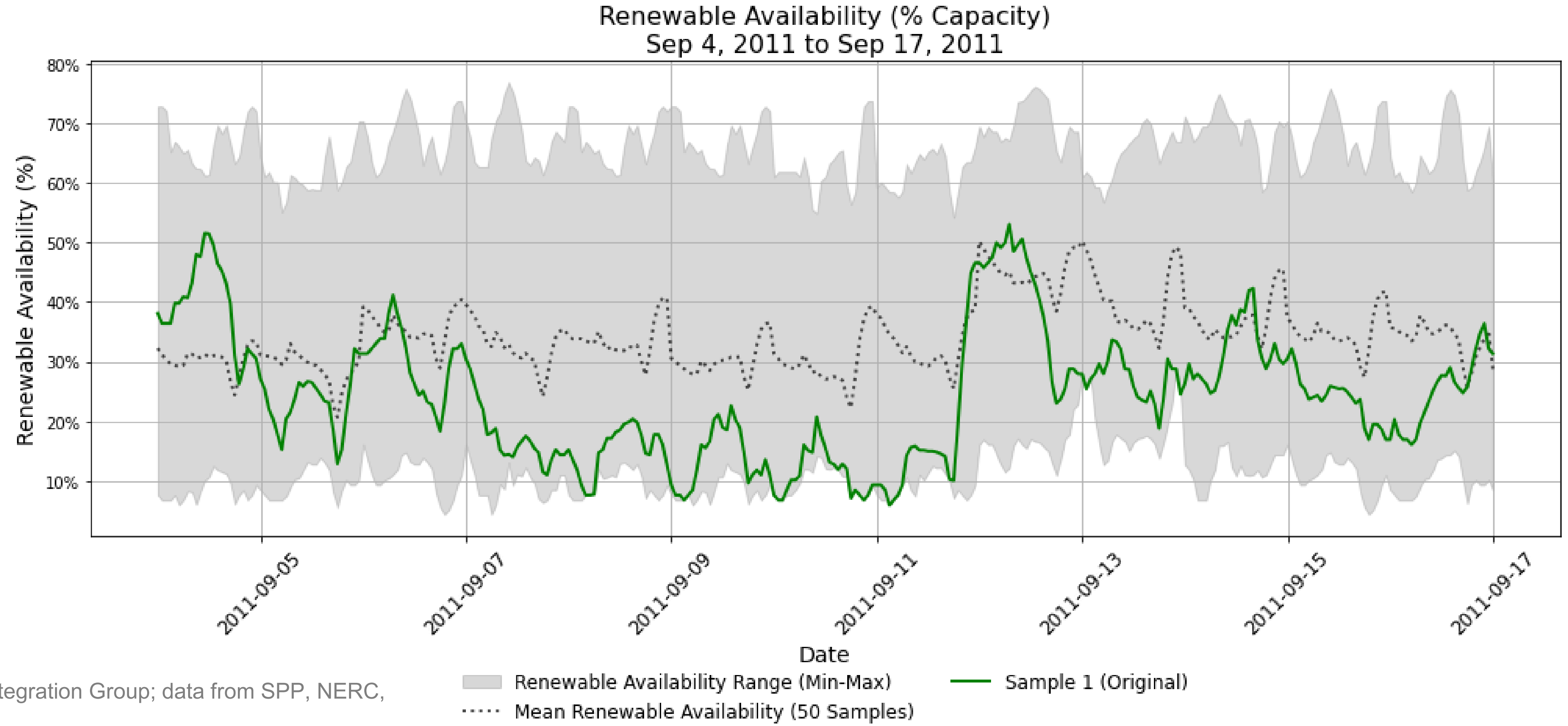


Source: Energy Systems Integration Group; data from SPP, NERC, and PNNL.

Unique renewable profiles were created to stress the event if different plausible renewable conditions occurred.

Variability in renewable generation is high, even when days with similar load levels are re-sampled.

50 combinations of variations hourly profiles were generated based on days where load levels were similar in August and September. The original data show the five-day wind drought. Variations in wind availability surrounding this type of event drive additional risk.



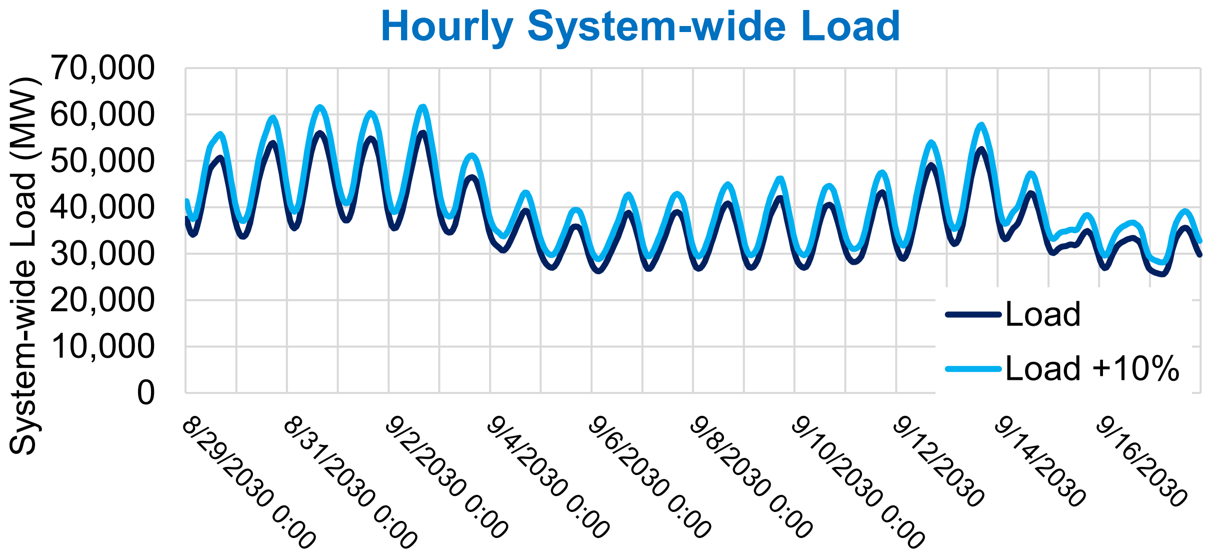
Source: Energy Systems Integration Group; data from SPP, NERC, NREL, EIA, and PNNL.

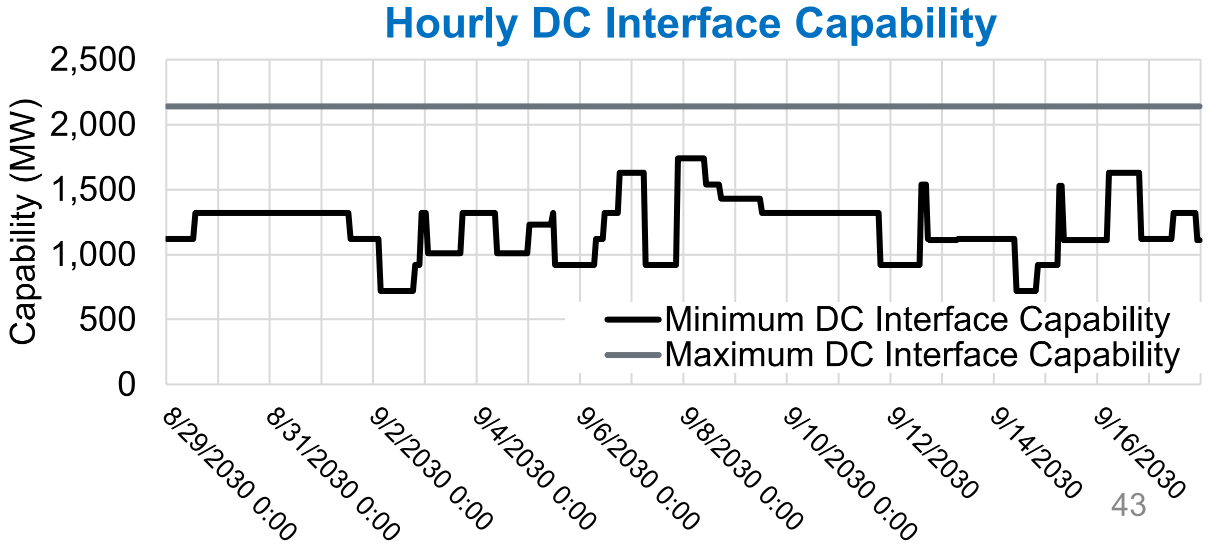
Load, generator maintenance, and DC interface capability for SPP were also stressed to increase risks and evaluate resilience.

Early in the modeled period loads reach 60 GW in the +10% case. Prior to the wind drought higher temperatures drive this risk.

Randomized forced and maintenance outages were modeled on SPP DC interfaces with capabilities ranging from 100% available to <50%.

Combinations of higher load, variations in renewable profiles, and thermal availability at 85% drive risk in this event.





Source: Energy Systems Integration Group; data from SPP.

During the wind drought event, a period of high demand requires imports when stressed.

When load is increased in the +10% scenario, SPP requires imports above net firm import levels and avoids load shedding.

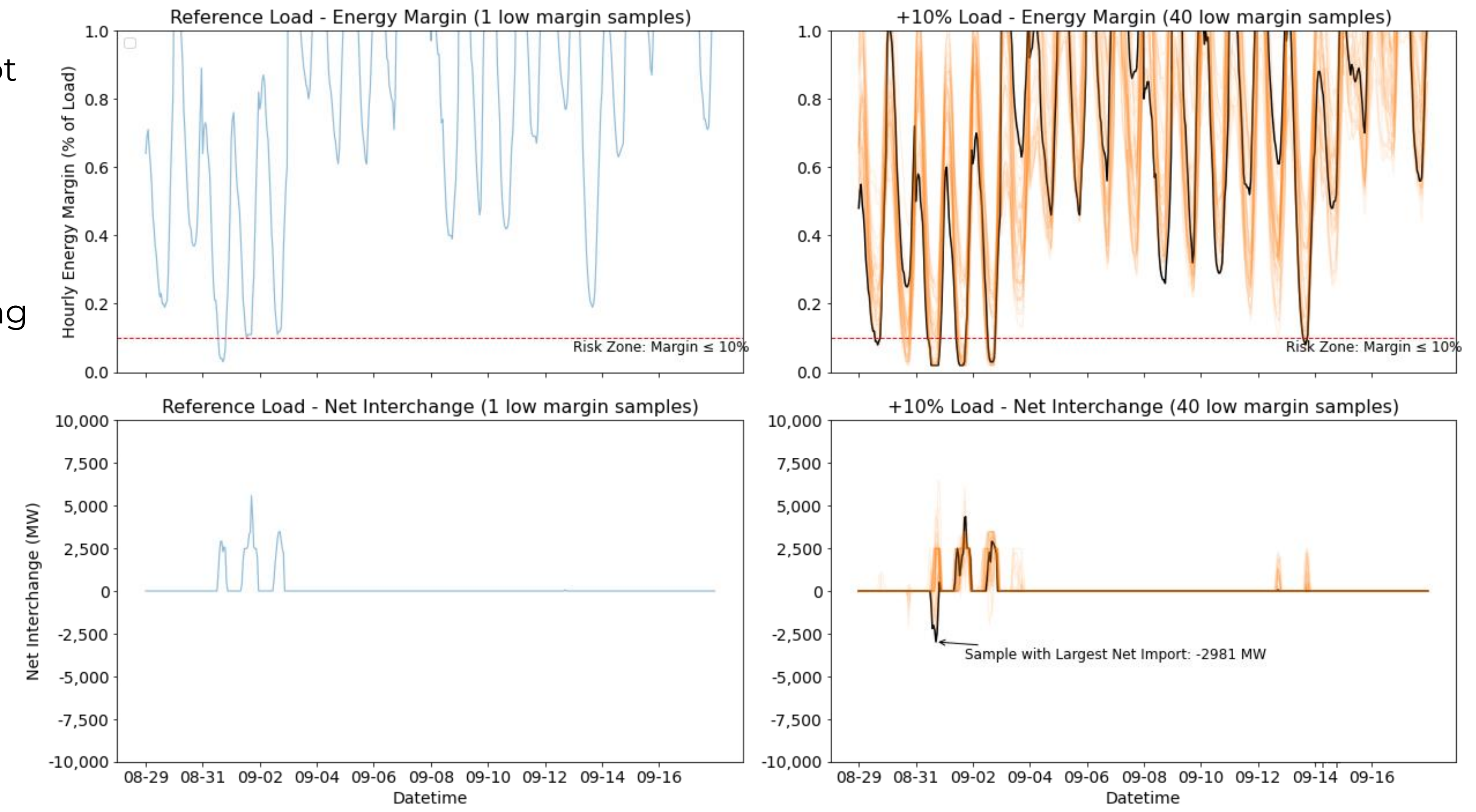
Reference load conditions for the wind drought given the 2029 SPP resource mix do not show significant stress.

In the higher load scenario, imports do exceed net firm levels during a high-temperature period preceding low wind conditions.

Result	Reference Load	+10% Load
Hours Margin <10%	114	1,458
Hours Margin <3%	1	322
Max Net Imports (MW)	118	2,981
Longest Duration Net Imports (hours)	1	7
Max Unserved Energy (MW)	0	0

Source: Energy Systems Integration Group

August 29th – September 18th, 2011, Wind Drought Samples with Hours <3% Energy Margin



Wind drought event: Capping imports amplifies the shortfall risk under higher load conditions.

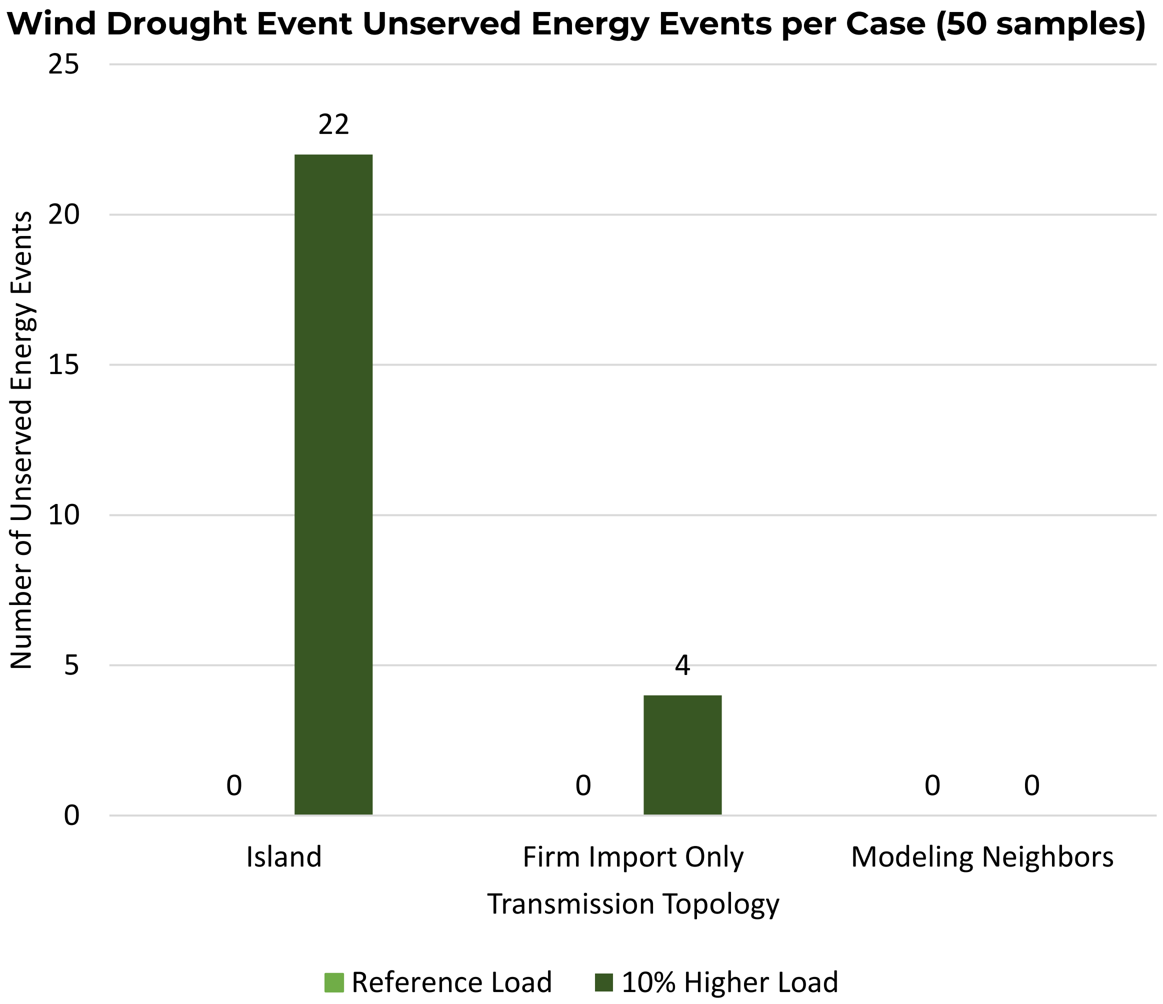
Comparing topologies shows reduced occurrence of shortfall events when the model represents interregional transfer capability.

Across the three system representations, modeling neighboring resource availability and existing transfer capability shows the system is resilient to risk.

Pushing the system to high load levels was required to see unserved energy.

The availability of thermal resources and interregional transmission offsets the periods of high temperature and low wind production

Constraining import capabilities shows increased risk under high load scenarios.

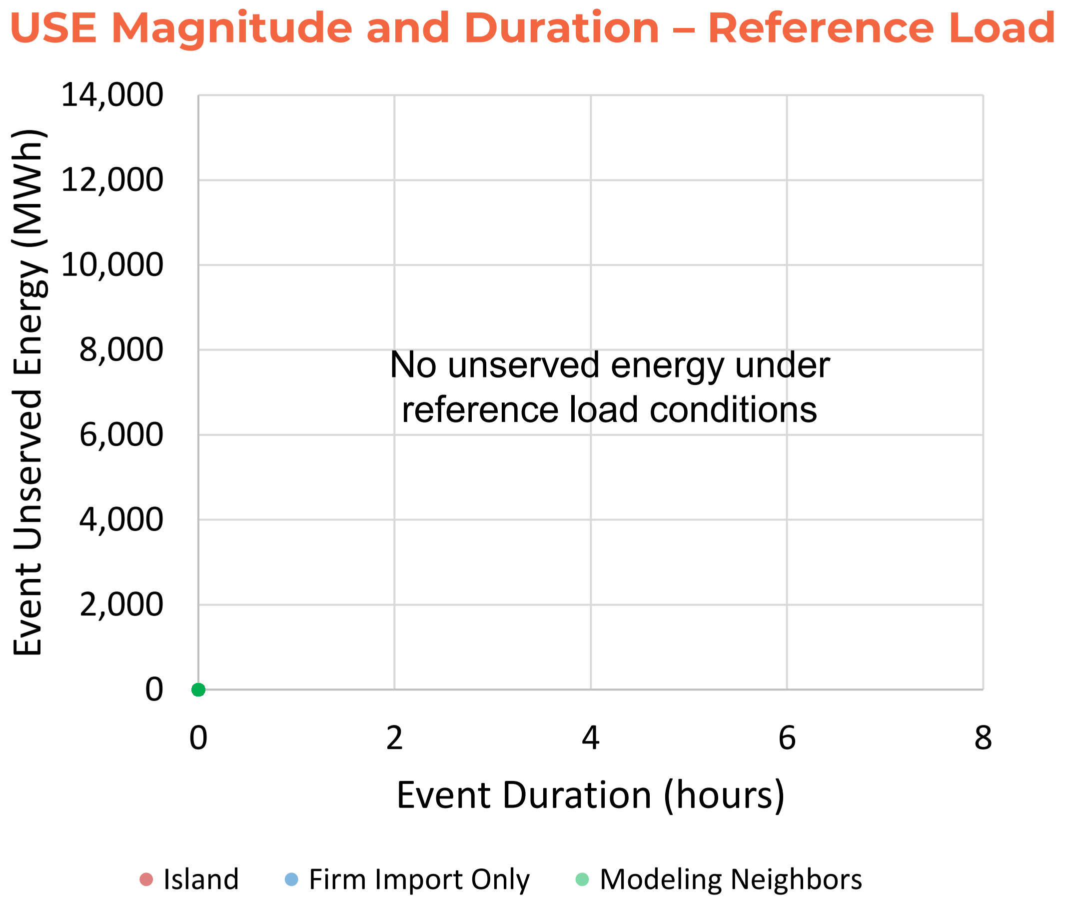


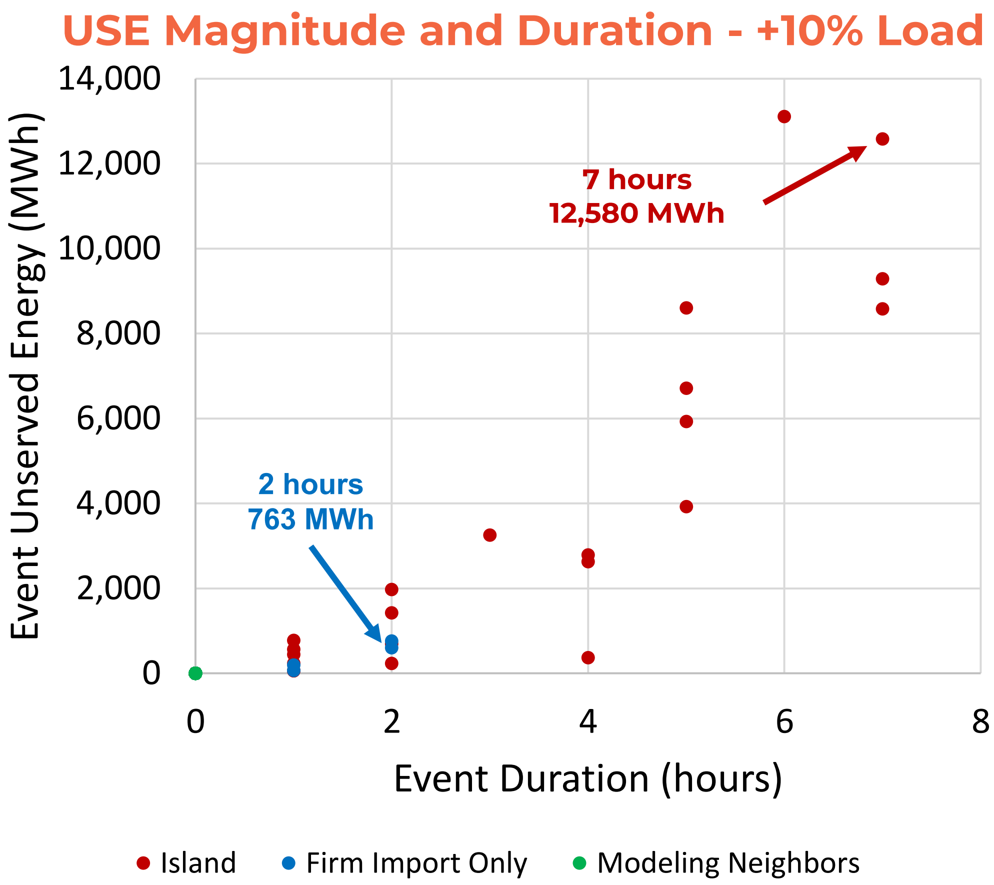
Source: Energy Systems Integration Group

Wind drought event: Reference load conditions show no unserved energy; higher load produces modest shortfalls.

Unserved energy results are sensitive both to load levels and whether or not interregional transmission is represented in the model.

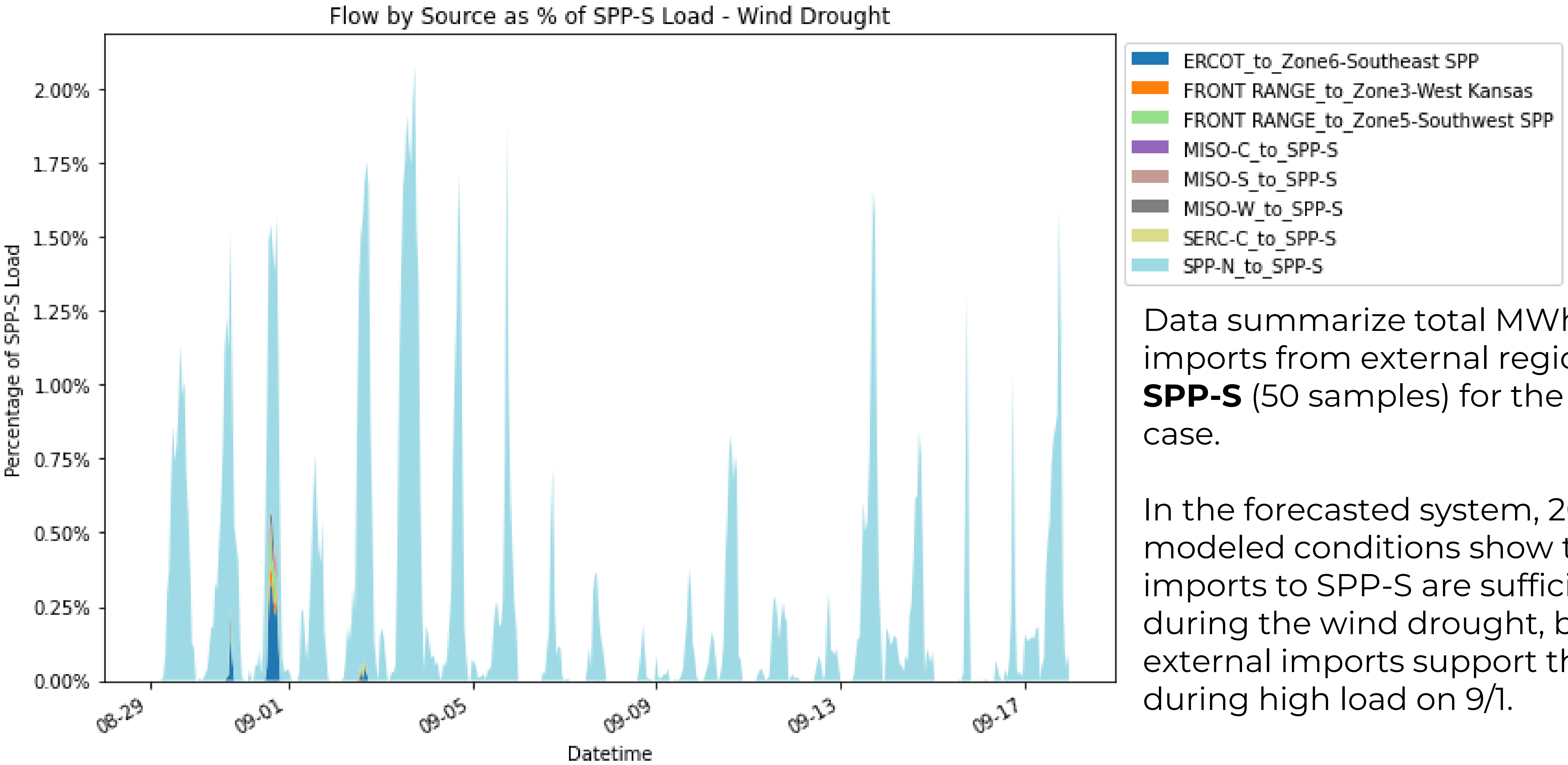
Under the reference load case, there are no unserved energy events occurring. Substantially increasing load levels results in small unmitigated unserved energy unless modeling neighbors.





Source: Energy Systems Integration Group; data from SPP.

Wind drought: External imports are needed only on the hottest day during the low wind period; otherwise, SPP-N provides enough support for SPP-S.

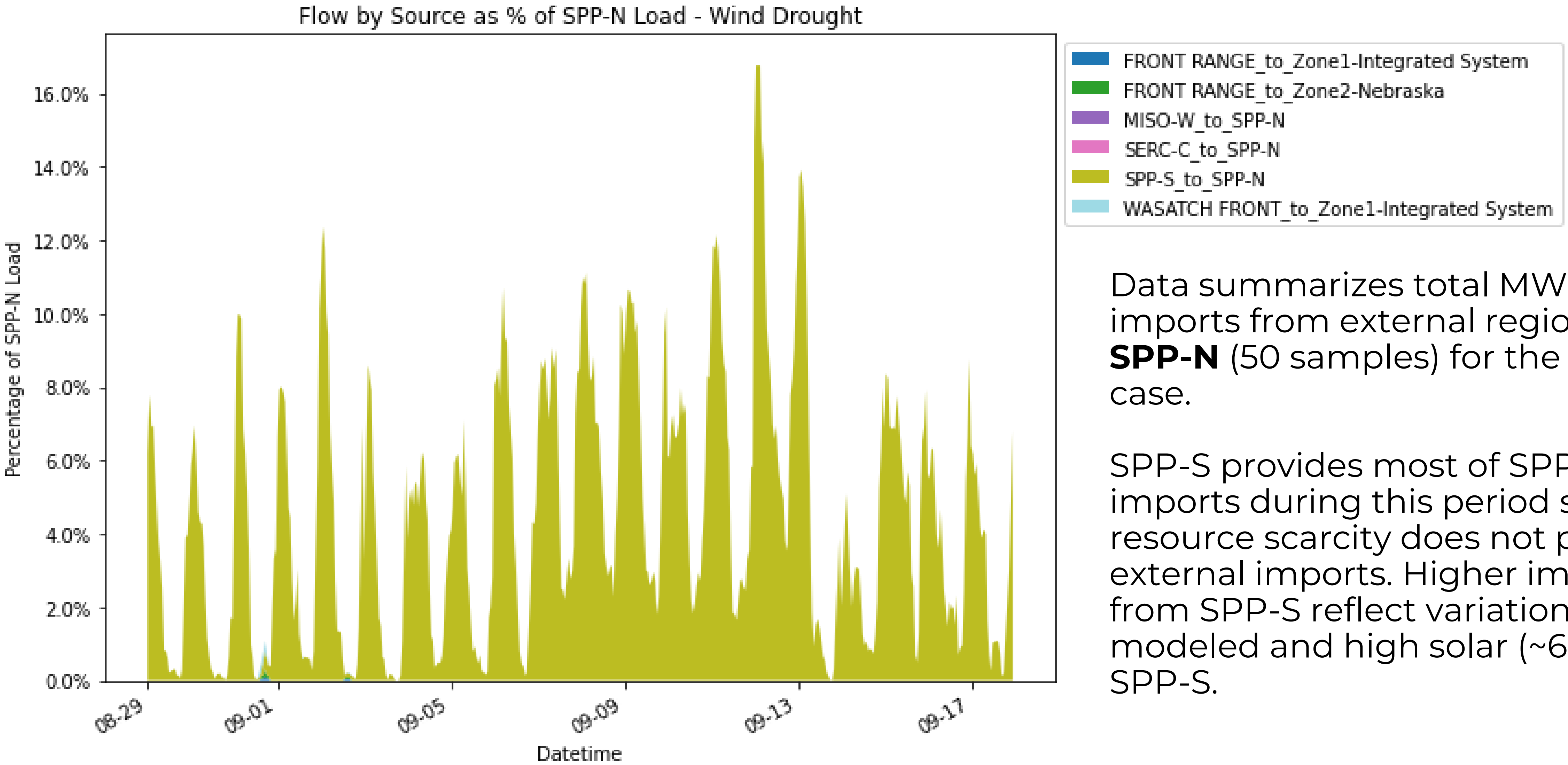


Data summarize total MWh of imports from external regions **into SPP-S** (50 samples) for the +10% load case.

In the forecasted system, 2029/2030 modeled conditions show that SPP-N imports to SPP-S are sufficient during the wind drought, but external imports support the system during high load on 9/1.

Source: Energy Systems Integration Group; data from SPP

Wind drought: When imports are needed, SPP-N only requires looking to SPP-S for support across the stress tests



Data summarizes total MWh of imports from external regions **into SPP-N** (50 samples) for the +10% load case.

SPP-S provides most of SPP-N imports during this period since resource scarcity does not prompt external imports. Higher imports from SPP-S reflect variation in wind modeled and high solar (~6 GW) in SPP-S.

Source: Energy Systems Integration Group; data from SPP

Compound Event Summary

Based on Period from January 31 to February 14, 2010

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Compound event: Temperatures are low and net load is high, but overall load is moderate.

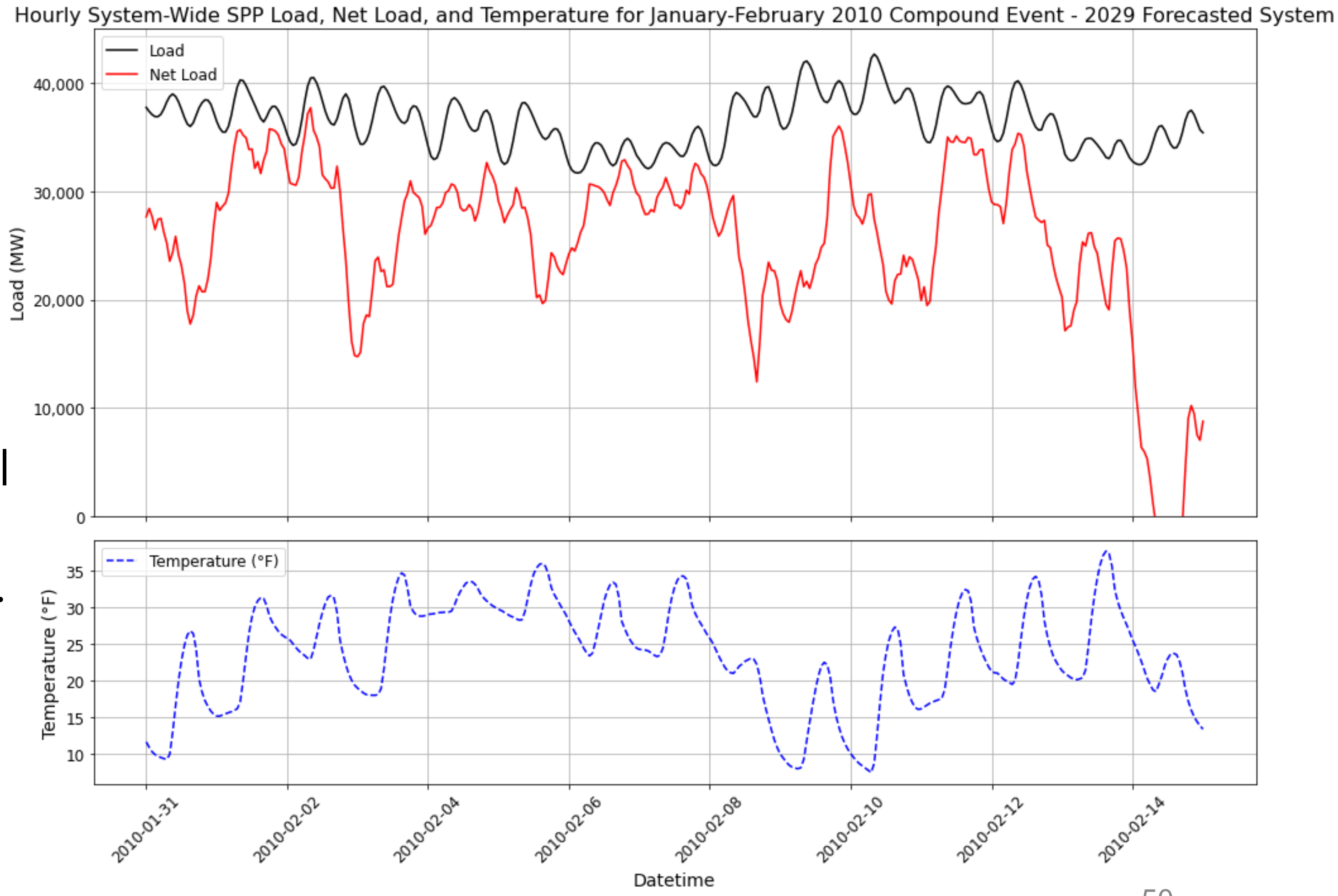
The compound event could pose risks, but for the 2029 SPP system stress testing results show that the moderate load levels mean no unserved energy.

A two-week period with high net load conditions and high winter load conditions is re-simulated.

Temperatures are persistently at or below freezing.

Periods of high net load pose potential risks if correlated with high thermal outages or minimal import availability.

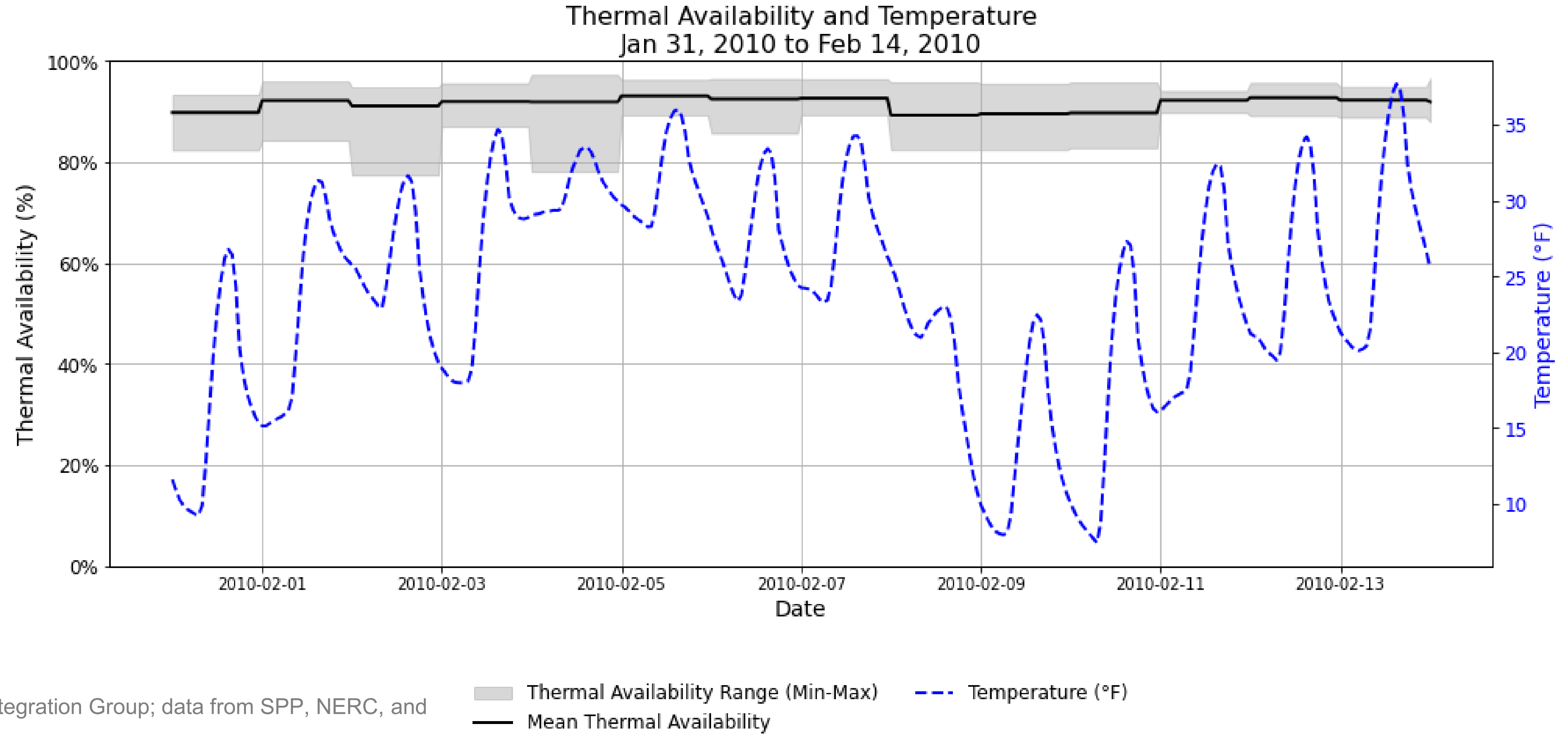
Winter Storm Uri load is persistently above 40 GW. This period is less risky with respect to load.



Thermal availability is varied for each day based on temperature-outage relationships.

Thermal availability drops to about 80% but is less extreme than the Uri-like event (discussed above) due to more moderate cold temperatures.

Across the 50 samples, thermal availability risks drop as low as 80%. Risks for shortages during this cold period are less severe than the Uri event due to higher minimum temperatures.



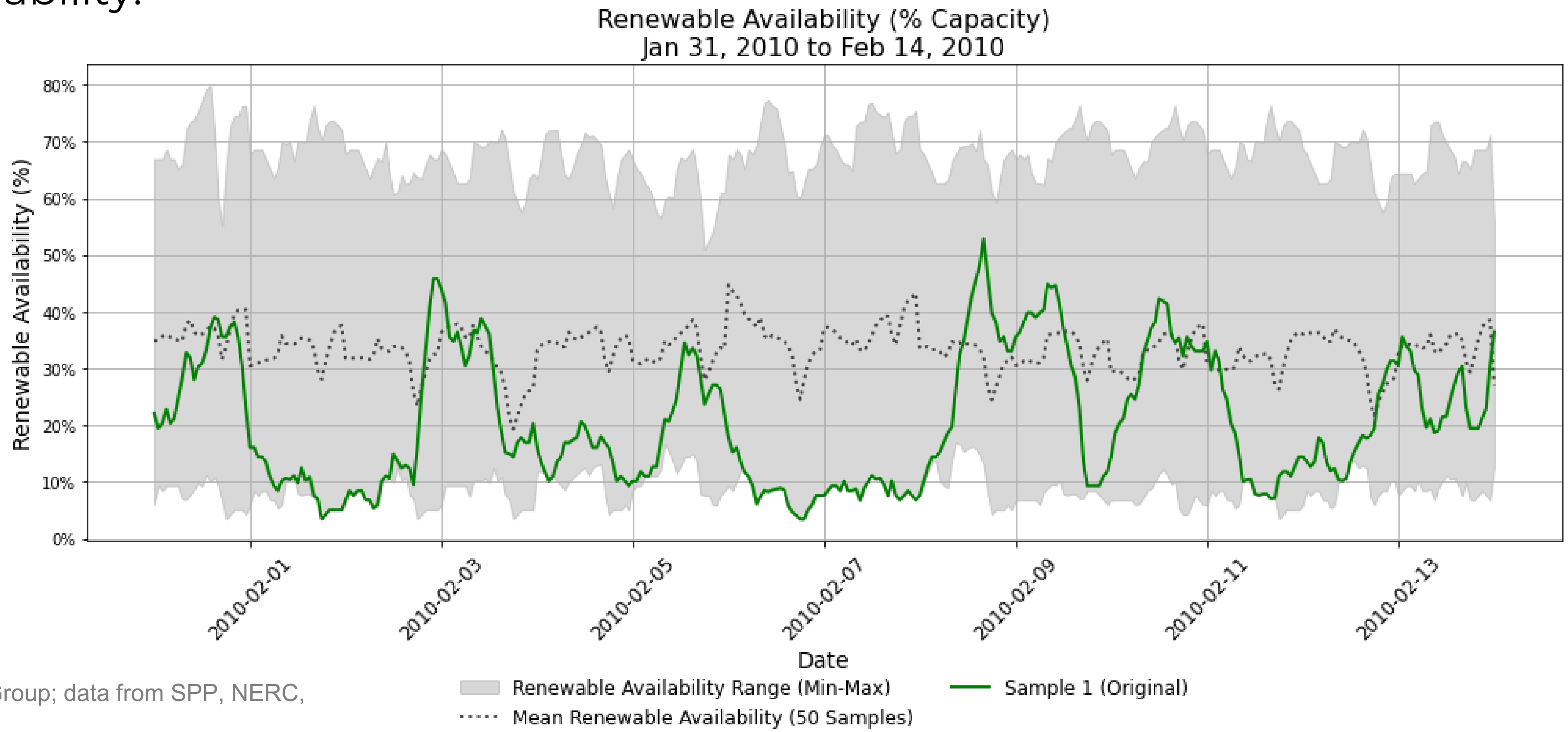
Source: Energy Systems Integration Group; data from SPP, NERC, and PNNL.

Unique renewable profiles were created to stress the event if different plausible renewable conditions occurred.

Variability in renewable generation is high, even when days with similar load levels are re-sampled.

The original data show the multiple periods of very low wind and solar availability. This event may be more drastic in a higher-renewable and lower-thermal generation system.

Resampling of the renewable profiles creates additional risks across different hours in the two-week period. For example, two of the coldest days (2/9 and 2/10) have alternative profiles to evaluate lower renewable availability.



Source: Energy Systems Integration Group; data from SPP, NERC, NREL, EIA, and PNNL.

Load, generator maintenance, and DC interface capability for SPP were also stressed to increase risks and evaluate resilience.

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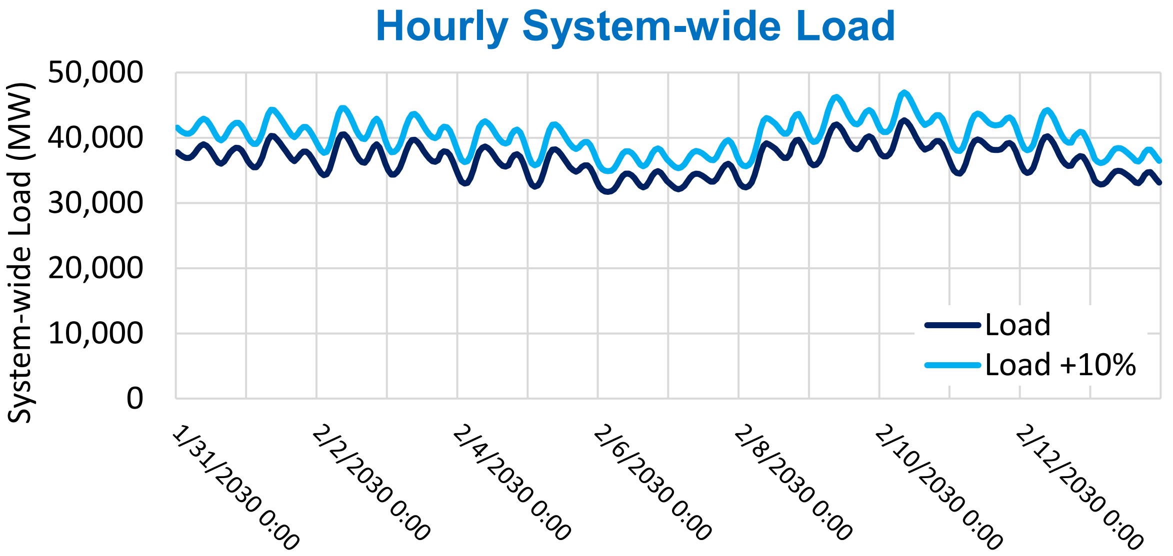
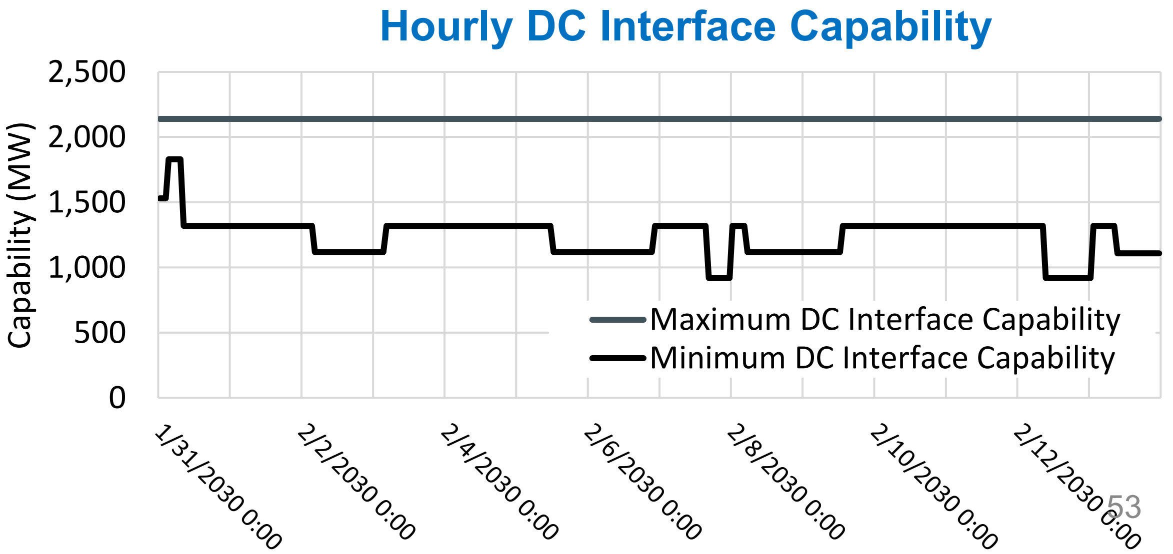
Load is much lower throughout this winter compound event compared to the cold event.

Randomized forced and maintenance outages were modeled on SPP DC interfaces with capabilities ranging from 100% available to less than 50%.

Variations in renewable profiles, and thermal availability as low as 82% drive risk in this event. However, lower load coupled with reasonable thermal availability can mitigate high net-load risks.





Source: Energy Systems Integration Group; data from SPP

During the compound event, demand is moderate enough that outages and low renewables don't result in stress.

Imports are not needed in this case except for in a single case at minimal levels.

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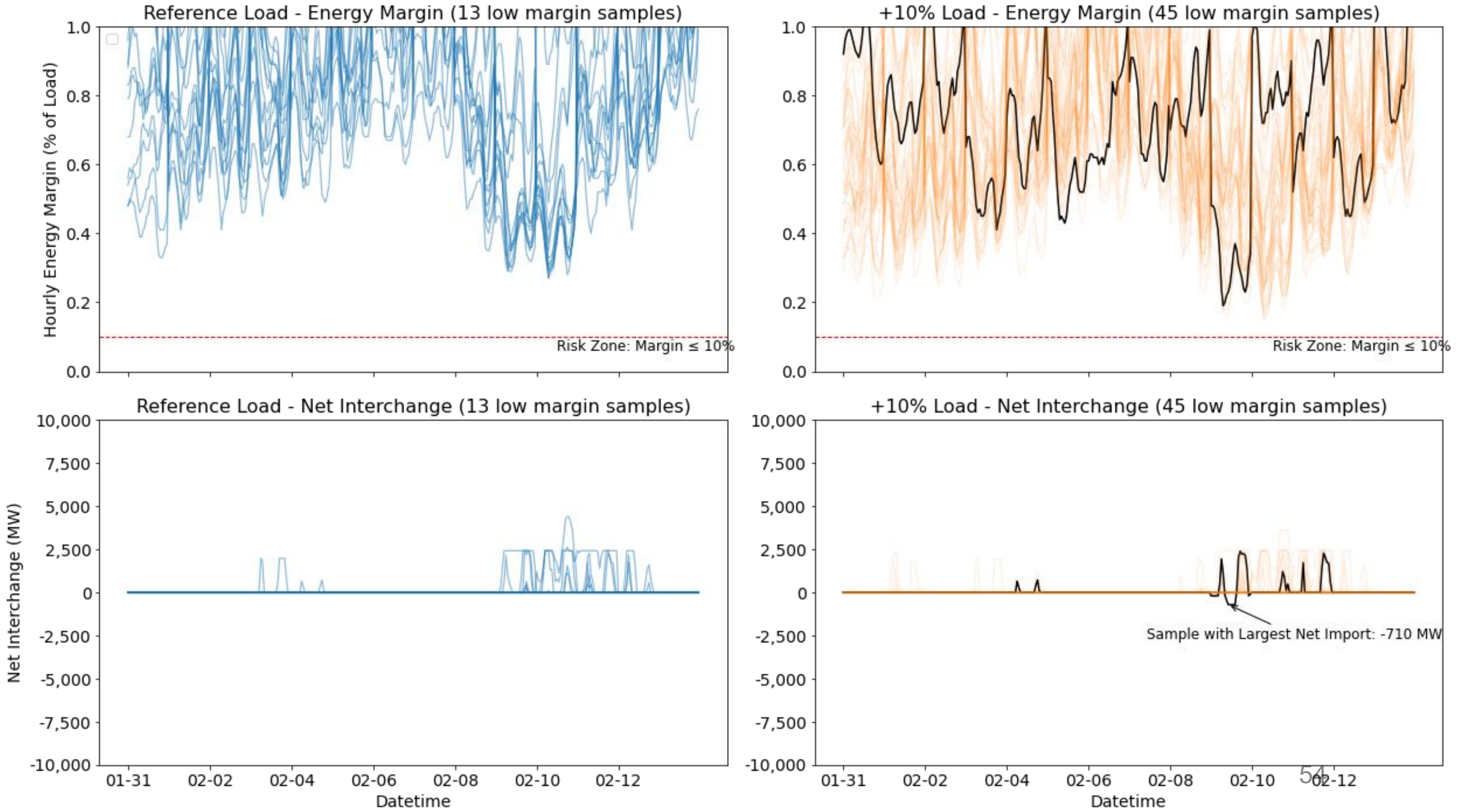
Conditions modeled across the chosen compound event did not result in significant net imports.

Hourly energy margins stayed well above 10%, even in the high load case.

Result	Reference Load	+10% Load
Hours Margin <10%	0	0
Hours Margin <3%	0	0
Max Net Imports (MW)	4	710
Longest Duration Net Imports (hours)	1	7
Max Unserved Energy (MW)	0	0

January 31st – February 14th, 2010, Compound Event Samples with Hours <35% Energy Margin



Source: Energy Systems Integration Group

Compound event: No unserved energy events occur for this event based on the 2029 SPP system.

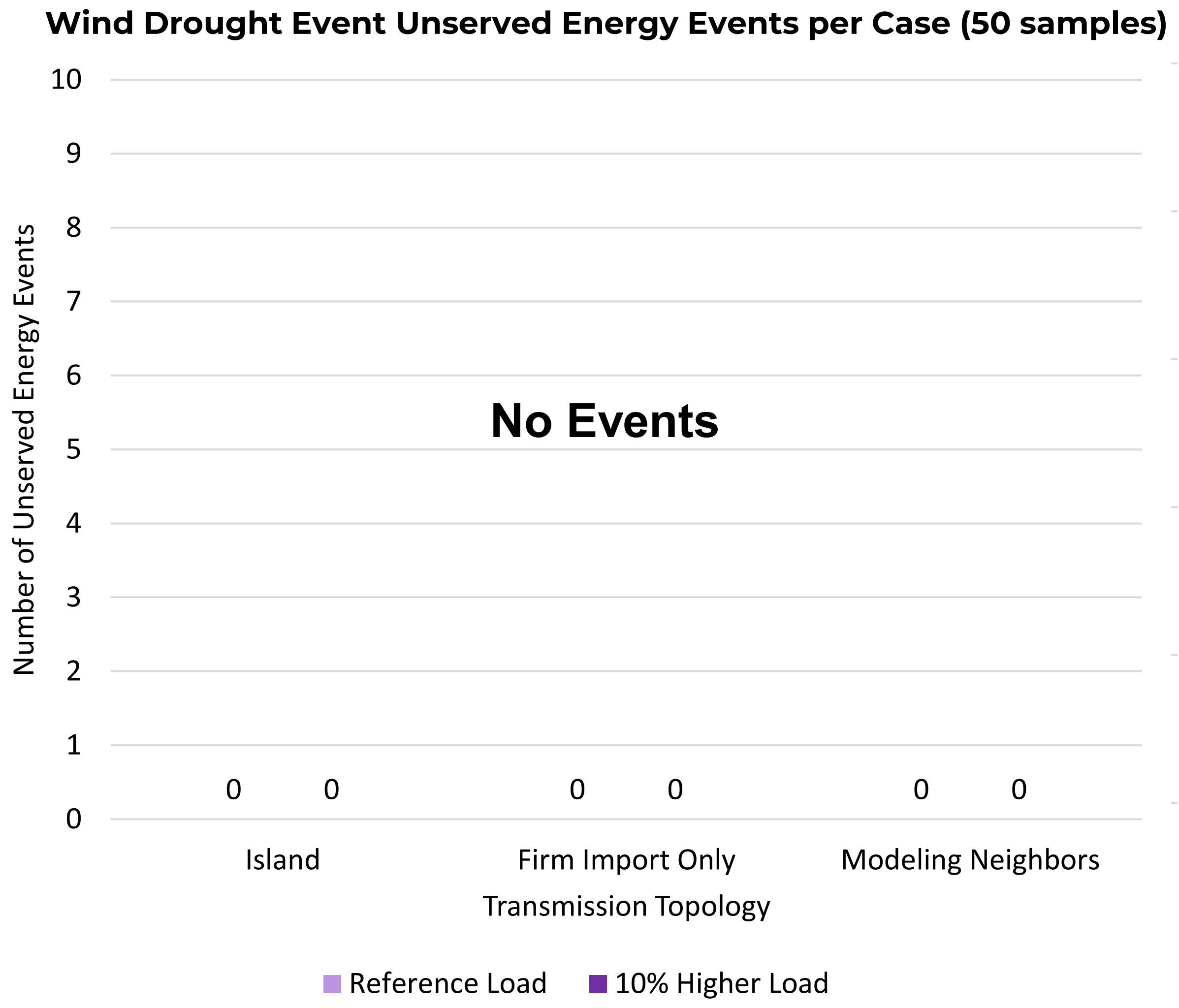
The moderate load levels and less severe cold weather outages result in a system that is not stressed.

Across the three system representations, there are no unserved energy events.

Ultimately, load levels are moderate during this period, even when increased by 10%.

Outage levels can be high across thermal resources, and renewable generation can be low, but load is moderate, so risks do not materialize for the 2029 system.

Changes in the resource mix, such as reduced thermal resources, may show elevated risk that would need to be met with renewables, imports, or storage.

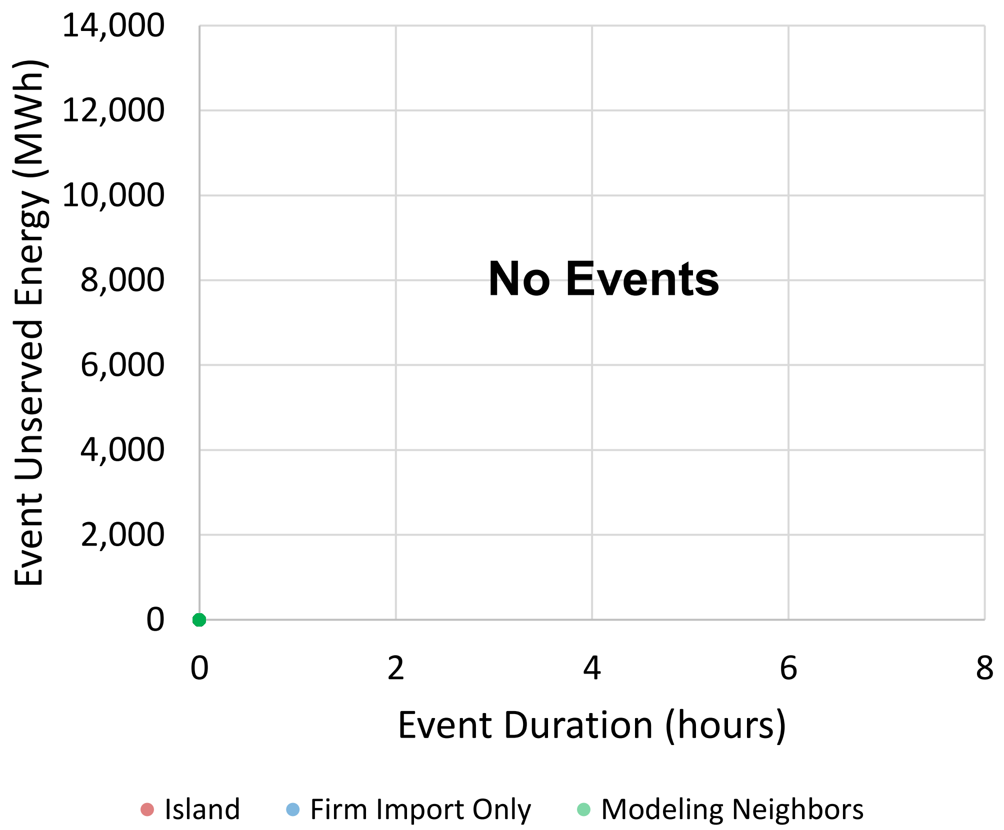


Source: Energy Systems Integration Group

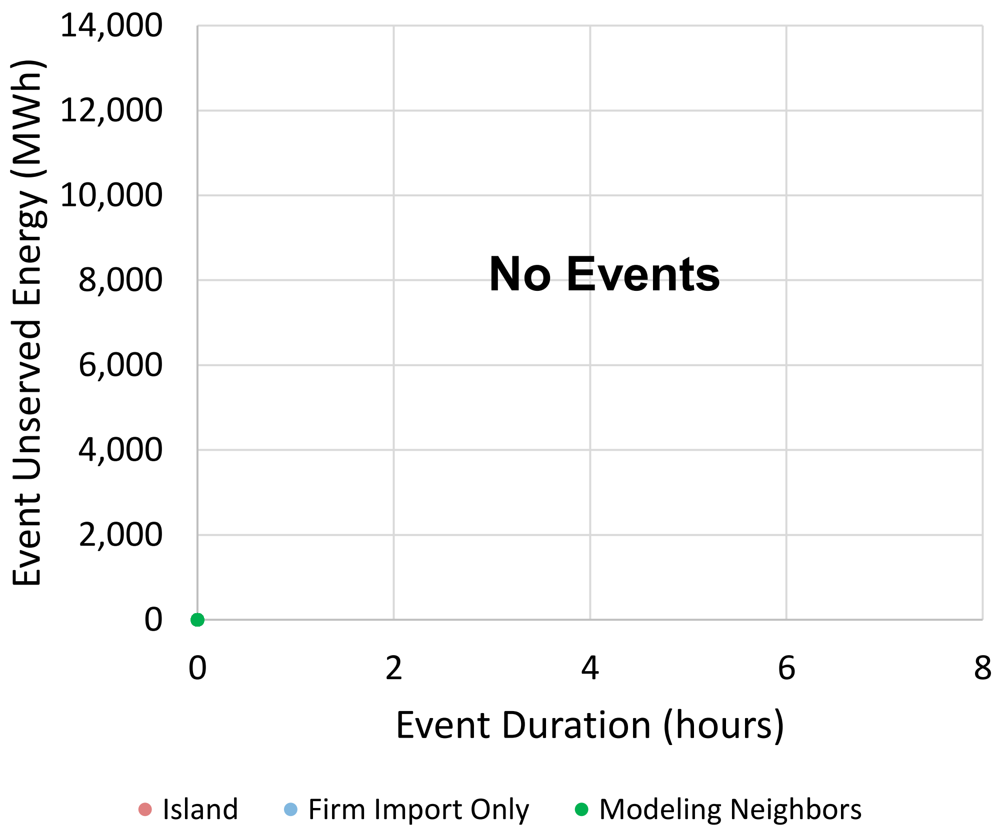
Compound event: Load levels were not extreme enough to exhibit system stress in terms of unserved energy.

The compound event had potential for both high outage levels due to cold temperatures and low renewable generation. Although load was high, it was not extreme enough to show shortages.

USE Magnitude and Duration – Reference Load

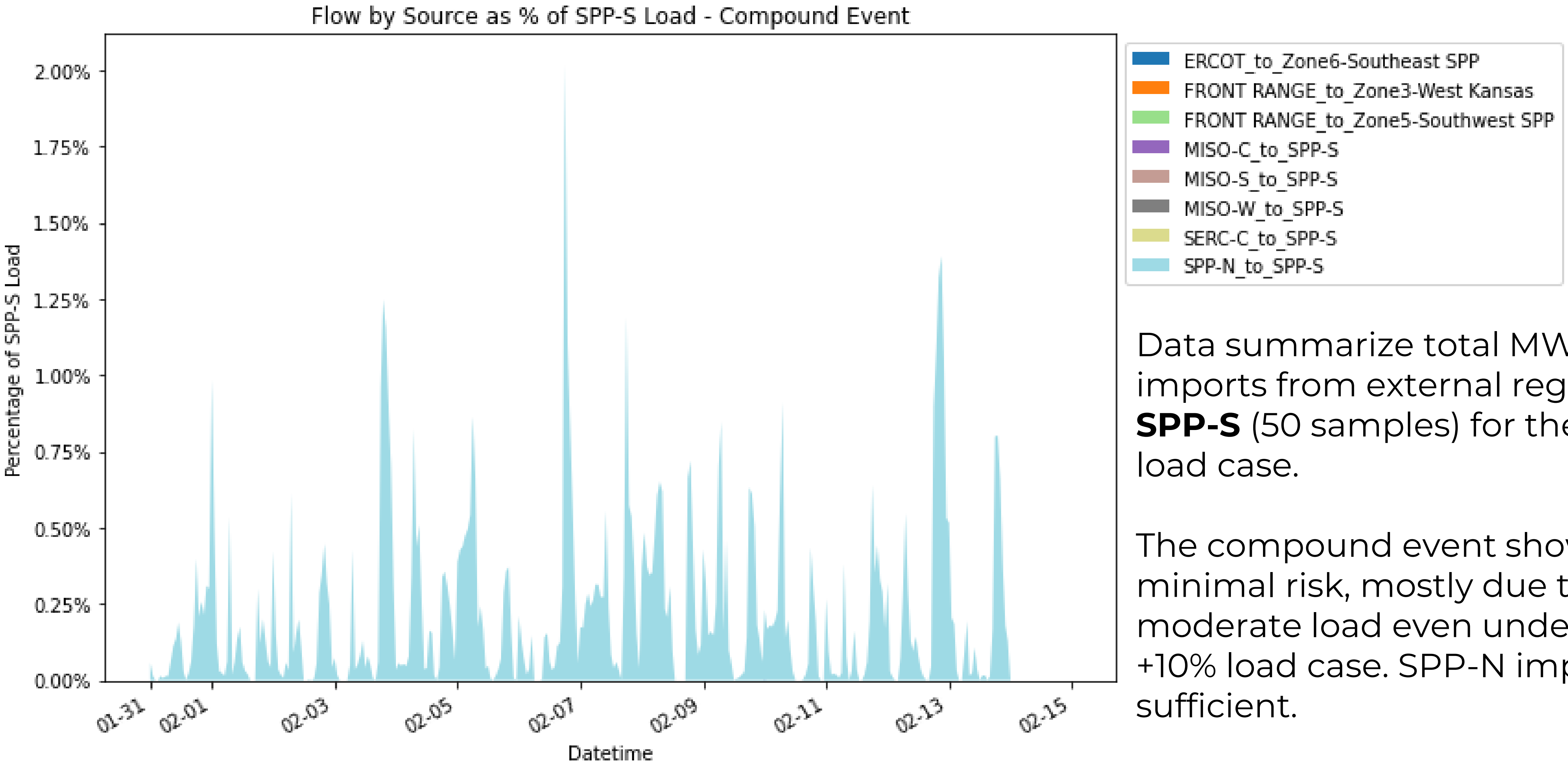


USE Magnitude and Duration - +10% Load



Source: Energy Systems Integration Group; data from SPP

Compound event: SPP-S import needs are fully satisfied by SPP-N during the compound event.



Data summarize total MWh of imports from external regions **into SPP-S** (50 samples) for the +10% load case.

The compound event shows minimal risk, mostly due to moderate load even under the +10% load case. SPP-N imports are sufficient.

Source: Energy Systems Integration Group; data from SPP

Compound event: Minimal imports are needed, but diversity from Front-Range (Western Electricity Coordinating Council) is leveraged by SPP-N in some cases.

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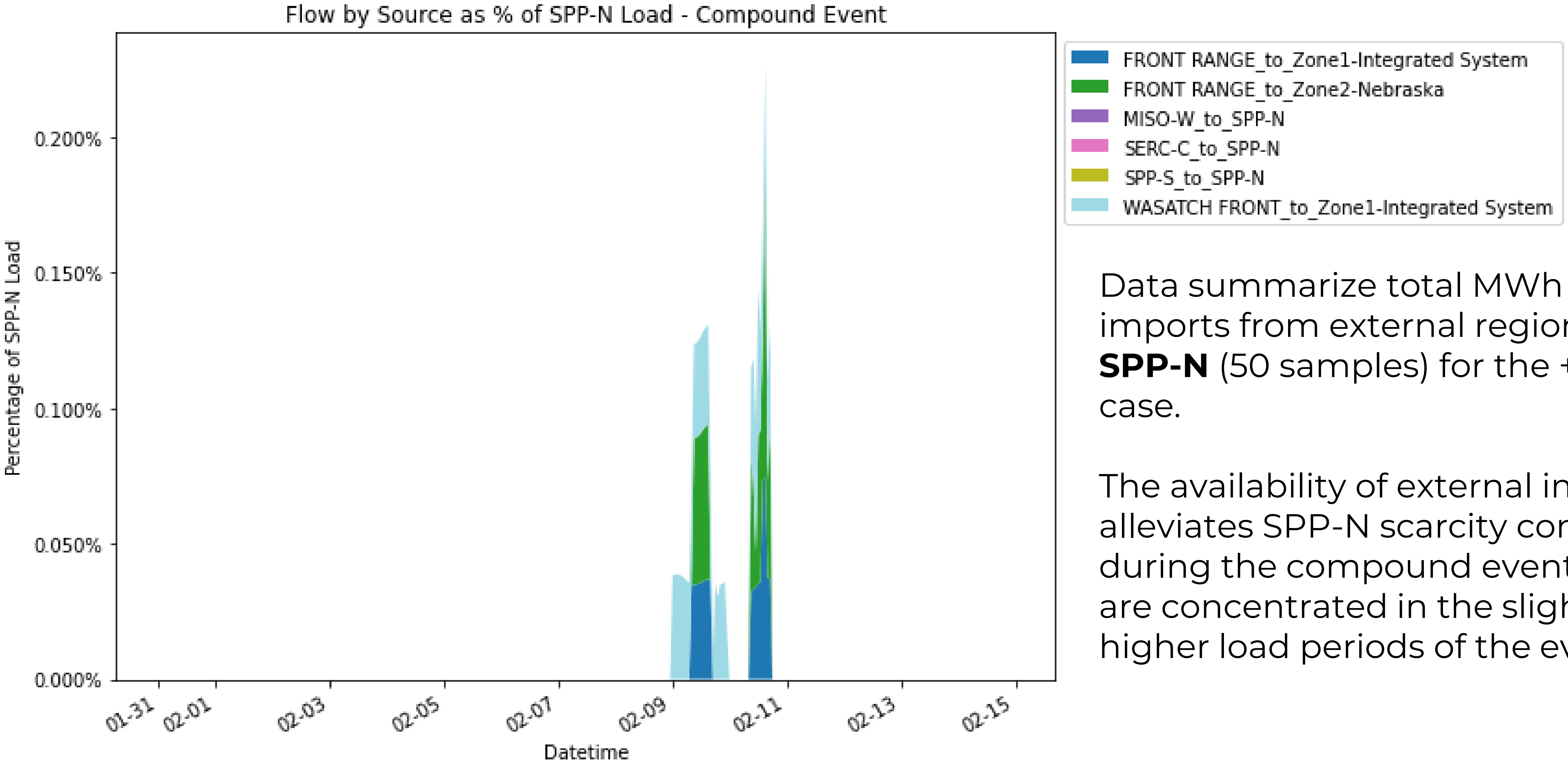

Data summarize total MWh of imports from external regions **into SPP-N** (50 samples) for the +10% load case.

The availability of external imports alleviates SPP-N scarcity constraints during the compound event. Imports are concentrated in the slightly higher load periods of the event.

Source: Energy Systems Integration Group; data from SPP

Stress Testing Key Findings and Recommendations

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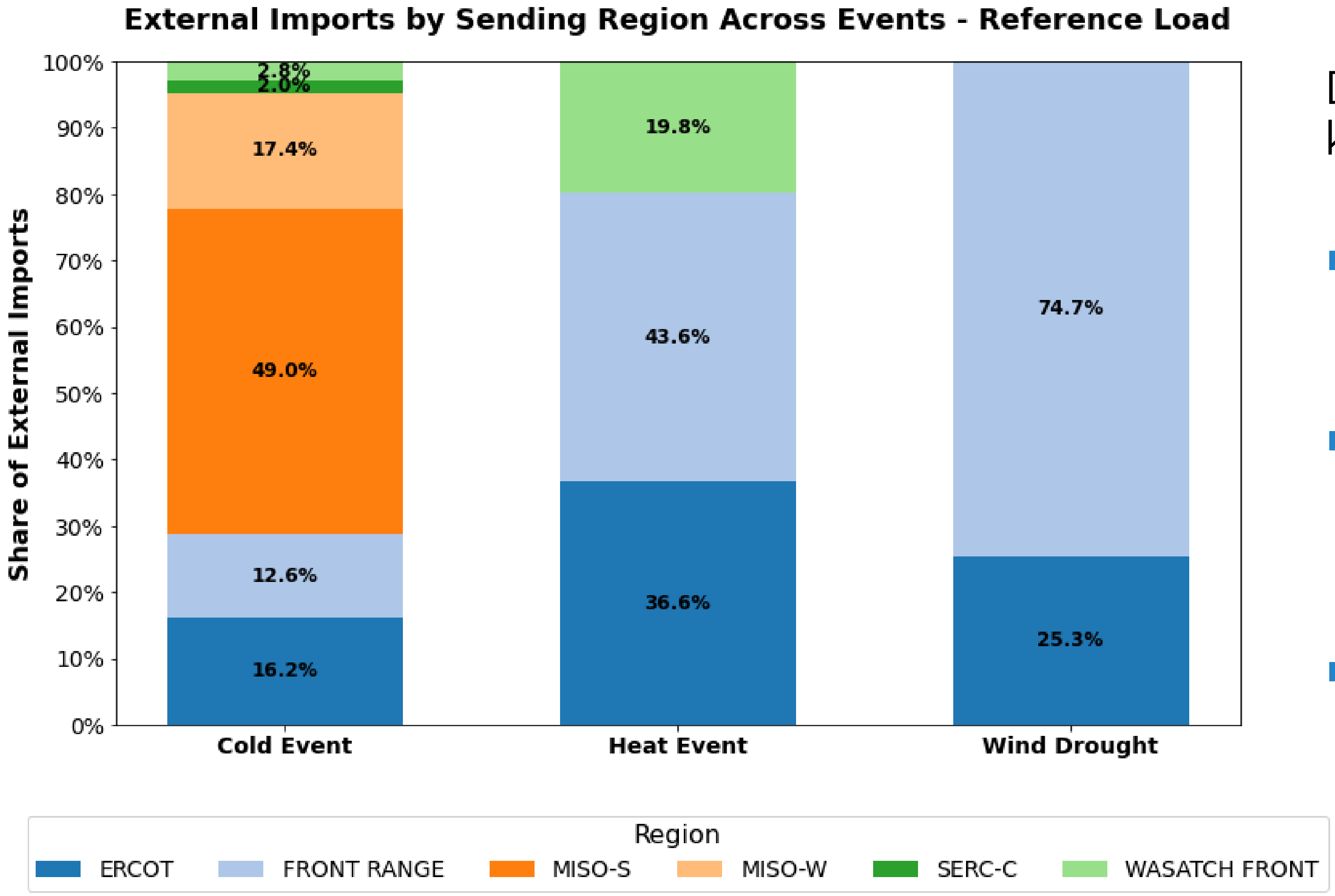
Under reference load, different events shift which neighbors supply the most support.

Import shares change across cold, heat, and wind drought conditions, indicating event-specific neighbor effectiveness.



Different stress events reveal different key supporting regions:

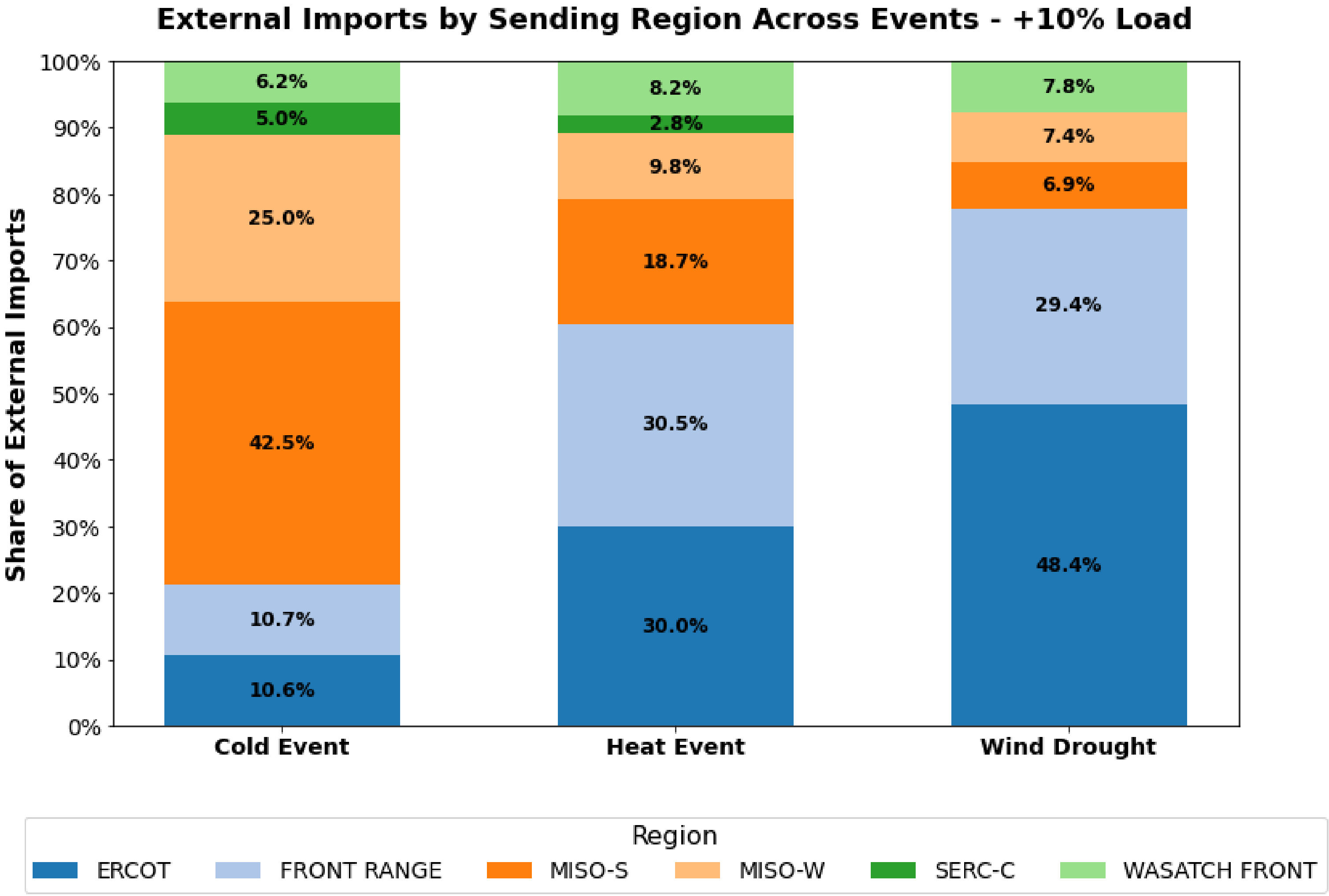
- **Cold event support**: MISO-W and MISO-S (67% of imports)
- **Heat event support:** Separate Interconnections via ERCOT and WECC Regions
- **Wind drought:** Separate Interconnections via ERCOT and WECC Regions

Source: Energy Systems Integration Group

*Data for the compound event are not shown due to identified dates not resulting in high stress for the 2030 SPP system; therefore, no imports occurred.

Under higher load, a broader set of interfaces contributes meaningful support.

As stress increases, more paths contribute and different interfaces or surplus resource availability constrain imports by event and hour.



Proportion of support diversifies under even higher load conditions:

- **Cold event support**: SERC-C and Wasatch Front support grows
- **Heat event support:** MISO and SERC regions get involved
- **Wind drought:** MISO and Wasatch Front regions get involved

Source: Energy Systems Integration Group

*Data for the compound event are not shown due to identified dates not resulting in high stress for the 2030 SPP system; therefore, no imports occurred.

Key Findings from SPP Stress Testing

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External assistance and interregional transmission are important for modeling stress events.

- When coupled with interregional transmission, the future SPP resource mix is resilient to the modeled events, although some unserved energy remains in the high load scenario.
- External regions can offer substantial support, even during periods of extreme weather or renewable droughts occurring in external regions coincident with the study region.

Stress testing offers a method to evaluate outlier events in more detail.

- Difficulties assigning probabilities for events and gaining consensus on those probabilities can be avoided by modeling them discretely in stress testing.
- Digging more deeply into events that drive reserve margin levels and capacity needs is warranted. This includes evaluating the importance of existing and future interregional transmission for system resilience and to minimize costs.

Evaluating different renewable profiles for specific events can expand risk analysis.

- Limited weather data for national datasets can benefit from resampling renewable profiles for similar load days to extend stress testing analysis to new combinations of load and renewables.
- More historical and synthetic weather-correlated load and renewables data are becoming available, which can further enhance this process.

Future Stress Testing Work

Improve how external assistance and interregional transfer capabilities are modeled

- Incorporate more power flow modeling, potentially nodal or hybrid nodal details
- Perform transfer analysis on multiple load and weather dispatch conditions
- Use stress testing periods in power flow analyses to inform how capabilities change under different weather conditions
- Refine transfer capability to capture existing firm exports/import contracts

Improve how stress events are developed

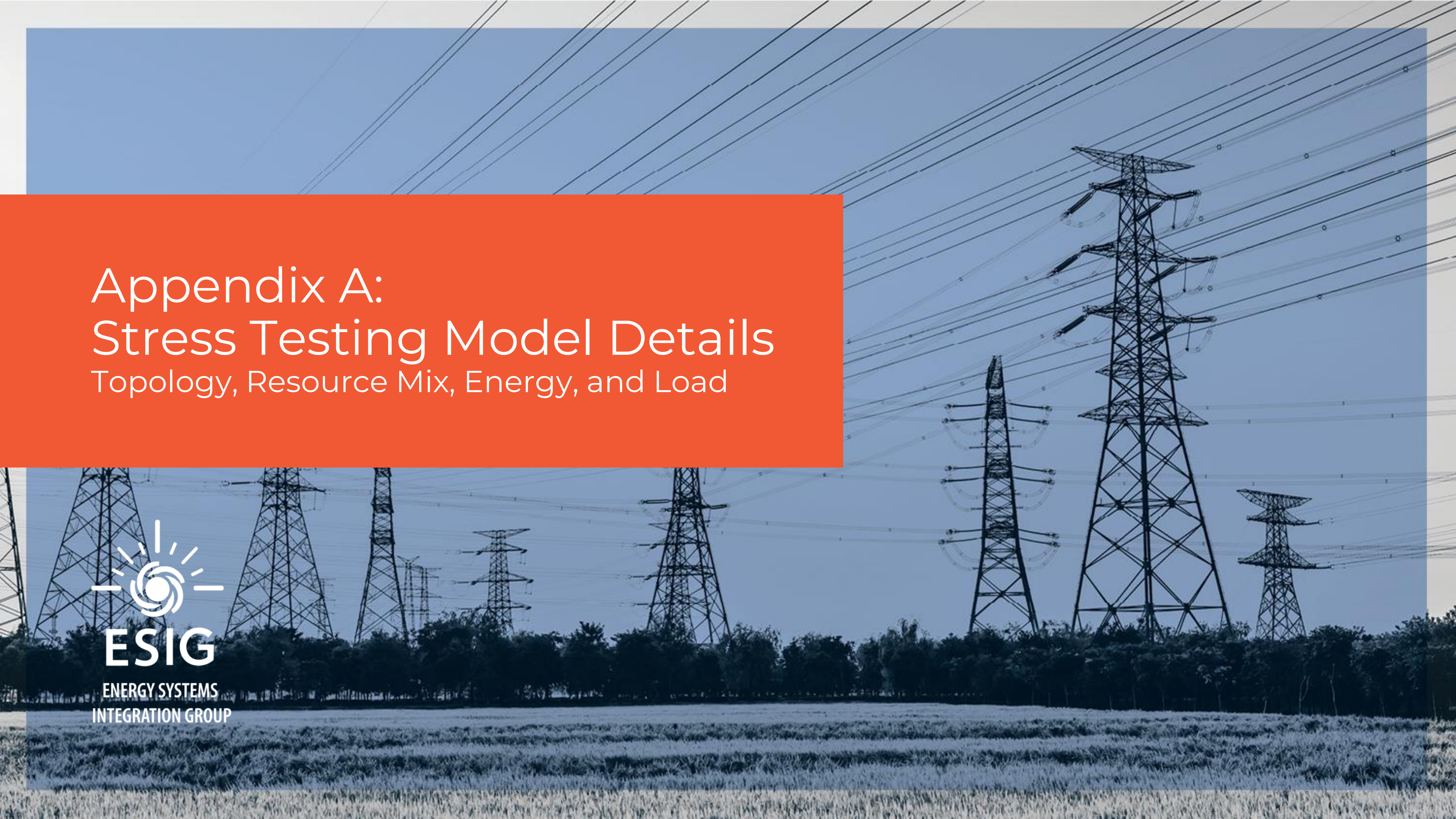
- Evaluate more stress events beyond those shown here and include additional extreme event variables such as precipitation, wind chill, declines in gas production, tornadoes, hurricanes (for systems where relevant)
- Use a longer historical, correlated national weather dataset to improve stress sample creation
- Leverage synthetic datasets and/or climate change datasets like Sup3rCC

Use stress testing to evaluate multiple types of risk mitigation solutions

- Use stress testing as a sandbox to evaluate risk mitigation beyond adding capacity resources (which is typically the result of resource adequacy analysis)
- Consider the outsized effect of low average event benefit but high extreme event benefit mitigation options (e.g., winterization, demand response, virtual power plants)

Appendix A:
Stress Testing Model Details

Topology, Resource Mix, Energy, and Load



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2030 System Model
Using realistic systems

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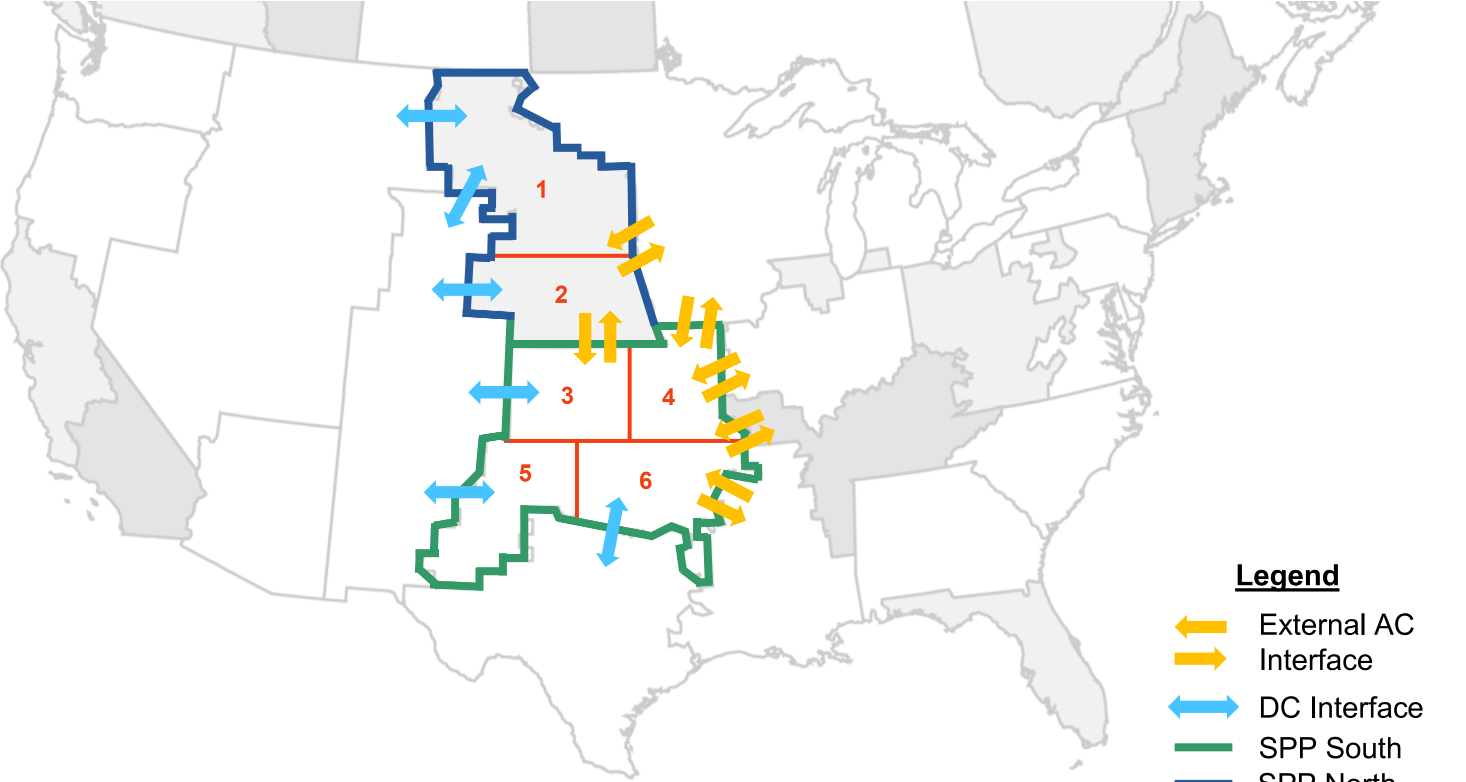
Detailed SPP subregional modeling with 2029 loss-of-load expectation (LOLE) study system
- Includes internal zonal transmission limits

External regions based on EIA 860 2030 additions and retirements aggregated to NERC ITCS Part 1 study regions.
- Includes resulting region-to-region interfaces and simultaneous import constraints

External region load uses NREL 2023 Cambium high load growth scenario for discrete weather years (2007-2013 and 2019-2023).

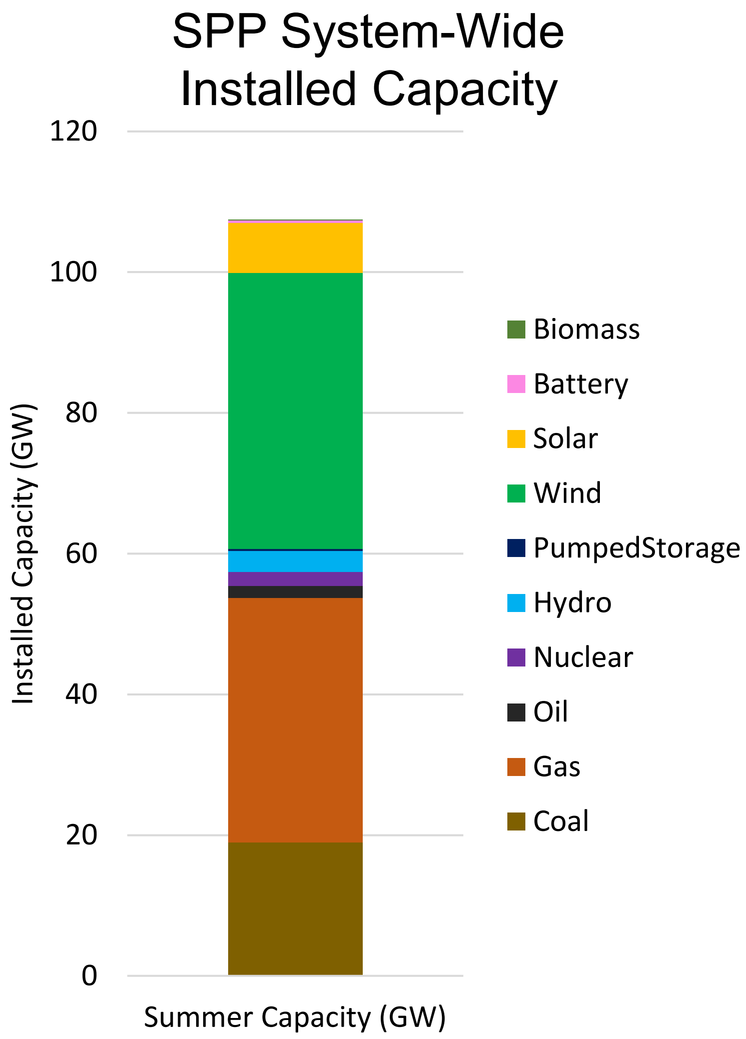
SPP Stress Testing Model Topology

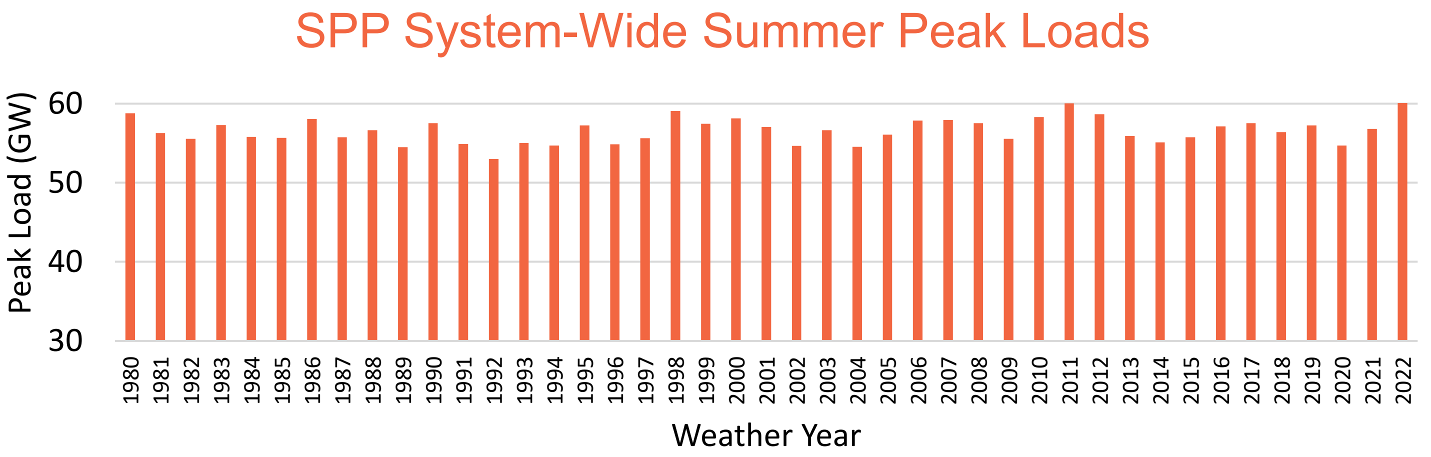


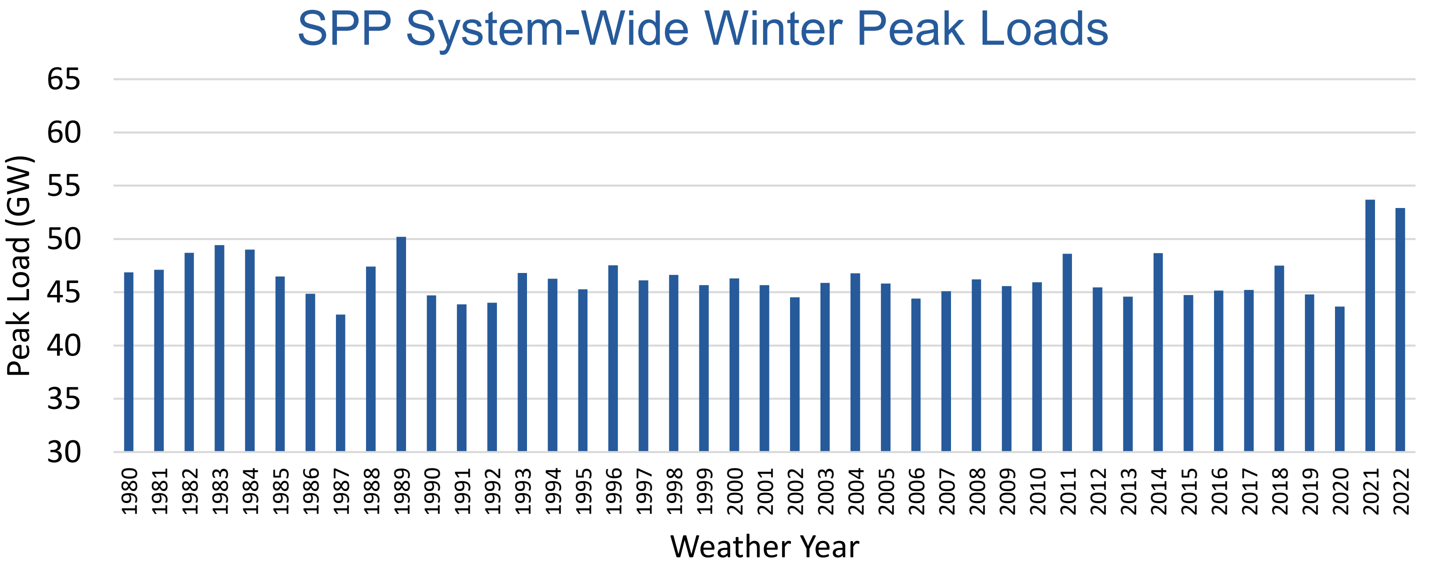
*All region boundaries are approximate and do not show overlapping territory
** All internal SPP interfaces connect to a central "SPP System" node for DR and respective SPP-S and SPP-N nodes for internal transfers

Source: Energy Systems Integration Group.

2029 SPP System Resource Mix and Load







Source: Energy Systems Integration Group; data from SPP

2030 External System Resource Mix

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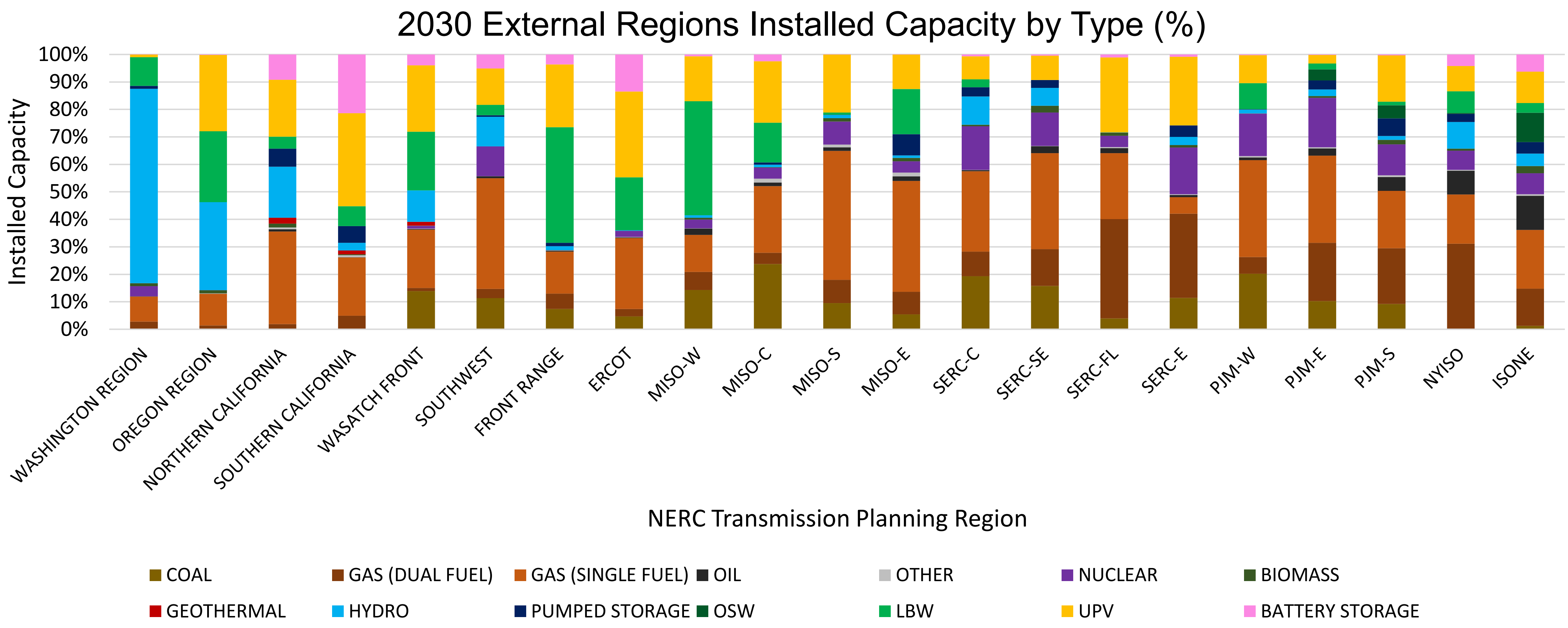
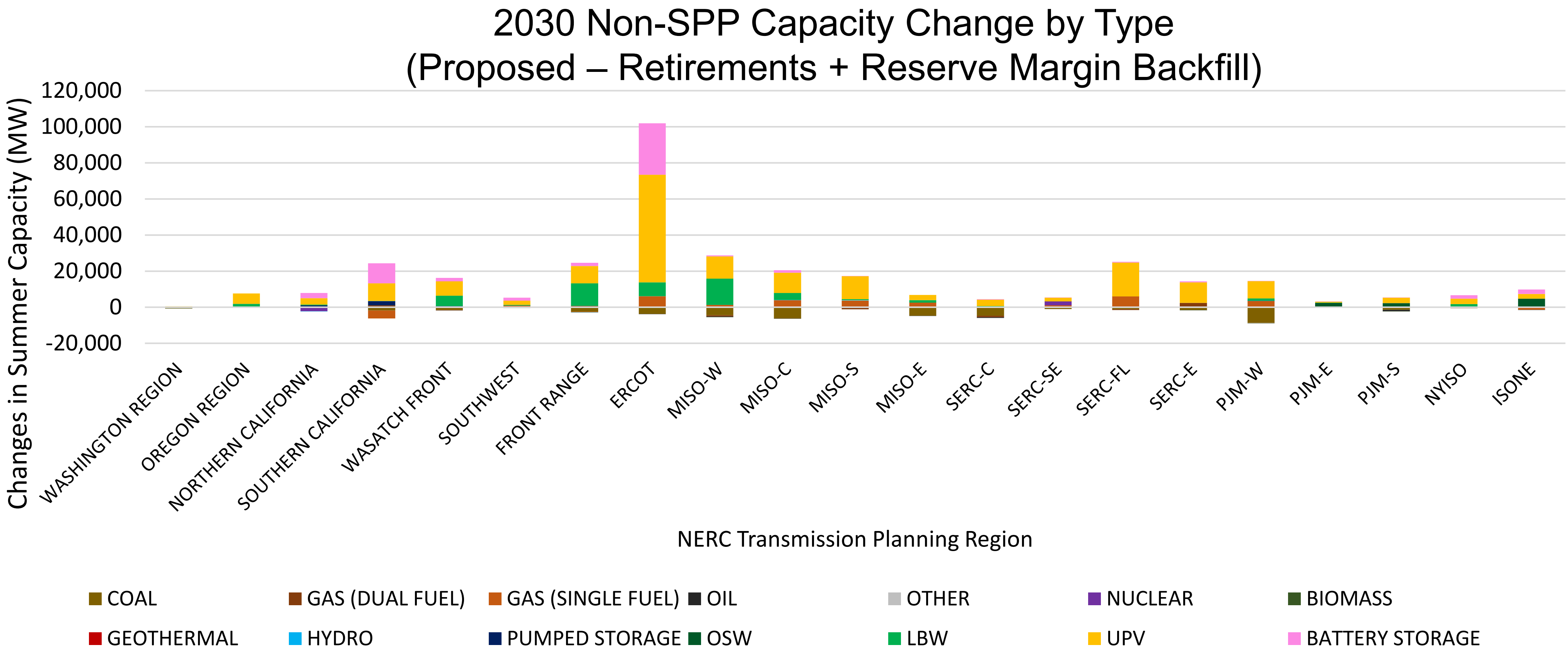
External regions used EIA 860 proposed resource changes for 2030 aggregated based on the NERC ITCS regions.



Source: Energy Systems Integration Group; data from EIA 860

2030 External System Resource Mix



Type	Net Change (MW)
Thermal	-22,780
Storage	59,005
Renewable	255,223

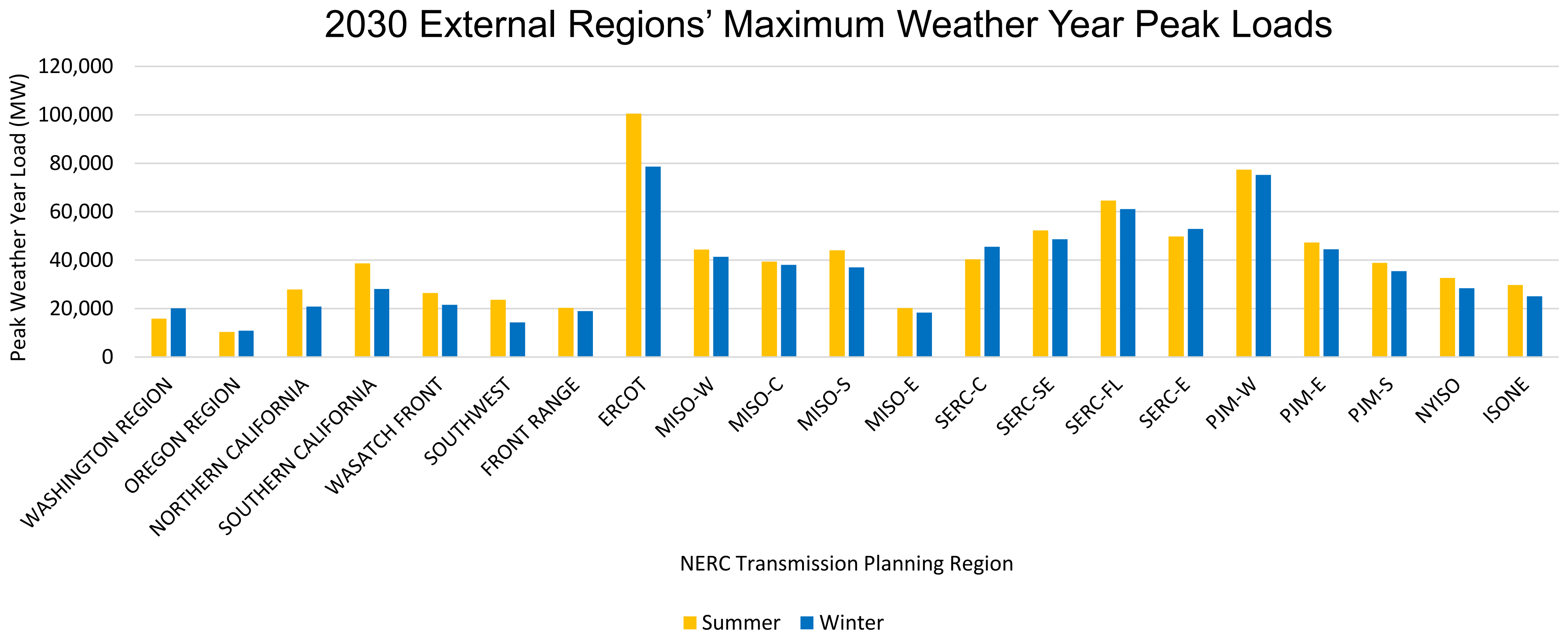
1. Net changes in resource types were based on the 2022 EIA Form 860 using operable, proposed, and proposed retirement dates.
2. Regional effective capacity was calculated based on unforced capacity (thermals) and estimated ELCCs (renewables and storage) so that each region's reserve margin could be calculated. If regions were <15%, additional effective MWs were added based on the ratio of proposed resources for that region in the EIA data.
3. All regions were set to the same reserve margin to for consistency due to the lack of standardized national resource planning datasets. The 15% was an annual reserve margin.

Source: Energy Systems Integration Group

2030 External System Peak Load and Energy

Future loads for external regions were based on the high demand growth scenario from the National Laboratory of the Rockies' (NLR) 2023 Cambium study, which provided 2007-2013 weather year hourly load data.

- Additional weather years based on 2019-2023 from EIA were scaled to match the 2030 median peak and energy forecasts from the NLR data on a seasonal basis.

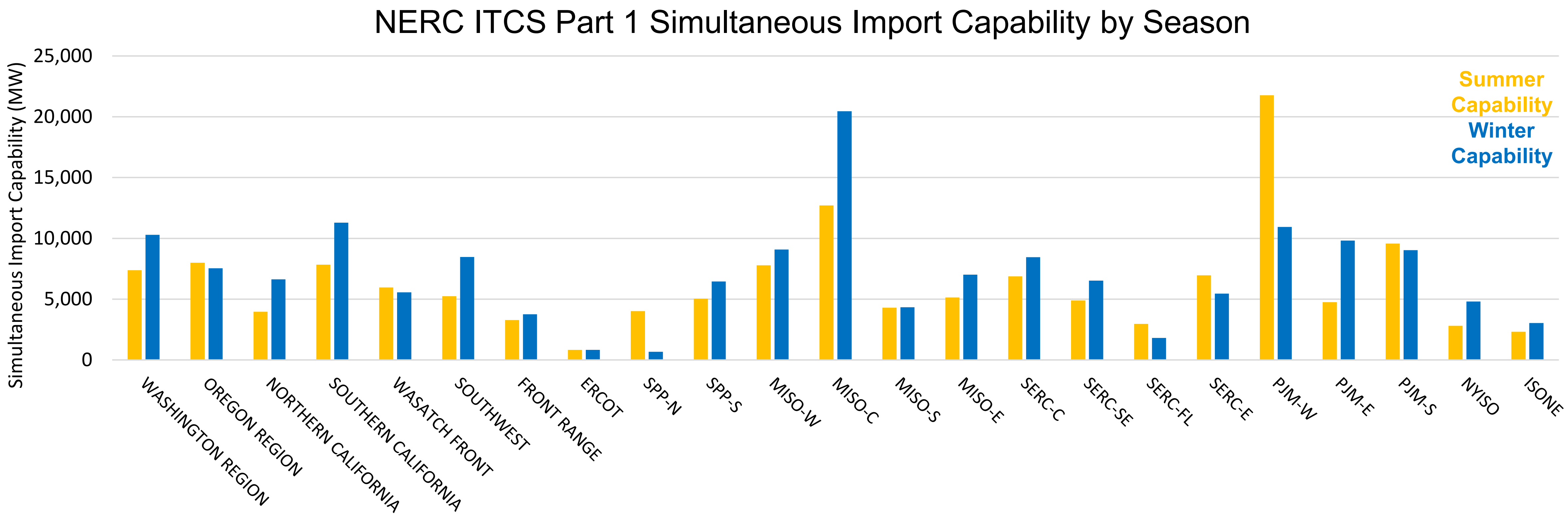


Source: Energy Systems Integration Group; data from NLR, EIA 930, and topology based on NERC ITCS

Simultaneous Transfer Capability Data

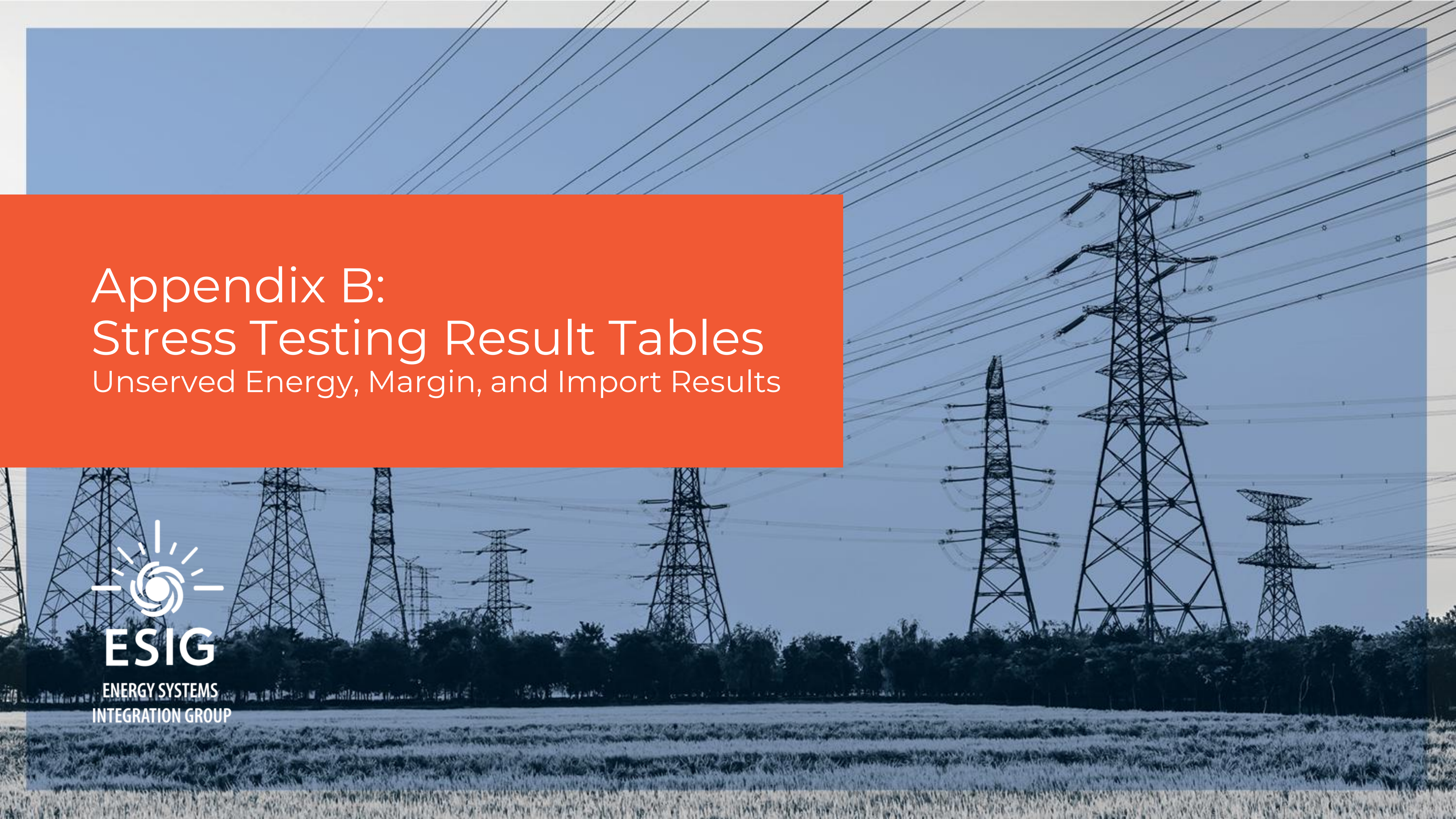
NERC Transmission Planning Regions were used as the basis for the external system to leverage the recent Interregional Transfer Capability Study results.

- The ITCS only provides for 2024 transfer capabilities, meaning this study uses conservative transfer capability assumptions for a 2030 system.



Source: Energy Systems Integration Group; data from NERC ITCS

Appendix B:
Stress Testing Result Tables
Unserved Energy, Margin, and Import Results



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Cold Event Results

2/11/2021 – 2/24/2021 Weather Case Summary Data

Result Type	Property	Reference Load			10% Higher Load		
		Island	Firm Import Only	Modeling Neighbors	Island	Firm Import Only	Modeling Neighbors
Unserved Energy Data	Maximum Unserved Load (MW)	3,560	1,255	0	8,758	6,563	1,315
	Average Unserved Load (MW)	1,136	840	0	2,404	1,756	790
	Maximum Unserved Energy (MWh)	20,217	5,366	0	84,896	52,703	4,087
	Average Unserved Energy (MWh)	4,683	2,298	0	14,947	7,875	2,119
	Total Unserved Energy Events (Count)	13	3	0	66	41	3
	Maximum Duration (hours)	9	5	0	24	13	5
	Average Duration (hour)	3	2	0	5	4	3
Hourly Energy Margin	Hours <10% Energy Margin (Count)	601	212	419	1608	985	1458
	Hours <3% Energy Margin (Count)	446	45	66	1002	262	322
Net Import Data	Hours with Imports (Count)	NA	91	88	NA	642	583
	Maximum Import (MW)	NA	2,233	5,089	NA	2,233	8,233
	Average Import (MW)	NA	1,026	1,419	NA	1,129	1,981
	Maximum Import Energy (MWh)	NA	15,878	24,349	NA	39,973	69,981
	Average Import Energy (MWh)	NA	4,032	6,721	NA	7,892	11,562
	Maximum Import Duration (hours)	NA	10	10	NA	24	24
	Average Import Duration (hours)	NA	3	3	NA	6	6

Source: Energy Systems Integration Group

Heat Event Results

7/13/2011 – 8/9/2011 Weather Case Summary Data

Result Type	Property	Reference Load			10% Higher Load		
		Island	Firm Import Only	Modeling Neighbors	Island	Firm Import Only	Modeling Neighbors
Unserved Energy Data	Maximum Unserved Load (MW)	0	0	0	4,230	2,405	0
	Average Unserved Load (MW)	0	0	0	1,427	723	0
	Maximum Unserved Energy (MWh)	0	0	0	28,038	13,216	0
	Average Unserved Energy (MWh)	0	0	0	5,597	2,467	0
	Total Unserved Energy Events (Count)	0	0	0	150	49	0
	Maximum Duration (hours)	0	0	0	9	8	0
	Average Duration (hour)	0	0	0	3	3	0
Hourly Energy Margin	Hours <10% Energy Margin (Count)	390	386	1078	3230	3269	3264
	Hours <3% Energy Margin (Count)	5	5	213	827	709	0
Net Import Data	Hours with Imports (Count)	NA	4	4	NA	742	1,180
	Maximum Import (MW)	NA	544	582	NA	2,255	7,730
	Average Import (MW)	NA	386	421	NA	1,398	2,140
	Maximum Import Energy (MWh)	NA	1,047	1,114	NA	18,765	48,720
	Average Import Energy (MWh)	NA	522	562	NA	5,449	8,790
	Maximum Import Duration (hours)	NA	2	2	NA	10	10
	Average Import Duration (hours)	NA	1	1	NA	3	4

Source: Energy Systems Integration Group

Wind Drought Event Results

8/29/2011 – 9/18/2011 Weather Case Summary Data

Result Type	Property	Reference Load			10% Higher Load		
		Island	Firm Import Only	Modeling Neighbors	Island	Firm Import Only	Modeling Neighbors
Unserved Energy Data	Maximum Unserved Load (MW)	0	0	0	2,893	601	0
	Average Unserved Load (MW)	0	0	0	1,108	271	0
	Maximum Unserved Energy (MWh)	0	0	0	13,114	764	0
	Average Unserved Energy (MWh)	0	0	0	3,497	428	0
	Total Unserved Energy Events (Count)	0	0	0	22	4	0
	Maximum Duration (hours)	0	0	0	7	2	0
	Average Duration (hour)	0	0	0	3	1	0
Hourly Energy Margin	Hours <10% Energy Margin (Count)	23	24	114	1608	985	1458
	Hours <3% Energy Margin (Count)	0	0	1	1002	262	322
Net Import Data	Hours with Imports (Count)	NA	0	4	NA	85	86
	Maximum Import (MW)	NA	0	118	NA	2,255	2,981
	Average Import (MW)	NA	0	40	NA	1,065	1,092
	Maximum Import Energy (MWh)	NA	0	118	NA	12,200	13,530
	Average Import Energy (MWh)	NA	0	40	NA	3,263	3,647
	Maximum Import Duration (hours)	NA	0	1	NA	7	7
	Average Import Duration (hours)	NA	0	1	NA	3	3

Source: Energy Systems Integration Group

Wind Drought Event Results

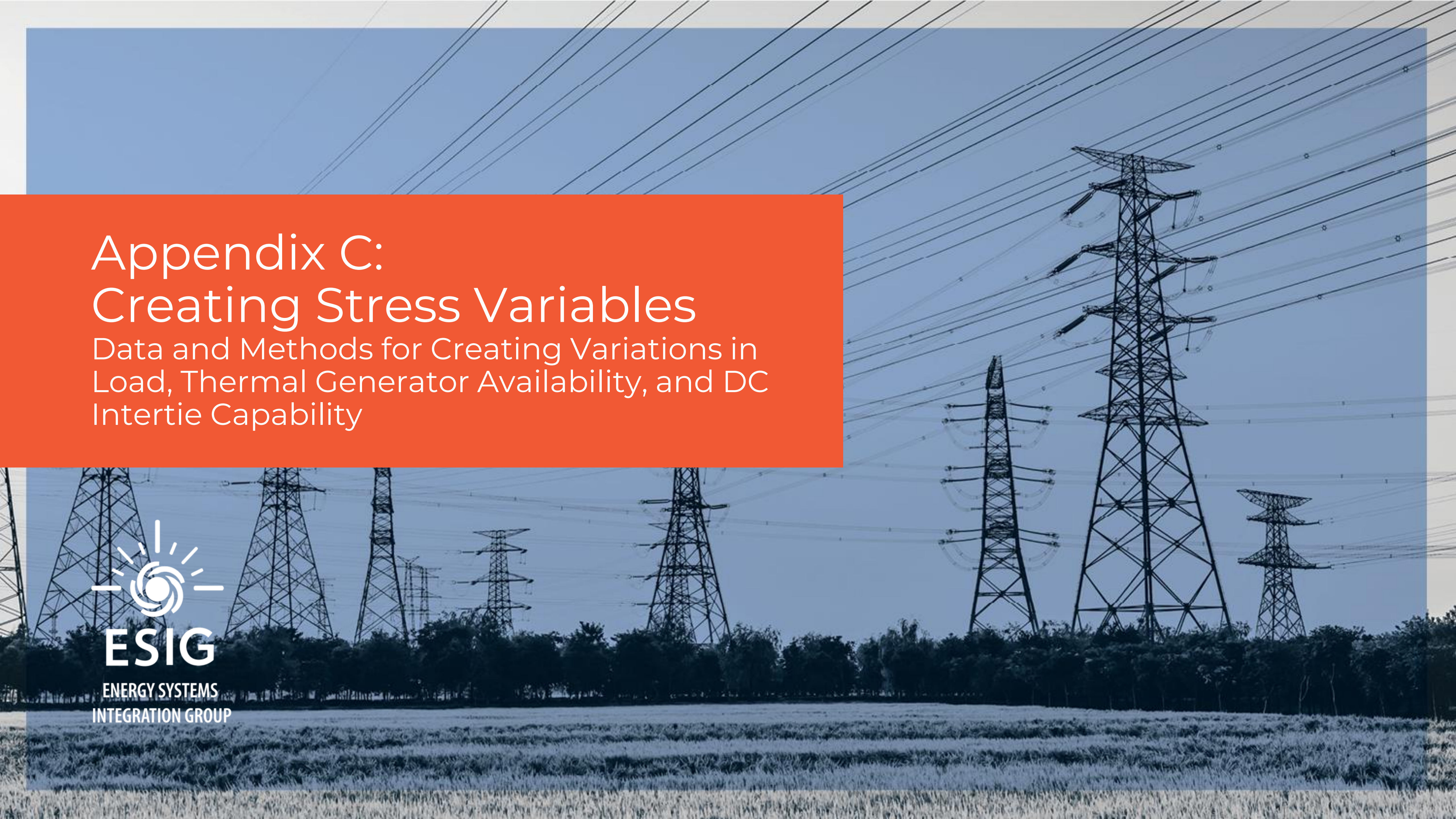
8/29/2011 – 9/18/2011 Weather Case Summary Data

Result Type	Property	Reference Load			10% Higher Load		
		Island	Firm Import Only	Modeling Neighbors	Island	Firm Import Only	Modeling Neighbors
Unserved Energy Data	Maximum Unserved Load (MW)	0	0	0	0	0	0
	Average Unserved Load (MW)	0	0	0	0	0	0
	Maximum Unserved Energy (MWh)	0	0	0	0	0	0
	Average Unserved Energy (MWh)	0	0	0	0	0	0
	Total Unserved Energy Events (Count)	0	0	0	0	0	0
	Maximum Duration (hours)	0	0	0	0	0	0
	Average Duration (hour)	0	0	0	0	0	0
Hourly Energy Margin	Hours <10% Energy Margin (Count)	0	0	0	75	0	0
	Hours <3% Energy Margin (Count)	0	0	0	0	0	0
Net Import Data	Hours with Imports (Count)	NA	2	2	NA	54	16
	Maximum Import (MW)	NA	9	4	NA	465	710
	Average Import (MW)	NA	8	4	NA	288	351
	Maximum Import Energy (MWh)	NA	17	4	NA	8,461	1,662
	Average Import Energy (MWh)	NA	12	4	NA	3,320	728
	Maximum Import Duration (hours)	NA	2	1	NA	24	7
	Average Import Duration (hours)	NA	2	1	NA	10	3

Source: Energy Systems Integration Group

Appendix C: Creating Stress Variables

Data and Methods for Creating Variations in Load, Thermal Generator Availability, and DC Intertie Capability



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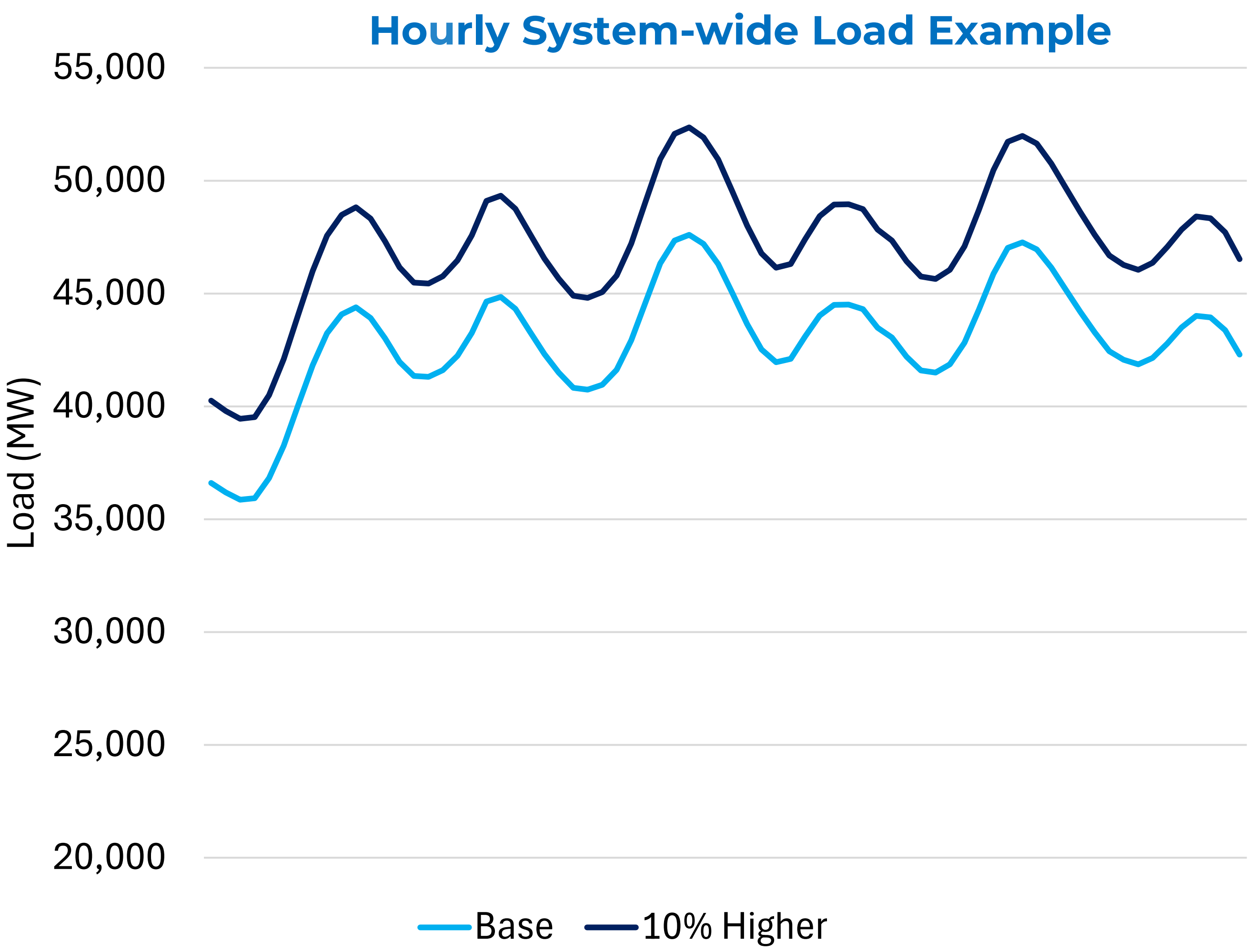
Higher Load Levels



Scale up: We chose a simple method that tightens supply for all hours in each period (+10% load).

Rationale: The goal was to represent extreme levels of load relative to the reference. Results show resilience to much higher load during the events.

Alternative approaches:

- Historical load forecast error scenarios
- Multiple load growth forecasts for testing

Source: Energy Systems Integration Group; data from SPP

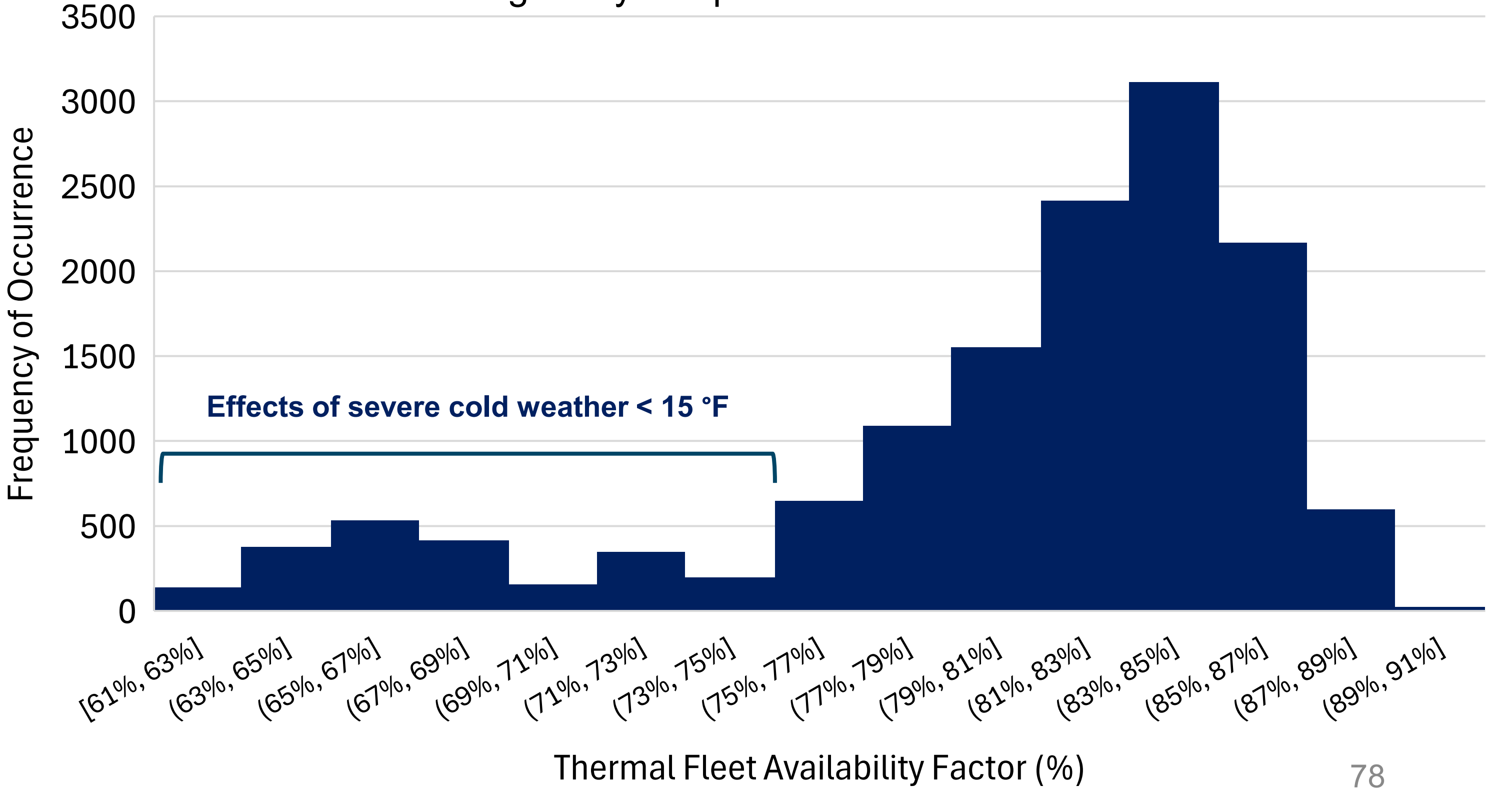
Thermal Availability

Approach: Group historical outages for each fuel type into temperature bins for that day. Re-sample temperature bins for outage conditions to create new daily outage levels.

- Availability by fuel type changes daily.
- Both typical random outages and correlated outages are represented using these data.
- Randomly sampling from temperature bins for each stress period creates unique outage profiles with a range of risks.
- Cold events may have normal or extreme outage levels.

Thermal Fleet Availability Factors for 1/28/2011 – 2/10/2011

Avg. Daily Temperature in SPP South: 6 - 45 °F

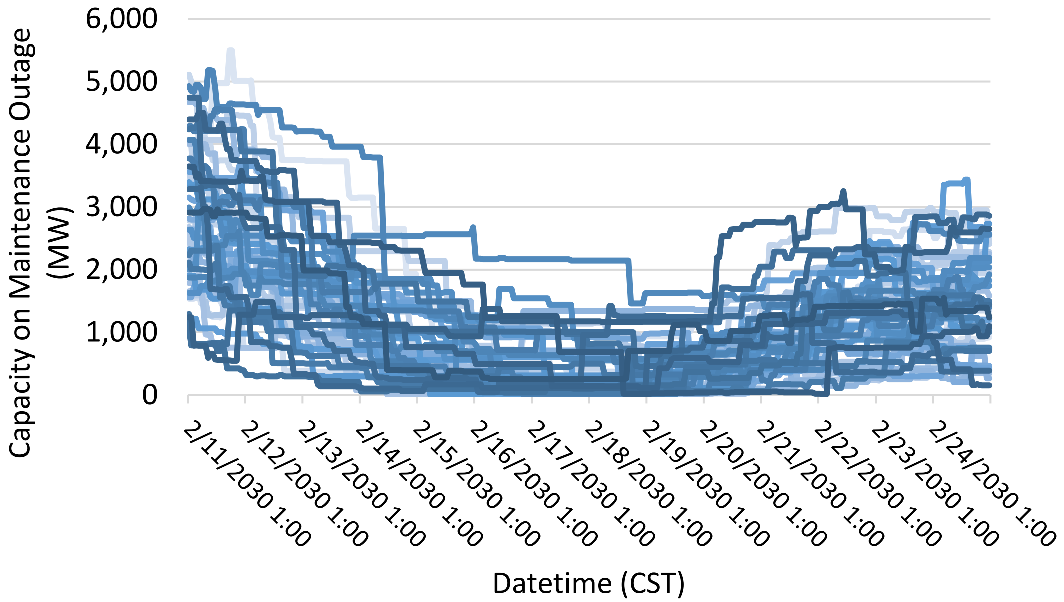


Source: Energy Systems Integration Group; data from NERC and PNNL.

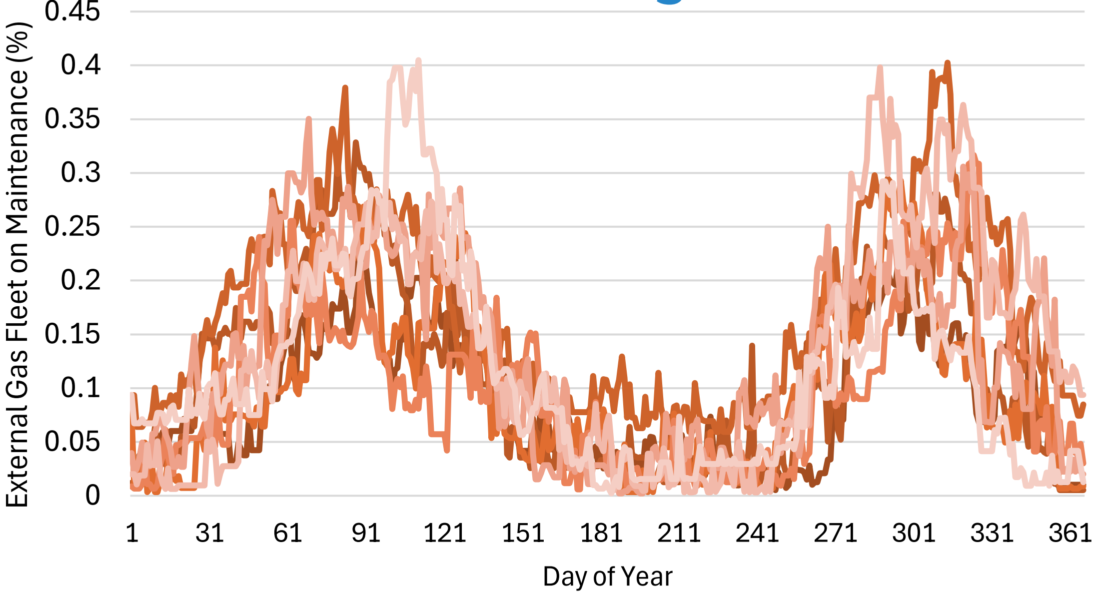
Thermal Maintenance

Unit Level (SPP) and Fleetwide (External)

SPP Model Scheduled Maintenance



Example Maintenance Outage Levels for an External Region



Method: Scheduled by unit across a year by PLEXOS. Optimized around low load periods. Multiple samples created with different profiles to reflect a range of maintenance based on NERC GADS Planned and Maintenance outage statistics by unit type.

Method: Historical maintenance patterns at a fleet level by fuel type for external regions. Randomly selected a yearly profile for each sample. Data have limited variability but are consistent with historical trends.

Source: Energy Systems Integration Group; maintenance data from NERC

Transfer Capability Levels

AC Interfaces and DC Intertie Outages

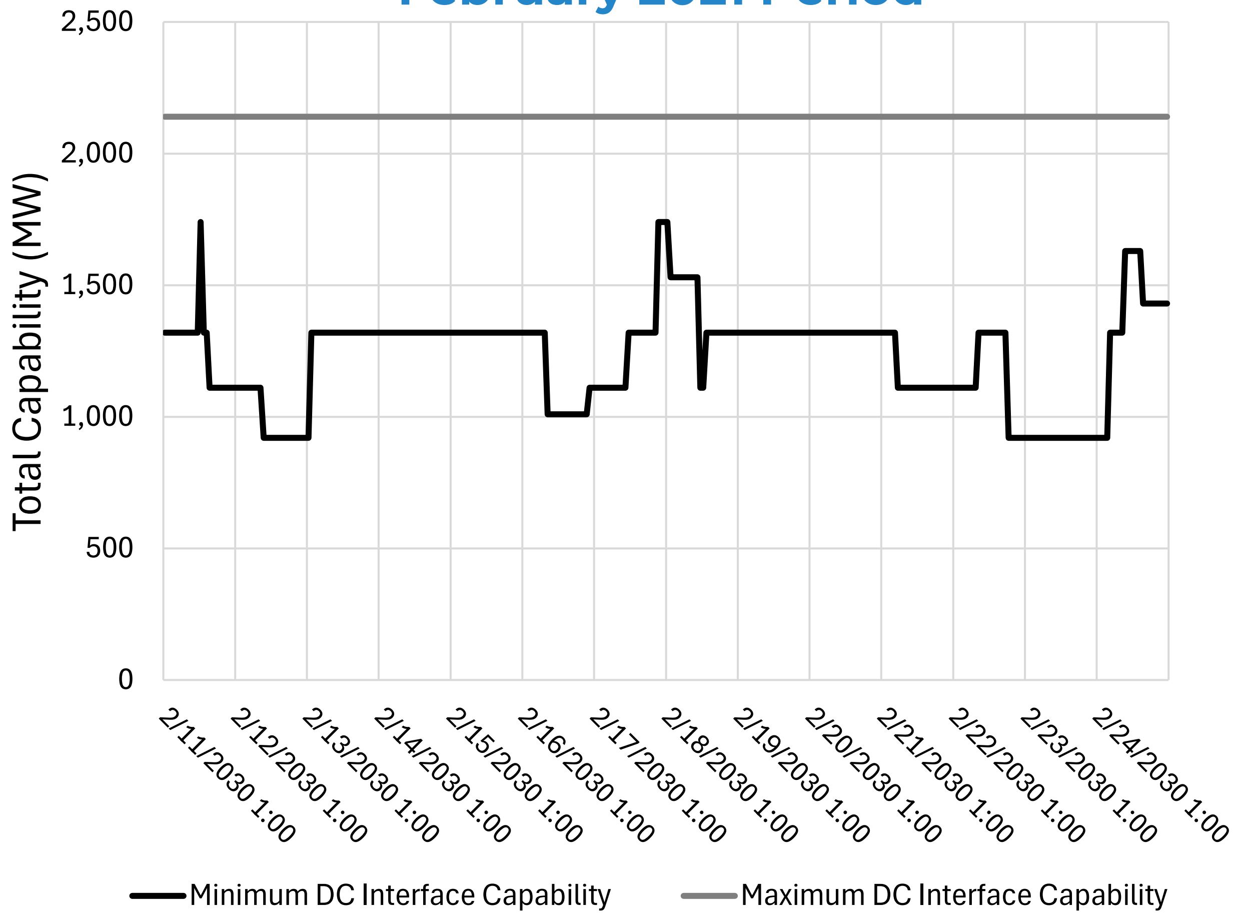
AC interfaces: Used summer and winter capabilities.

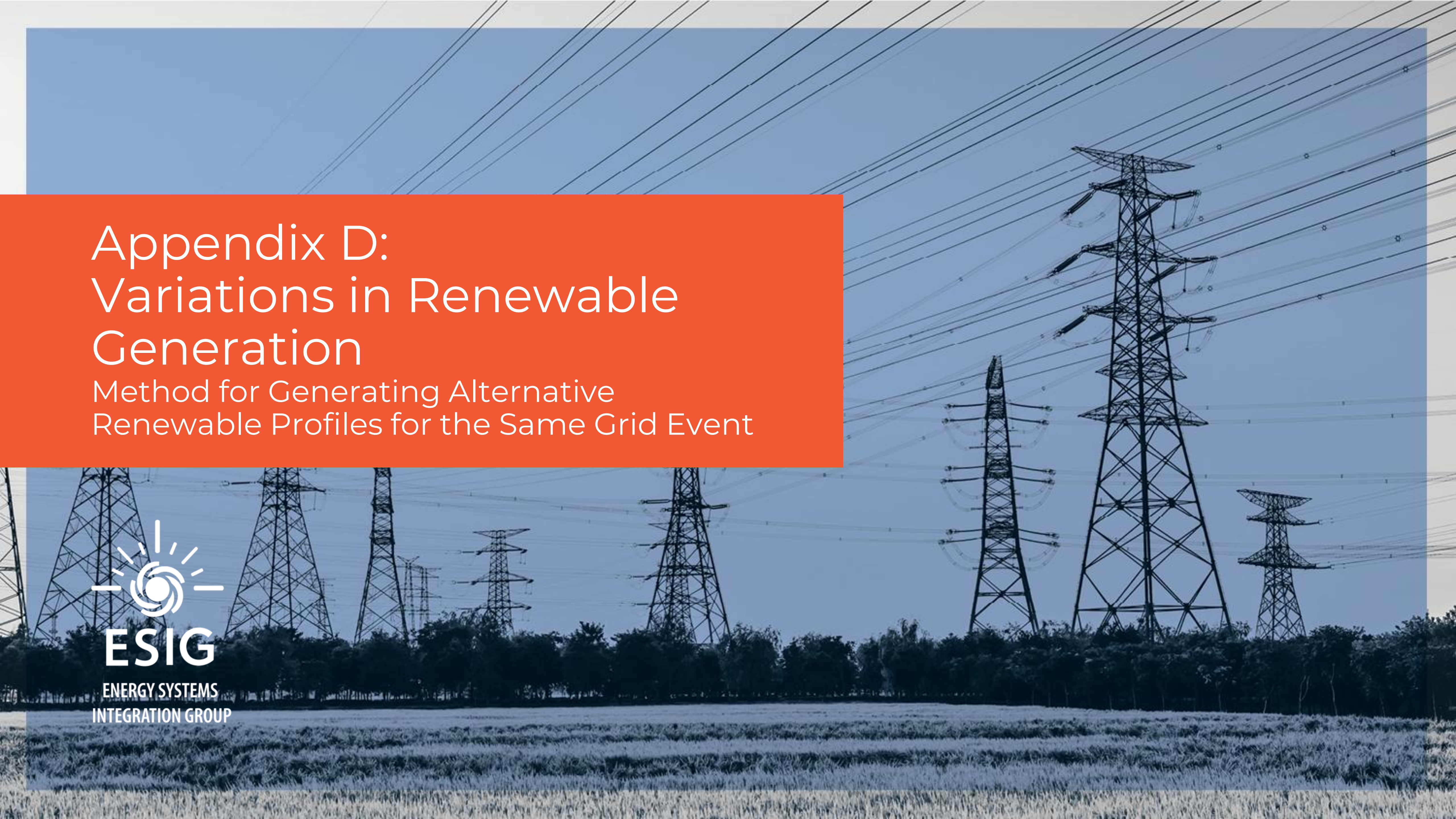
- More robust evaluation of transfer capability for varying grid conditions is needed in the industry.

DC interties: Modeled forced and maintenance outages for SPP and its neighbors in WECC and ERCOT.

- Data for forced and maintenance outage rates from MWTG DC Intertie Value Study

Total SPP DC Intertie Capability for February 2021 Period





Appendix D: Variations in Renewable Generation

Method for Generating Alternative Renewable Profiles for the Same Grid Event

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Renewable Generation Levels

Approach: Create new stress conditions driven by renewable generation by resampling historical weather year data to test different hourly renewable generation profiles for similar load days.

Step 1 - Identify what level of load occurs each day during the stress period and what renewable output was

Step 2 - For the same month, group days with similar load levels to sample from (e.g., load days within a 5 percentile of the target day's load percentile)

Step 3 - For each day in the stress period, randomly select a new day from the days of similar load levels

Result - Create new hourly renewable generation profiles by merging the daily resampled data at an hourly level. This method assumes that load levels are a reasonable proxy for weather conditions (temperature, wind speed, solar irradiance, etc.)

Wind Stress Test Example

8/1/2011 – 8/3/2011 heat event

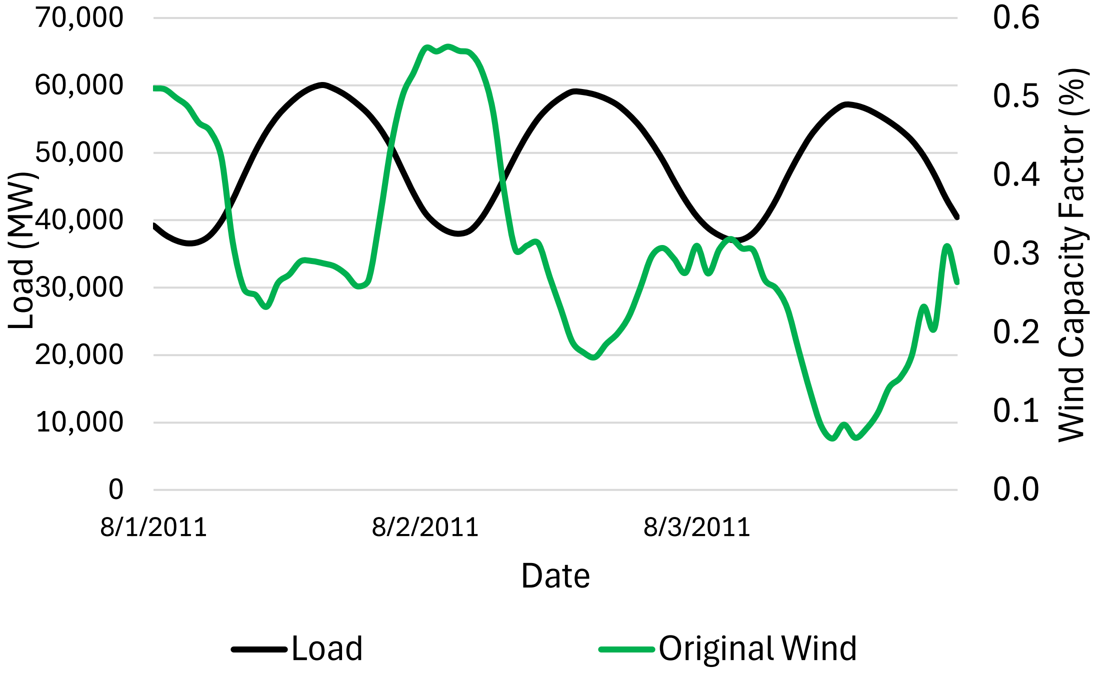
Step 1 Identify what level of load occurs each day during the stress period and what renewable output was like

Daily Load Conditions and Average Wind Output

Event Dates	Summer Load Day Percentile	Original Wind Daily CF (%)
8/1/2011	**99.6**	36%
8/2/2011	**1**	34%
8/3/2011	**97.3**	20%

Summer Load Day Percentile is based on 2007-2013 and 2019-2022 summer days only

Heat Event Example Historical Data



Source: Energy Systems Integration Group; data from SPP and PNNL.

Wind Stress Test Example

8/1/2011 – 8/3/2011 heat event

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Step 2 Identify a set of days with similar load levels to sample hourly wind data from (e.g., 8/2/2011 would look at summer load days above the 95th percentile)

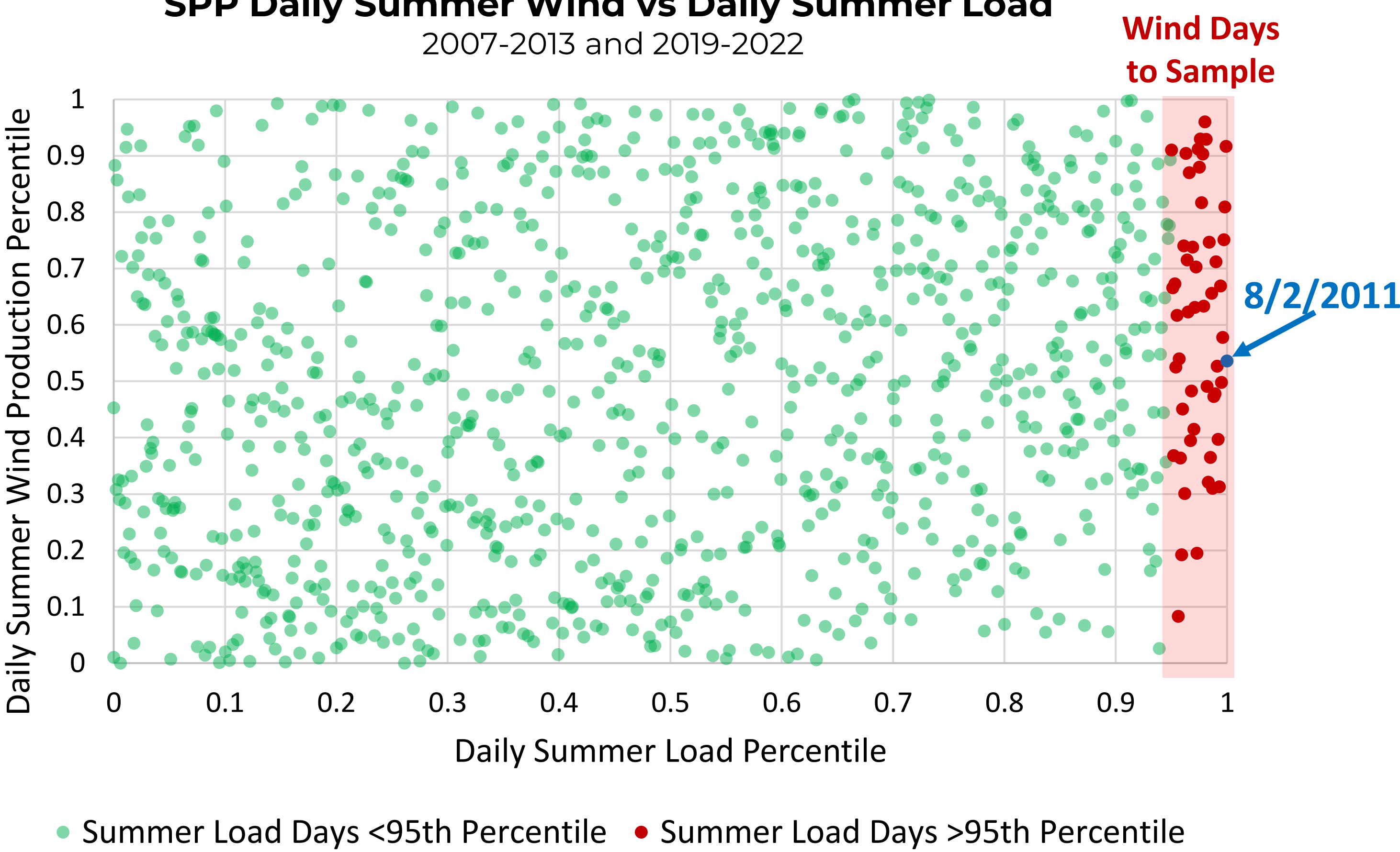
Daily Load Conditions and Average Wind Output

Event Dates	Summer Load Day Percentile	Original Wind Daily CF (%)
8/1/2011	**99.6**	36%
8/2/2011	**1**	34%
8/3/2011	**97.3**	20%

Summer Load Day Percentile is based on 2007-2013 and 2019-2022 summer days only

SPP Daily Summer Wind vs Daily Summer Load

2007-2013 and 2019-2022



Source: Energy Systems Integration Group; data from SPP and PNNL.

Creating Renewable Stress Conditions [Ryan, can you please phrase this more completely?]

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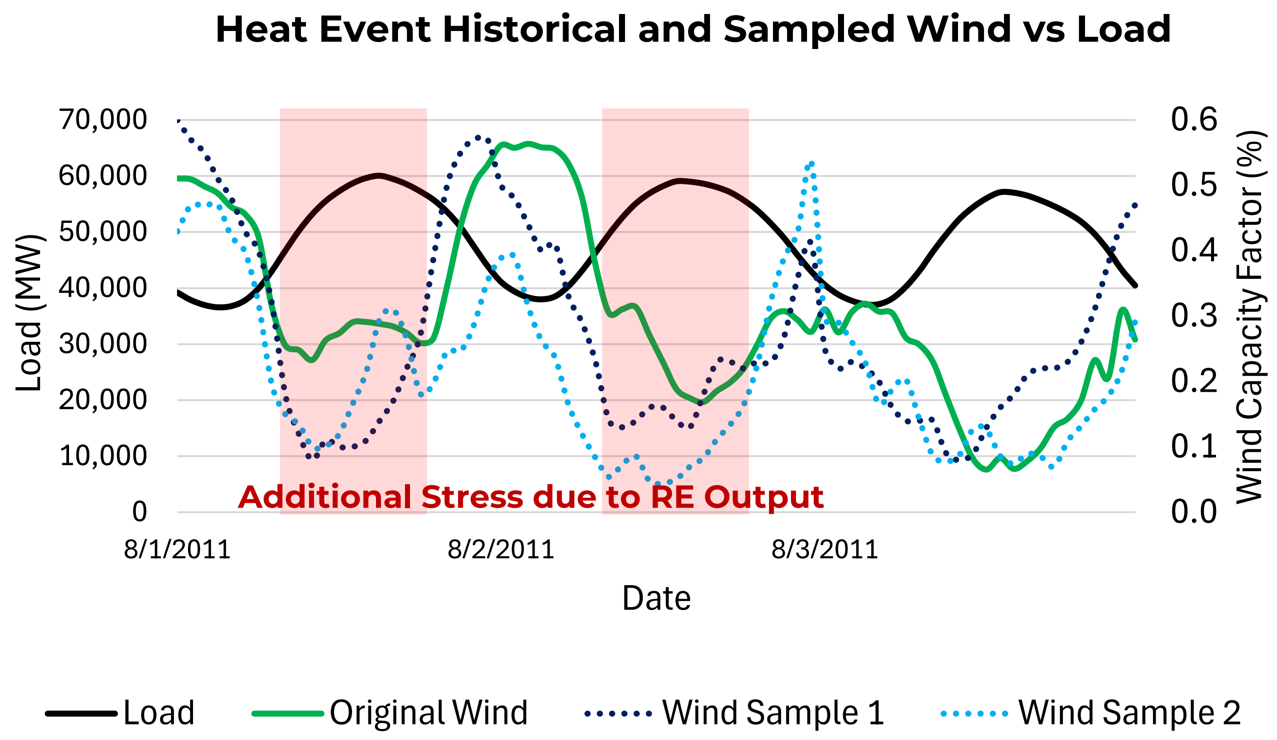
Step 3 Randomly select a set of load days to re-map to the original stress period dates

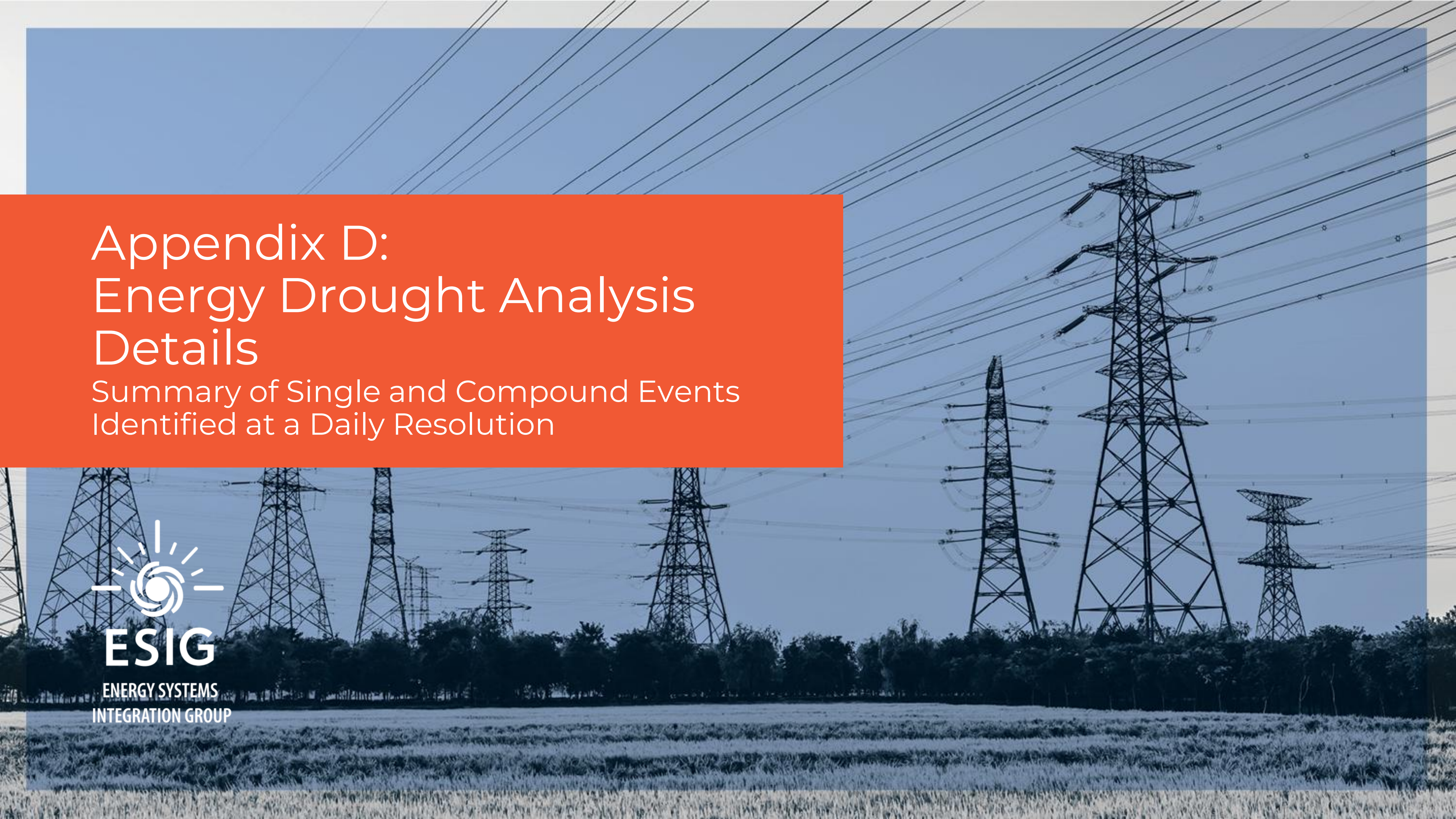


Daily Load Conditions and Average Wind Output by Sample

Event Dates	Summer Load Percentile	Original Wind Daily CF (%)	Sample 1 Daily CF (%)	Sample 2 Daily CF (%)
8/1/2011	99.6	36%	34%	27%
8/2/2011	1	34%	27%	20%
8/3/2011	97.3	20%	22%	16%

Result New hourly wind profiles for three days during a heat event with high summer load. Potential for additional risk during extreme heat on 8/1/2011 and 8/2/2011. Do this for 50 unique profiles.

Source: Energy Systems Integration Group; data from SPP and PNNL.



Appendix D: Energy Drought Analysis Details

Summary of Single and Compound Events Identified at a Daily Resolution

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Energy Drought Analysis Results

Single and Compound Risk Events Identified for SPP

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We used time series data for load, worst-case thermal availability, and wind/solar generation to identify periods of single factor risk (e.g., wind drought) and compound risks (e.g., wind drought + high load).

- Data were standardized across daily, weekly, and monthly time scales adapting the approach in Bracken et al., and we used the 10^{th} and 90^{th} percentiles as the threshold for an "event." Consecutive days share the same event ID to track consecutive periods of stress.
- Renewable generation and load are represented hourly for 1980-2022 and were provided by SPP. Thermal availability was based on randomly generating 50 daily outage profiles based on historical data correlated to temperature.

Summary of Energy Drought Analysis Events Using Daily Aggregation

Event Type	# of Events	Avg. Duration (days)	Max Duration (days)	# of Events > 5 days
Wind Drought	1160	1.4	8	5
Solar Drought	1044	1.5	21	11
Thermal Availability Risk	837	1.9	15	34
Wind + Solar Drought	119	1.1	3	0
High Net Load	852	1.8	18	30
Load + Wind + Solar	48	1.1	2	0
Load + Wind + Solar + Thermal	22	1.0	1	0

Source: Energy Systems Integration Group; data from SPP, NERC and PNNL.

Appendix E: Additional Weather Event Characterization

SPP Coldest and Hottest Three-Day Weather Event Rankings with Respect to FERC 1000 Regions

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Characterizing SPP Stress Events

Top Cold Events Based on Three-Day Periods

Multi-Day Cold Events

- Cold events tend to be wide-area relative to heat events, with similar conditions across many regions.
- Only events for 2007-2013 and 2019-2023 were considered to match national correlated datasets used in the study. Notable that four out of five top SPP events pre-2000 are not able to be evaluated with our consistent dataset.

Top 15 SPP Weather Years with Coldest 3-Day Temperature Periods

Year	Month	Northwest	CAISO	Southwest	ERCOT	SPP	MISO	SERC	FRCC	PJM	NYISO	ISONE
1982	1				13	5	7	4	8	6	7	6
1983	12	3			3	2	4	2	3	3		
1984	1	13			14	13	3	16		2	3	
1985	1				11	10	10	1	1	4		
1985	2	5	12	6	9	7	9					
1989	2	2	2			12			13			
1989	12				1	1	5	3	2	5		
1990	12	1	1	1		16						
1996	2	11			5	3	1	5		7	16	
1997	1				12	6	12	11	12	13		
2010	1				7	8			7			
2011	2			2	4	11	13					
2014	1					14	6	9		12		
2018	1				10	15		17	16	14	9	7
2021	2				2	4	14					
2022	12				8	9		6	11			

SPP 2023 LOLE Results - 2029

Weather Year	Percent Contribution to Winter Risk
1981	2%
1983	8%
1984	5%
1985	4%
1989	22%
1996	22%
2021	**37%**

Winter of 2021 (Winter Storm Uri) shows temperature stress and loss-of-load risk in SPP modeling and stands as a good candidate to model.

Source: Energy Systems Integration Group; data from SPP and PNNL.

Characterizing SPP Stress Events

Top Heat Events Based on Three-Day Periods

Multi-Day Heat Events

- Heat events tend to be more localized and affect fewer regions simultaneously.
- Recent events in 2011 and 2012 showed up as good candidates to included in our stress testing work.

Top 10 SPP Weather Years with Hottest Three-Day Temperature Periods

Year	Month	Northwest	CAISO	Southwest	ERCOT	SPP	MISO	SERC	FRCC	PJM	NYISO	ISONE
1980	7				9	10	8	8		13	14	18
1980	8					11						
2003	8				6	7						
2005	7			8		13						
2006	7	2	3			3	7					
2006	8					12	3			5	4	4
2011	7					8	11	14		6	2	3
2011	8				4	2		5				
2011	9					6						
2012	6				7	5	10	3		10		
2012	7					4	2	1		1		
2012	8					1	6					
2018	7		9		3	9					15	

SPP 2023 LOLE Results - 2029

Weather Year	Percent Contribution to Summer Risk
1980	21%
1986	3%
1999	3%
2001	3%
2011	41%
2012	24%
2022	3%

Summer of 2011 shows up as stressful temperature and loss-of-load risk in SPP resource adequacy modeling.

Source: Energy Systems Integration Group; data from SPP and PNNL.