EPRI

Resource Adequacy For a Decarbonized Future

2023 TECHNICAL REPORT

Resource Adequacy Gap Assessment

EPRI Resource Adequacy Assessment Framework

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ABSTRACT

Resource adequacy studies have changed significantly over the past several years to account for significant resource mix changes, changing load profiles, and decarbonization planning. EPRI's Resource Adequacy for a Decarbonized Future project, as well as other industry reports, provide guidance on how metrics, data needs, and best practices should evolve to evaluate resource adequacy of the future power system. While resource adequacy studies across the industry are continuously improving, there are remaining gaps and limitations that must be evaluated further.

To identify and characterize these gaps, EPRI reviewed industry studies to consolidate lessons learned from the project case studies and reflect on discussions with industry stakeholders. Based on the comprehensive review and stakeholder discussions, the project team identified seven high priority gaps that warrant further discussion or further research and development. This report addresses the gaps based on how well recognized they are, whether there are methods available to address the gap, and their impact on resource adequacy studies.

Keywords

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EXECUTIVE SUMMARY

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Primary Audience: Electric company staff and regulatory analysts engaged in resource adequacy (RA) studies

Secondary Audience: Electric company and regulatory analysts, managers, and executives engaged in resource adequacy (RA) studies

KEY RESEARCH QUESTION

This report, part of EPRI's Resource Adequacy for a Decarbonized Future Initiative, is intended to identify major gaps in resource adequacy (RA) assessment, based on the work carried out throughout the initiative. The gaps are assessed based on how well recognized they are, whether there are methods available to address the gap, and their impact on resource adequacy studies.

RESEARCH OVERVIEW

Starting with input from advisors and industry review, as well as the case studies being carried out in the Resource Adequacy for a Decarbonized Future Initiative, several gaps were identified. These were then prioritized and assessed based on a set of pre-determined categories. A score is developed for each based on recognition, availability of methods, and the impact on results. In addition to the score, examples are given from case studies to show how the gap could be addressed, and recommendations are made for how the gaps may be filled in the future.

KEY FINDINGS

- Resource adequacy continues to evolve and gaps assessed here are in various stages of being addressed in the industry. Each gap is assessed in a section of the report, across a variety of different categories.
- Some gaps, such as the need for new metrics, assessment of interregional coordination, and the incorporation of consistent and correlated datasets are well recognized in the industry, and are a key focus of several efforts, including this project. Other gaps, such as those based on outlying events, winter risk, and improved load forecasting, are less recognized but this work shows they can be relevant gaps that need to be addressed.
- Methods exist, mostly in the R&D space, for several of the gaps identified, including metrics, integration of RA and resource planning, and the use of appropriate datasets. Others, such

as the identification of high-risk events and load forecasting, are less well developed and methods are needed to address the gap.

- The impact of the different gaps will vary, with some having a major impact on the results from RA studies – this includes the metrics used, capturing winter risk, and improved load forecasting. Other gaps may be less impactful, though the specific impacts vary by region.
- Project advisor surveys identified the most important gaps as the need for improved and more detailed resource adequacy metrics, improved load forecasting considering weather impacts and electrification, and capturing winter risk associated with fuel supply and weather-dependent outages.
- Other gaps also exist, as described in the conclusions section.

WHY THIS MATTERS

This report allows practitioners to understand the current major gaps in RA assessment, how close they are to being solved, why they may be more or less important, and what methods may be useful in the future to address the gaps. This can help identify further work as well as ensure that the industry understands the key gaps.

HOW TO APPLY RESULTS

End users can implement the results of this report by working with their tool providers, researchers such as EPRI and others, and their counterparts in other organizations to both raise awareness of and address these gaps. Together with the other findings from this EPRI Initiative, they can assess where their own organization stands in terms of importance of the gaps identified and how they can address them over the coming years.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- This report can be used together with other reports from the Initiative, found at www.epri.com/resource-adequacy, to improve RA assessment. Deliverables from that initiative can form the basis of improved RA assessment methods and processes.
- EPRI continues to engage in this area through several ongoing efforts, including a regular RA forum and ongoing Annual Research Portfolio work in the Integration of Renewables and DER program (Program 173). Gridops.epri.com/adequacy also contains relevant information.

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PROGRAM: Bulk System Integration of Renewables and Distributed Energy Resources (DER), P173

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1 INTRODUCTION

Resource adequacy studies have changed significantly over the past several years to account for significant resource mix changes, changing load profiles, and decarbonization planning. EPRI's Resource Adequacy for a Decarbonized Future initiative, as well as other industry efforts, provide guidance on how metrics, data needs, and best practices should evolve to evaluate resource adequacy of the future power system. While resource adequacy studies across the industry are continuously improving, there are remaining gaps and limitations that must be evaluated further.

To identify and characterize these gaps, EPRI reviewed industry studies to consolidate lessons learned from the project case studies and reflect on discussions with industry stakeholders. Based on the comprehensive review and stakeholder discussions, the project team identified seven high priority gaps that warrant further discussion or further research and development (not listed in order of priority):

1. Need for improved and more detailed resource adequacy metrics.
2. Holistic integration of resource adequacy with other planning activities.
3. Improved load forecasting considering weather impacts, electrification, and climate change.
4. Identification and analysis of outlier, high-impact, low-probability, events.
5. Capturing winter risk associated with fuel supply and weather-dependent outages.
6. Interregional coordination.
7. Incorporating consistent and correlated weather datasets.

Gap Severity Index

To evaluate these gaps, the project team developed a rubric that ranks the severity of the gap at three levels: low, moderate, and high. This ranking is done across three measures:

1. recognition,
2. known solutions, and
3. impact on resource adequacy study results.

Each measure is rated on a scale from 1 to 3, with 1 being the least severe and 3 being the highest severity. The total score for each gap therefore ranges from 3 to 9.

The **Recognition** measure qualitatively assesses the extent to which the gap is recognized in the industry, with more severe gaps being ones that are rarely acknowledged or evaluated by industry practitioners and regulators. A score of 1 is given if the gap is widely recognized and often addressed in practice by both research and grid planners. A score of 2 is given if it has been identified by practitioners (but not necessarily analyzed) but is being consistently evaluated in the research community. A score of 3 is assigned if the gap is often omitted or ignored by practitioners and is only starting to be assessed by the research community.

The **Known Solutions** measure assesses whether there are known, pragmatic solutions or methods available to practitioners to address the identified gap. A score of 1 is given if there are known solutions and methods for addressing the gap, but inconsistent application – without an agreed upon or commonly accepted standard - of these methods across the industry. In addition, there is a need for standardization and adoption of methods to address the gap across a larger set of practitioners, regulators, and industry stakeholders. A score of 1 also means modeling tools have standard outputs or features available to address the gap without custom analysis. A score of 2 is assigned if methods and solutions for addressing the gap are still being developed and data is limited. There are also inconsistent or disparate applications across the industry and tools require manual adjustment. Finally, a score of 3 is assigned if there is no clear solution or method available to practitioners, data is unavailable, and tools do not provide options to address the gap without significant manual adjustment or pre/post-processing.

The **Impact** measure assesses the impact of the gap on resource adequacy study results. A score of 1 is given if the gap does not materially change results of a study, but simply limits the interpretation of analysis results. A score of 2 is assigned if the selected approach may influence results depending on power system specifics, the exact portfolio under analysis, and data used in the study. Lastly, a score of 3 is assigned if resolving the gap will significantly change study results and materially change the assessment findings. A summary of the gap severity rubric is outlined in Table 1.

Table 1. Gap Severity Rubric

	[A] Recognition	[B] Known Solutions	[C] Impact
[1] Low	Gap is widely recognized by practitioners, and it is often addressed by practitioners.	There are known solutions & methods, but inconsistent application across the industry. Need for standardization and adoption. Modeling tools include standard features to address the gap.	Does not materially change results of a study but could limit interpretation of results.
[2] Moderate	Gap has been identified by practitioners and is being consistently evaluated in the research community.	Methods and solutions are still being developed and data is limited. Inconsistent or disparate application across the industry. Tools require manual adjustment.	Selected approach may influence results, but depends on system, portfolio, and data.
[3] Severe	Gap is often omitted or ignored by practitioners but starting to be assessed by the research community.	No clear solution or method is available to the practitioner, and data is largely unavailable. Tools do not provide options to address gap without significant manual adjustment or pre/post-processing.	Whether or not gap is addressed will significantly change study results.

Based on the rubric, each gap can be categorized as low, moderate, or severe. A gap with a total score of 4 or 5 is categorized as low, a gap with a total score of 6 or 7 is categorized as moderate, and a gap with a total score of 8 or 9 is categorized as severe.

A gap that falls under the **Low Severity** category is widely recognized, and there are known solutions and methods for addressing the gap. However, addressing the gap is inconsistent across the industry, and there is a need for standardization and adoption. This gap has a low impact on resource adequacy study results.

A gap that falls under the **Moderate Severity** category is also widely recognized, but solutions and methods are still being developed to address the gap. Practitioners often address the gap in inconsistent or limited ways across the industry, and there is disparate implementation. Software tools do not have a standard or automated approach for handling the gap, and manual input from practitioners is required. The selected approach will influence resource adequacy study results.

A gap that falls under the **Severe** category is not widely recognized, and there is no clear solution or method available to practitioners. Tools do not provide options to address the gap without significant manual adjustment or pre/post-processing. The gap has the potential to significantly change resource adequacy study results.

Each gap in this report is evaluated across the nine-block rubric and provided at the start of each gap section. By assessing recognition, known solutions, and impact on resource adequacy study results, practitioners can prioritize addressing gaps that have a severe impact on study results. This rubric can also aid in standardizing and automating resource adequacy studies, ultimately resulting in more accurate understanding of resource adequacy risk.

Caveats: The intent of the rubric is to identify gaps as they were at the end of this project – as would be expected, those will evolve and in some cases may evolve quickly, when further attention is paid (for example, interregional planning could be addressed with action by regulators to put focus on this area). Additionally, the specific score for a given region may vary from the average scores proposed here – practitioners are encouraged to use the rubric here as an example, but apply it to their own situation and see where their main gaps are. The scores provided here give a general impression of the state of RA assessment based on the findings of the Initiative.

2 GAP 1. NEED FOR IMPROVED AND MORE DETAILED RESOURCE ADEQUACY METRICS

Gap Description

Resource adequacy (RA) metrics, like loss of load expectation (LOLE), are critical to ensure that the electric power system has enough resources to meet load, across a range of uncertainty. However, resource adequacy studies typically only report a single result: an expected value. These metrics, including LOLE, LOLH, LOLP, and EUE, summarize loss of load events across hundreds or thousands of samples, but only provide insights into the *expected* (or average) outcome, which is a probabilistic construct. Solely reporting an average metric provides limited insight into system risk and does not differentiate individual events by size, frequency, and duration.

This gap highlights that new metrics may not be required, but there is a need to move beyond single point expected values and to include metrics that can better characterize and differentiate individual events, capture tail risks, and better summarize outlier loss of load events. Probabilistic approaches are shown to be very beneficial to support planning decision making, but additional insight is needed into how society may experience an outage event and to properly evaluate and size mitigations. Moreover, these metrics should provide information on whether the system is capacity-limited or energy-deficient for individual events. This additional information can help planners better link resource adequacy metrics with appropriate mitigations, investments, and decisions.

Importance

The shortcomings of single-point expected values are particularly problematic in high renewable, energy-limited systems where LOLE and EUE may diverge and when the distribution of possible event outcomes becomes long-tailed. Multiple metrics and/or criteria may be necessary to understand system limitations, especially as the system transitions to higher levels of variable renewables and storage, where energy limitations become more important. In addition, this is important because mitigations and investments available to address resource adequacy concerns are no longer one-size-fits-all.

Options available to improve reliability include non-capacity measures such as:

1. Improved resource availability through reduced forced outages, weatherization and diligent maintenance scheduling,
2. Measures to improve upstream fuel supply chains during extreme events,
3. Increased alignment of retail tariffs to system stress conditions,
4. Proactive use of coupled energy systems to reduce stress in the power system (e.g. district heating management)

as well as traditional investment measure such as:

1. additional thermal resources (e.g. natural gas, geothermal),
2. additional variable resources (e.g. wind and solar),
3. additional energy limited resources (e.g. storage and load flexibility)
4. additional transmission, and
5. additional energy storage at additional resources (e.g. additional battery packs)

Knowing which resources best address resource adequacy risk requires better information on the size, frequency, duration, and cause of events.

Moreover, events have varying impacts on society and ratepayers depending on their magnitude and duration. Thus, capturing catastrophic or prolonged events is essential. For example, a prolonged loss of load event that occurs due to a cold weather event may have disproportionate impact on ratepayers – including loss of life – relative to a short event spanning only a couple hours on a summer evening. These two events require very different mitigations, investments, and contingency planning, but would not be separately identified if only single point metrics are reported.

This has important implications for establishing an appropriate reliability criterion (or multiple criteria). While a suite of reliability metrics and distributions can effectively summarize a resource adequacy study, it is ultimately the reliability criterion (i.e., 1-day-in-10-year LOLE) that determines how much capacity is needed for reliability. This gap highlights not only a need to develop improved metrics, but also to potentially revisit the underlying reliability criterion altogether.

Case Study Example

One illustration of the metrics gap is observed in the case study of the SPP region. Three renewable generation portfolios were assessed; nominally representing a relatively low, medium and high variable renewable and storage portfolios. Each resource portfolio was brought to the 0.1 days/year LOLE, meeting the requirement for adequacy in this system. On this dimension, each portfolio produces an acceptable outcome. However, when additional reliability metrics are assessed, a wider range of outcomes are observed as shown in Figure 1.

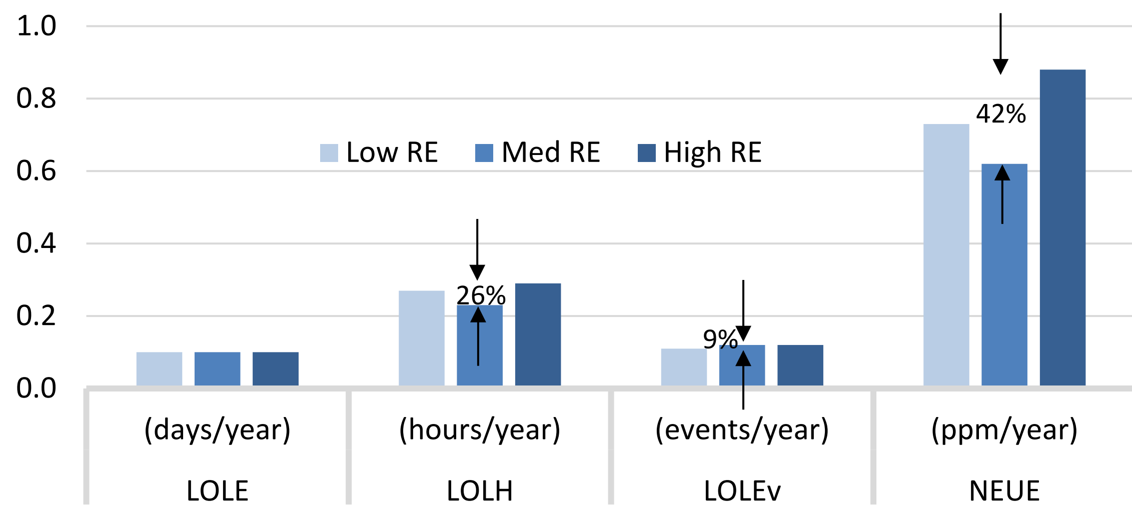
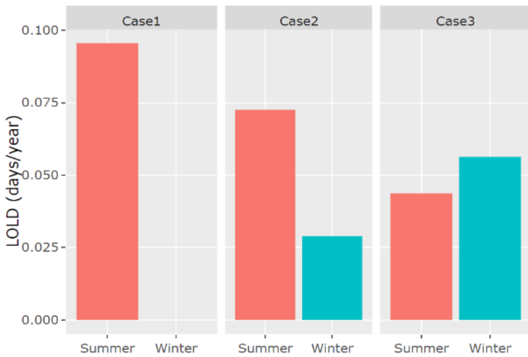
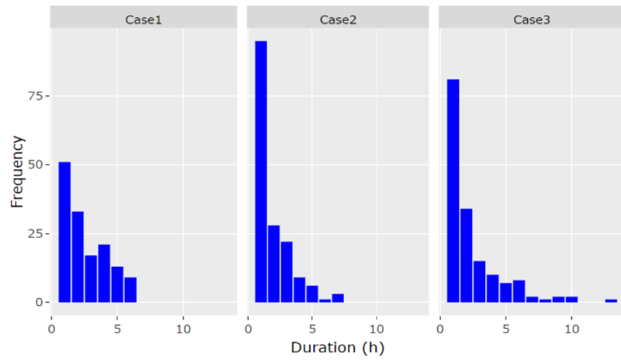


Figure 1. Resource adequacy metrics for low, medium and high VRE cases in the SPP case study [1]

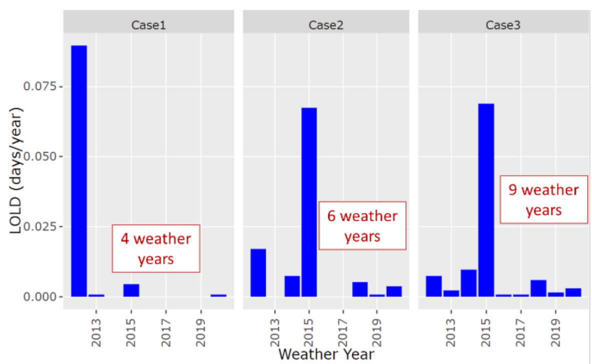
Similar to other case studies, the SPP case study demonstrated how the normalized expected unserved energy (NEUE) metric varies by 42% while loss of load hours varies by 26%. The variance implies different experiences of reliability by customers under each of those conditions that would traditionally have been interpreted as equivalent. Additional diagnostic reporting is also valuable at the event level to characterize shifts in the timing and nature of individual events (Figure 2). Timing and profile are important aspects in determining the impact of such events and the likely impact of mitigation measures. Diagnostics provide insight into evolving seasonality, changing duration events and the underlying impact of specific weather years on a given resource mix. Additional metrics focused on extreme events, event classification and reporting related to regional extent were explored in several other case studies.



Summer and winter contributions to loss of load days (LOLD) by case in the SPP study (low (1), medium (2) and high (3) VRE).



Relative frequency distribution of loss of load event duration by case in the SPP study.



Contribution of individual weather years to aggregate LOLD in the SPP case studies.

Figure 2. Additional diagnostic reporting of metrics by season, relative frequency plots of event duration and underlying contributions from weather years, based on the SPP case study [1].

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
6 Moderate	1	1	1
	2	2	2
	3	3	3

Recommendations

To address this gap, it is recommended to first report multiple RA metrics, including LOLE, LOLH, LOLEv, EUE, and NEUE, in a consistent manner. These metrics are described in detail in the related [2]. Providing multiple metrics can help evaluate changes in adequacy that may not be captured using a single metric. For example, a power system transitioning to higher levels of variable renewables and energy storage may maintain a constant 0.1 days/year LOLE, but the EUE may increase or the distribution of LOLP may be wider.

Second, practitioners should characterize the distribution of individual shortfall events, rather than only report expected values. To do this, results can include histograms or other charts that summarize the size, frequency, duration, and timing of events. Other examples may include heatmaps of event duration (hours), maximum shortfall (MW), or magnitude of energy loss (MWh). To do this, modeling tools, at a minimum, must be able to report individual event characteristics. To go further, tools and analyses can start to standardize the above data, metrics, and visuals.

In addition to characterizing individual shortfall events, there may be benefit in developing metrics to specifically report and quantify tail probability events. This can be similar to the "value at risk (VaR)" metric used by NWPCC to quantify the value of a shortfall event at a certain percentile. For example $VaR_{97.5}$ would report an LOLE metric not at the average, but at the 97.5th percentile of observations [3].

Finally, regulators are ultimately the ones that must determine the appropriate level of risk (to set the resource adequacy criteria) and implicit tradeoffs with economic efficiency. This is ultimately a judgement call but may benefit from improved context from new metrics. Additional education and outreach on resource adequacy metrics can help guide new investment decisions tailored to resource adequacy needs.

3 GAP 2. HOLISTIC INTEGRATION OF RESOURCE ADEQUACY WITH OTHER PLANNING ACTIVITIES

Gap Description

Resource adequacy analysis is only one facet of comprehensive power system planning. Today, however, resource adequacy analysis has limited connections with other planning processes, including capacity expansion planning, transmission planning, fuel supply analysis, etc. As a result, resource adequacy analysis often lacks integration within a holistic approach. The lack of linkage can result in inconsistent assumptions, inadequate system planning, and over- or under-investment in resources, leading to economic inefficiency or portfolios with lower levels of reliability.

One of the main challenges in RA planning is the lack of consistent linking between capacity expansion planning and resource adequacy studies. For example, capacity expansion modeling is typically “downstream” of a resource adequacy study. RA study results, such as planning reserve margin (PRM) and effective load-carrying capability (ELCC), are developed first, and used as inputs to the modeling process. However, as alternative portfolios are selected in the capacity expansion modeling, there is no guarantee that PRM and ELCC values remain the same or guarantee a consistent reliability output due to the portfolio-dependent nature of each metric. If the selected portfolios from the capacity expansion model deviate significantly from the ones evaluated in the resource adequacy study, the results could yield either decreased economic efficiency of decreased reliability.

Even if capacity expansion planning and resource adequacy studies are properly aligned, portfolios can still be inadequate if insufficient fuel supply constrains the availability of generators. Therefore, it is crucial to understand the dependency on other sectors (e.g., the gas network), to mitigate outages due to a lack of fuel.

Furthermore, RA studies often oversimplify transmission topology and do not consider different transmission outage conditions, leading to overstated transfer capability during risk periods. Due to the simplification of the transmission topology in resource adequacy studies, there needs to be a tight coupling between transmission and resource adequacy modeling efforts.

Finally, different tools are used across planning disciplines and within individual utilities for RA analysis, long-term capacity expansion planning, production cost simulations, and transmission analysis, with no consistent method for linking these tools or planning processes.

Importance

The holistic integration of resource adequacy planning with other planning activities is crucial for ensuring a reliable, operable, and cost-effective power system. Siloed planning practices can have serious implications on both the economic efficiency and reliability of the power system.

The most critical integration measure is to address resource accreditation within investment planning and capacity markets. Inaccurate PRM and ELCC values resulting from a lack of linkage between capacity expansion planning and resource adequacy studies can lead to either over-investment or under-investment in resources for reliability. The former results in an increasingly uneconomic system while the latter results in an increasingly unreliable one.

Furthermore, if transmission limitations are not sufficiently modeled in RA studies, planners may be overstating transfer capability during risk periods. While it may not be feasible for resource adequacy studies to accurately reflect transmission congestion (due to both thermal, voltage, and security constraints) at the nodal level, it is important to reflect major limits on transferring power across the system. Omission of transmission constraints could either miss resource adequacy risk that could occur in actual operations (reliability risk), or mis-quantify a resource's capacity accreditation due to its location.

Another important aspect of linking resource adequacy analysis in a broader planning framework is for fuel supply analysis. Ensuring that the underlying fuel supply and pipeline network restrictions are accurately reflected in resource adequacy models is critical. While a single model may be feasible, it will likely require tightly coupled fuel supply and resource adequacy modeling to ensure that natural gas and other fuel-supply constrained resources are accurately reflected. For instance, a gas combustion turbine might be a reasonable choice as peaking capacity, but only if this generator can also be called upon in times of need. Demand for gas in the power sector often peaks simultaneously with gas demand for heating purposes in winter peaking system, exacerbating fuel constraint issues.

Case Study Example

An exogenous analysis (conducted outside of a resource adequacy tool) was performed as part of the RA initiative to link fuel supply planning and resource adequacy. The general idea of this analysis is to provide a tool to screen for a potential portfolio ex-ante for potential shortages related to fuel insufficiency.

For this purpose, a spreadsheet tool was developed that calculates loss of load hours per year and unserved energy for a weather scenario and a user-defined portfolio. A screen shot of this tool is provided in Figure 3 and Figure 4, corresponding to the user inputs and selections, and outputs, respectively.

The user selects a weather scenario, defines average daily gas supply and defines the portfolio (non-gas generators, storages, and gas generators). Gas supply is simulated through daily firm and non-firm contracts, with non-firm gas availability subject to ambient temperatures.

Gas generators are parametrized by their capacity, heat rate and optional dual fuel back up capability. The tool leverages generator capacity with the following load serving priority: non-gas generators, gas generators (starting with minimum heat-rate generator and subject to gas availability), storage and dual-fuel back capacity. The tool is not an economic dispatch model, but rather uses a simplified heuristic methodology (without ramping and unit commitment constraints), subtracting generator capacity from load.

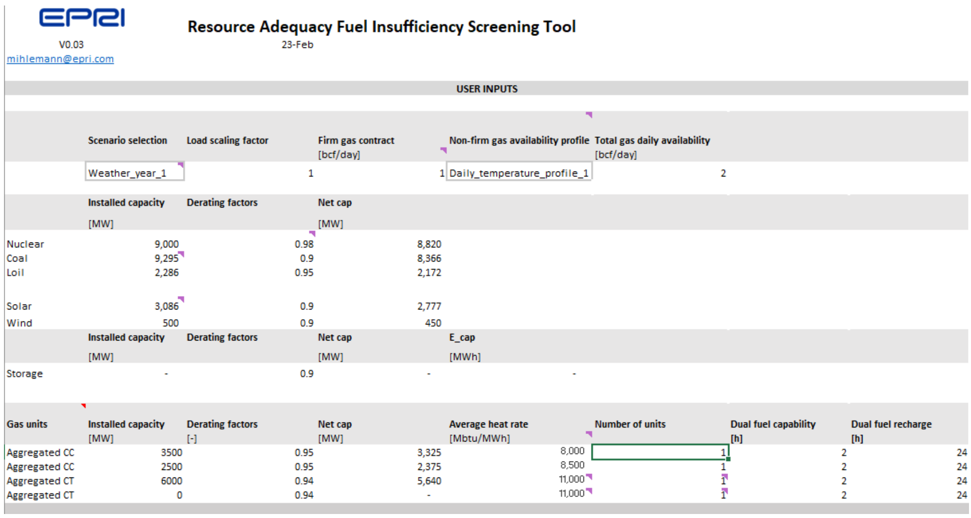


Figure 3. Input fuel insufficiency screening tool [4]

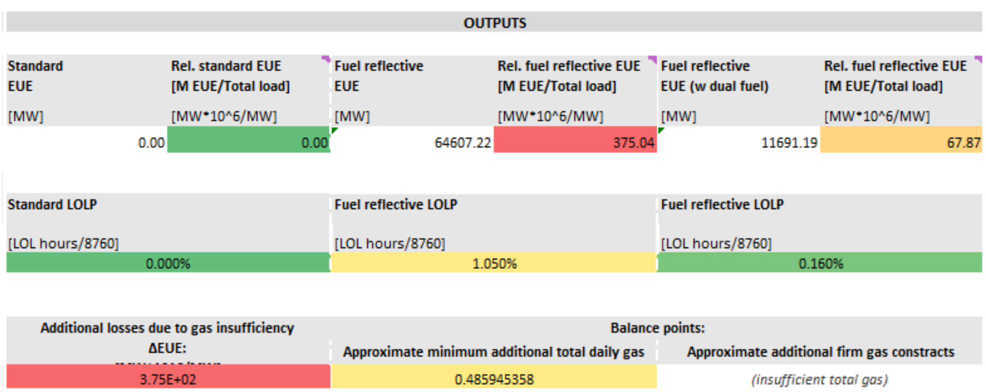


Figure 4. Output fuel insufficiency screening tool [4]

As illustrated in in Figure 4, the tool identifies general shortages (i.e., insufficient capacity regardless of fuel availability), and shortage due to insufficient gas supply with and without considering dual fuel capability. Further, the tool provides a gas balance point, i.e., how much gas would be minimally required to avoid fuel shortage, and the required number of firm contracts.

This type of information allows planners to link resource adequacy analysis with other parts of system planning, including both capacity expansion planning and fuel supply planning. Properly evaluating not only typical operating profiles, but also resource adequacy requirements, is necessary for properly sizing gas offtake agreements, dual fuel capability, and other pipeline considerations. The tool is intended to identify whether there is a need for a more detailed, integrated gas-electric coordination study.

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
6 Moderate	1	1	1
	2	2	2
	3	3	3

Recommendations

To fill this gap, tools used for different planning processes can be consolidated. Rather than having a separate process for transmission, capacity expansion, and resource adequacy modeling, tools can be improved to allow for multiple use cases and workflows that enable integrated assessments to occur. This can be done by bringing in multiple planning processes into a single tool, or through programmatic linking of inputs and outputs between tools.

In addition, resource adequacy tools could incorporate automated resource accreditation and PRM calculations to streamline the process of these calculations. The automated calculations would allow these calculations to be run more often and efficiently, yielding a tighter link between capacity expansion planning and resource adequacy studies.

It is recommended to always backcheck current and future portfolios with RA analysis to determine if the portfolios meet the desired reliability criteria. To do this, planners should develop a clear methodology for running capacity expansion and RA models in sequence with the outputs of one model used as inputs for the other. Linking capacity expansion and resource adequacy studies in this manner would allow for round-trip analysis between the two tools – where the outputs of a capacity expansion portfolio are automatically evaluated in a resource adequacy study.

In summary, better linking between RA analysis and other power system planning activities can help ensure the selection of the most cost-effective resource buildout to ensure an adequate system. Consistent linking between tools and assumptions, as well as detailed modeling of transmission topology, can lead to accurate evaluations of portfolios and reliability criteria.

4 GAP 3. IMPROVED LOAD FORECASTING CONSIDERING WEATHER IMPACTS, ELECTRIFICATION, AND CLIMATE CHANGE

Description

Appropriately capturing the impact of weather on demand is critical for ensuring the reliability of the electricity system. While this has always been an integral part of resource adequacy studies, electric demand is becoming increasingly weather-dependent due to electrification and climate change. Current resource adequacy studies typically do not use explicitly weather-dependent load profiles, and even fewer consider future weather-dependent electrification profiles of space heating, increased industrial process electrification, and electric vehicles (EVs). Furthermore, the relationship between space heating and EV electrification and electric demand is not well understood especially during outlier events like extreme cold snaps and heat waves, storms, and other anomalous events. This lack of insight hampers our ability to accurately forecast demand during extreme weather events and to incorporate the effects of electrification into load forecasting.

Load forecasts that do not consider climate trends also pose a challenge, as climate change is expected to increase the likelihood, severity, and timing of extreme weather events. Typically, current load forecasts do not adequately capture future climate impacts.

Therefore, improving load forecasts of extreme weather events and electrification requires better incorporation of weather-load relationships. This can be achieved with the development of multiple weather years of load data that is correlated with wind and solar availability, improved models for extreme event demand and other weather-driven inputs like fuel supply and weather-dependent outages.

Importance

Electric power demand has always been a function of the weather, but the extent of the correlation is intensifying due to increased electrification of end use technologies that are influenced both directly and indirectly by weather, and by climate change. Electric space heating is already common in the Southern U.S. and is expected to increase significantly in northern regions to reduce natural gas heating and associated emissions. Furthermore, electric vehicle demand is affected by the weather, particularly in cold periods when vehicles are less efficient.

Increased EV demand and space heating will lead to higher demand in winter periods and greater system winter reliability risk. Higher winter demand exacerbates the already increased reliability risk due to natural gas disruptions and multi-day periods of low wind and solar availability, both of which occur more often in the winter. Some winter natural gas demand may be offset by those electrification activities. Inclusion of weather and temperature dependent load profiles based on the same weather-year data as the solar and wind profiles within resource adequacy studies is critical to ensuring reliability risk is properly evaluated.

Observations from Winter Storm Elliott that occurred across the US eastern interconnection in February 2023 provided an example of the impact of severe weather on operational demand forecast error, which in turn influences fuel purchases, flexibility requirements and the performance of energy limited resources. These secondary effects have a direct implication for resource adequacy studies and can reasonably be expected to persist into the future, despite improving load forecasting. Consideration may be needed within the resource adequacy construct to anticipate for enhanced energy and flexibility needs resulting from residual demand forecast errors during extreme weather.

Case Study Example

In the Northeast case study, the system risk was evaluated for several different load forecasts, which varied by the level of end use electrification. The EPRI Regional Economy, Greenhouse Gas, and Energy (REGEN) model [5] was used to forecast load for a number of weather years and electrification scenarios. The REGEN model combines a detailed dispatch and capacity expansion model of the electric sector with an end-use model which represents trade-offs between end-use technologies and fuels for a wide range of disaggregated sectors and activities. The REGEN end-use model generates hourly electricity load shapes by sector and represents heterogeneous sets of customers who have choice and control to buy the technologies that best meet their needs, given differences across regions in terms of their policies, climatic conditions, population density, existing technologies and infrastructure, and energy supply costs.

Table 2 summarizes key adequacy risk metrics for the high VRE capacity buildout for region D across three different load forecast scenarios. Hourly load profiles in the “base” scenario were created by scaling historical load shapes from the 2007-2013 period to match an annual energy forecast and annual peak demand forecast provided by Region D. Hourly load profiles in the “REGEN reference” and “REGEN high heating” scenarios were created using the EPRI REGEN model for the 2007-2013 weather years. In contrast to the [5] load scenario, the “REGEN high heating” scenario enforces state-level targets for electric space and water heating with air-source heat pumps (ASHPs).

Table 2. Key adequacy risk metrics for the high VRE capacity buildout for Region D

Scenario	EUE (MWh/yr)	LOLE (days/yr)	LOLH (hours/yr)
Base	145	0.10	0.25
REGEN Reference	0	0.00	0.00
REGEN High Heating	456	0.42	1.10

When omitting ASHPs targets from the REGEN model [5], the adequacy risk in region D essentially disappears. This is because of the peak load in the REGEN reference load scenario being lower than in the base case scenario, as shown in Figure 5. Although the REGEN reference load forecast includes increased electrification, particularly of electric vehicles and heating load, it also includes significant energy efficiency savings due to assumed building trends (such as more effective building insulation) technology trends (such as more widespread LED adoption) and continued improvements, particularly driven by digitization and enhanced controls. As a result, the REGEN forecasted total load decreases in future years, thus diminishing loss of load risk.

In contrast, when state-level ASHP targets are enforced (as opposed to getting installed only based on economic viability), the winter load increases dramatically (as illustrated in Figure 5), leading to a significant increase across all the main risk metrics evaluated. The load increase is most significant in January and February, which sees sustained load growth throughout the day due to heating demand.

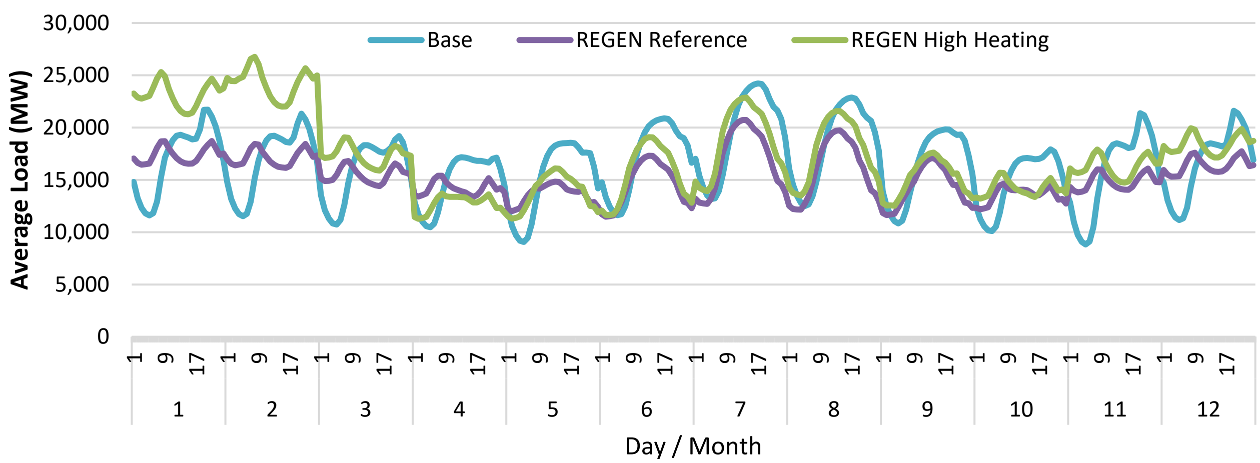


Figure 5. Average load by day per month for region D across various load scenarios

Figure 6 shows the EUE for all three scenarios for January and July. These charts show that risk in the base load forecast scenario is concentrated in afternoon and evening hours in July, whereas risk in the "REGEN High Heating" scenario is concentrated in the morning hours of January, which is when heating loads ramp up.

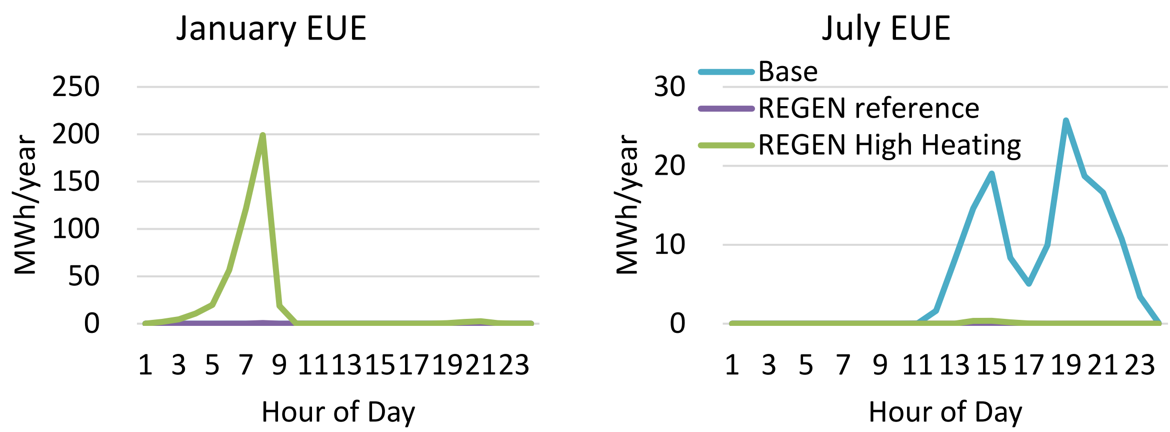


Figure 6. Expected unserved energy by hour of day in January and July by load scenario

An additional load sensitivity was run which considers the effect of climate change on adequacy risk metrics. To generate realistic timeseries of electrical load under climate change, adjusted temperature profiles were first created. To accomplish this, the spatial map of the average change from the 2007-2013 period to a future year period in the seasonally and monthly resolved temperature was calculated [6]. This map was then applied to timeseries from the years 2007 through 2013 at each point drawn from the ERA5 reanalysis data, to adjust them to future conditions. These climate-change adjusted temperatures were inserted into a model of the temperature-dependent load for each region to simulate the weather-dependent component of the load.

Figure 7 shows LOLH at margin state 1, which corresponds to how often the region relied on external assistance, instead of actual shortage hours. As temperatures increase due to climate change, adequacy risk decreases in winter months due to a decrease in heating load and increases in summer months due to an increase in cooling load. Given that adequacy risk occurs primarily in winter months in both load scenarios, as shown in Figure 7 , accounting for climate change in this region caused a decrease in adequacy risk. In contrast, a summer peaking region would see an increase in adequacy risk if climate change were accounted for.

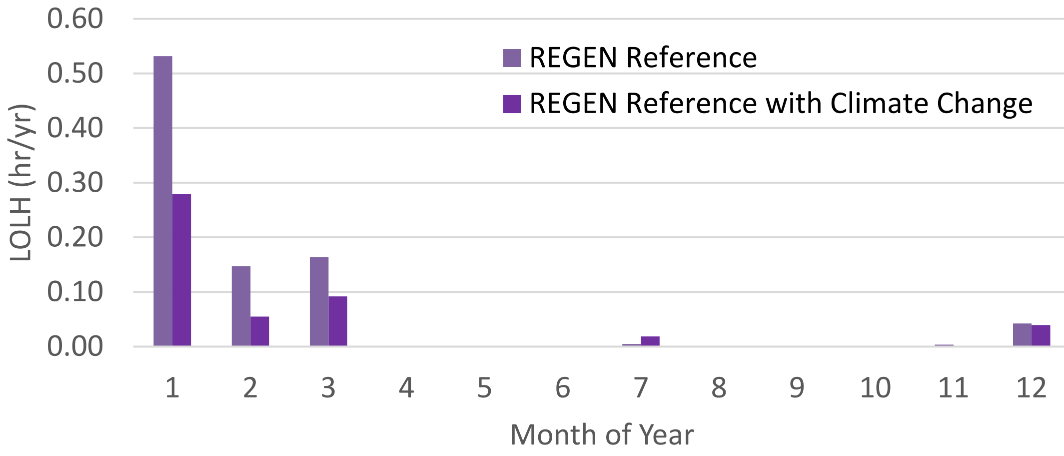


Figure 7. LOLH by month of the year with and without climate change effects (Margin State 1)

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
8 Severe	1	1	1
	2	2	2
	3	3	3

Recommendations

To improve load data's incorporation of weather impacts and electrification, a weather-dependent bottoms-up approach yielding load by sector and end use should be developed. For example, rather than using an annual energy and peak demand forecast for a region based on econometric relationships, load forecasters can develop a bottom's up load forecast comprised of hourly demand for space heating and cooling, water heating, other residential and commercial loads, industrial demand, and transportation. By modeling end use directly, load forecasters can more readily establish weather impacts and develop a multiple weather year forecast for demand, including impacts of further electrification.

The multiple weather year load dataset should be developed using the same weather-years as wind and solar profiles, weather-dependent outages, and fuel supply constraints. Load forecasting tools should be employed over scaling methods, where possible, to ensure weather correlation across load, renewable generation, and thermal plant availability is maintained and load shapes are preserved.

Resource adequacy models and tools do not need to be adjusted significantly, as much of the load analysis can be done outside of the power system modeling tools, but additional load forecast tools normally available in the operational setting may be required. This approach allows statistical or econometric models to be developed separately and provide resource adequacy models with hourly system demand. By following these recommendations, system operators can improve increasingly weather-dependent load forecasts and ensure the reliability of the electricity system.

5 GAP 4. IDENTIFICATION AND ANALYSIS OF OUTLIER, HIGH-IMPACT LOW-PROBABILITY, EVENTS

Gap Description

In power system planning there is a blurred line distinguishing resilience and resource adequacy. While resource adequacy evaluates a broad range of system conditions and summarizes the loss of load probability across many future outcomes, resilience measures the ability of a system to withstand or recover from specific outlier events.

While it is important to capture the likelihood of events in resource adequacy planning, it is also important to explicitly study extreme, outlier weather events via stress testing. Stress testing involves explicitly evaluating system conditions that may be outside of the historical record but represent feasible conditions that could have a significant reliability impact. These credible high-impact, low probability outliers should be captured in the analysis even if a specific probability can't be assigned.

However, data is often lacking for extreme events, or there are too few extreme events to ascertain the probabilities of such extreme events occurring. This challenge is amplified by climate change that increases uncertainty and probability of events with no historical record. Most climate change models may provide accurate estimates on *average* temperature trends but are insufficient at capturing the changing nature of extreme events. Furthermore, where operational experience has been gained in the past, it is unlikely to be representative of future demand or generation mixes.

Importance

High-impact, low probability events will have a disproportionate impact on system reliability. These events not only have an outsized effect on loss of load metrics (like EUE, and LOLH), but more importantly will have larger societal impacts such as significant economic and societal damage including loss of life.

If resource adequacy models don't evaluate outlier events, planners may be missing system risk and under-investing in mitigations required to reduce their impact. Winter Storm Uri is a good example of an outlier event. Winterization and improved fuel supply (via dual fuel capability) is relatively low cost when compared to the damages a 1-in-100-year storm poses. Even relatively expensive mitigations, like building new interregional transmission, may become prudent investments if the outlier events are included in power system planning and analyses.

Case Study Example

In the MISO Case Study, loss of load events were measured and categorized by their characteristics such as magnitude, duration, frequency, and seasonality. To establish a baseline for this analysis, the model was run using the Base Case portfolio as outlined here, and the LOLE measured. The baseline analysis assumed no transmission constraints (i.e., a copper sheet), but did assume some seasonality in incremental forced outages (up to 6,000 incremental MW offline at the coldest temperatures).

The Base Case yields the following reliability metrics (Table 3). The Base Case is a useful reference point to measure impacts to the conventional Resource Adequacy framework as more granular constraints are applied.

Table 3. Base Case Metrics in the MISO Case Study [7]

Metric	Units	Value
Summer LOLE	Days / Year	0.10
Winter LOLE	Days / Year	0.00
LOLH	Hours / Year	0.37
Average Duration	Hours / Expected Unserved Energy Event	3.7
Value at Risk (VAR), 95th percentile	Hours / Expected Unserved Energy Event	6

As shown in the table above, an additional metric not often included was the 95th percentile of all load-shed event durations, which is discussed further in the related [2]. This was measured as 6 hours, and as shown in later results is a useful metric to gauge the risk associated with a certain LOLE target. For example, a 0.1 LOLE may be acceptable but the possibility of a 48-hour event may be untenable.

Visualizing the 95th percentile of events (see Figure 8) indicates winter events are generally riskier in nature. This can be measured by the tail events within the loss of load event duration curve. The vertical line in the figure below shows the 95th percentile of load shed duration for each region, intercepting at 8 hours, 10 hours, and 11 hours for MISO North, MISO South, and LRZ5 [7] respectively.

Further investigation of the primary drivers of these long duration events is warranted to understand why they occur, mitigations that may be available to reduce duration, and how public policy programs and emergency response can be designed to mitigate the damages of long-duration shortfall events. In addition, future reliability criteria could be developed that limit both the average frequency of events (i.e., LOLE and LOLH) while also limiting the severity of the most extreme events (i.e., value at risk (VaR), or conditional value at risk (CVaR) metrics which measure RA metrics in the tail ends of the sampled distributions).

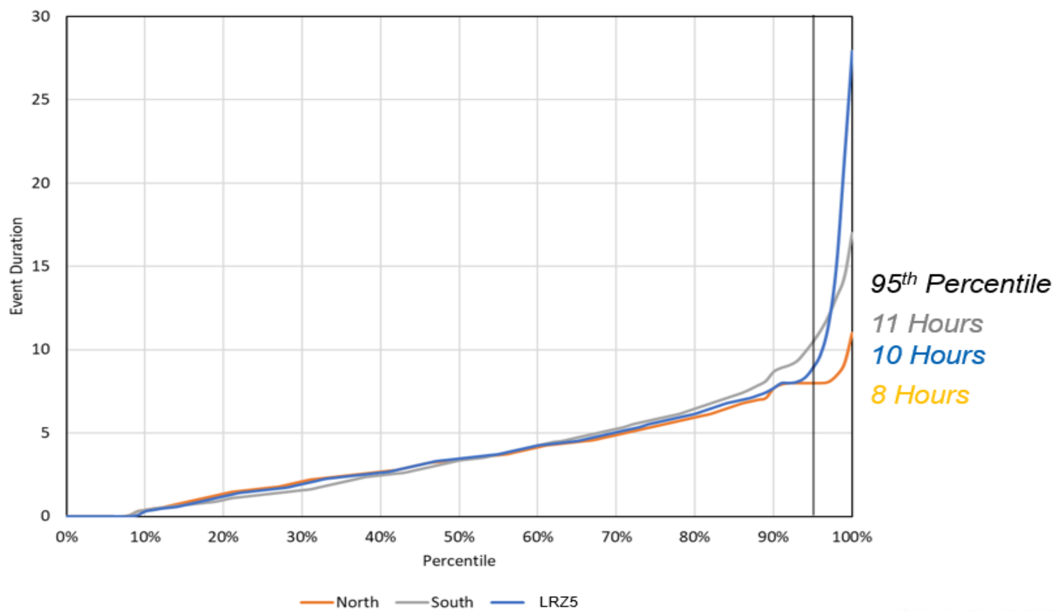


Figure 8. 95th Percentile of load shed by MISO Zone

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
8 Severe	1	1	1
	2	2	2
	3	3	3

Recommendations

While the probabilistic framework for resource adequacy analysis is still valuable, it may not be sufficient – in isolation – for long term planning. In addition, analyses should introduce individual event-based planning, particularly around potential “black swan” events that may not be in the historical record or may be difficult to assign a probability to. Stress testing of specific historical – and potential future – events in a high degree of detail is still needed, rather than simply including the event as one of many hundreds or thousands of probabilistic replications. In other words, while probabilistic analysis is helpful to review a wide range of potential future conditions, it should be done in conjunction with more detailed stress testing of specific events that are of most concern to system planners.

New metrics can also be developed to better capture size, frequency, and duration of individual events, especially tracking metrics related to the more extreme, tail end risks. While introducing new metrics will give planners more insight into system risk, it may also be prudent to develop a secondary reliability criterion (in addition to the resource adequacy reliability criterion) that drives investment decisions based on tail event risk. For example, a dual-criteria could be established that maintains the average 1-day-in-10 loss of load expectation, but also introduces a second threshold that minimizes the impact of the largest, tail event(s).

Resource Adequacy Severity Scale [2] [8]

Current practice focuses on determining expected value statistics for load shedding in terms of frequency, duration and magnitude. An additional approach was presented throughout the project to classify individual events based on their anticipated impact and to report their anticipated return period. This approach, deemed a “Severity Scale”, may compliment currently available percentile approaches in future. See the EPRI project website for more details on this concept.

This gap must also be addressed with improved data, particularly around climate modeling of weather impacts. Ideally climate data should capture not just potential average trends, but also the increasing severity of extreme events. Resource adequacy tools can also be adjusted via improved analytics and reporting that summarize outlier metrics.

Finally, in most regions regulators are ultimately in charge of clearly defining the reliability criteria and determining the appropriate tradeoff between economic efficiency and bulk system reliability. Careful review of resource adequacy risks should be conducted, and new criteria could be developed to determine if and how the system should be designed to meet both resource adequacy and resilience objectives.

6 GAP 5. CAPTURING WINTER RISK ASSOCIATED WITH FUEL SUPPLY AND WEATHER-DEPENDENT OUTAGES

Gap Description

Typically, resource adequacy analyses assume that generator outages occur randomly and independently throughout the year. This methodology does not account for correlated outage risk due to weather or other drivers. During extreme cold snaps, heat waves, and other events, generator outages increase. The power system is thus susceptible to weather-dependent outages and/or fuel supply constraints.

The absence of common mode failure of generators in adequacy assessments creates a gap in our understanding of the actual risks associated with weather events. While attention is often given to understanding correlated wind and solar availability (via weather-dependent production profiles), the same approach is rarely applied to thermal resources. Today, few resource adequacy studies surveyed incorporated weather-dependent outages or fuel supply constraints in the simulations. Some initial research [9] and [10] and the EPRI case studies have started to evaluate this risk. In addition, ISO-NE and PJM, for example, have started to incorporate these risks in their capacity accreditation proposals and adequacy assessments.

However, current publicly available generator outage data (i.e., NERC GADS data) is insufficient to model weather-dependent outage risk and the data is severely lacking – providing no public information on generator outages as a function of temperature or location. The ability to forecast future resource performance under extreme weather is a similar gap. Most RA tools cannot handle time varying outage and repair rates that are required to implement resource adequacy assessments without a need for labor-intensive pre-processing or manual workarounds, if at all.

In addition to weather-dependent outages, there are limited examples of explicit modeling of integrated power and natural gas sector coupling. With sector coupling, the power system model endogenously considers fuel supply (i.e., natural gas production) and transportation (natural gas pipelines and compressor stations). Improved modeling of sector coupling between natural gas and electric power networks is necessary to understand how the electric power system is impacted by the underlying natural gas system, as has been reflected in many public forums. However, data on generator fuel supply contracts, generator dual fuel capabilities, generator connections to the natural gas system, and generator on-site fuel storage is often unavailable, making it difficult to model fuel supply constraints accurately.

Importance

Incorporating fuel supply constraints and weather-dependent outages is necessary to properly evaluate winter risks on the power system. As discussed in earlier sections of the report, resource adequacy risk is shifting from summer to winter months in many places due to the transition to wind and solar resources and increased electrification. In addition to those trends, an increased reliance on natural gas generators (due to coal retirements) and increased age of the thermal fleet further exacerbates the winter resource adequacy risks.

As a result, most resource adequacy analyses are understating winter risk and overstating reliability contributions of thermal generation. Winter Storm Uri in February 2021 and Elliott in December 2022 both led to power system supply shortfalls, highlighting the winter risk challenge. Furthermore, Winter Storm Uri was notable as it caused significant disruptions in ERCOT, which was typically concerned with resource adequacy only during summer peak demand periods.

Historically, winter storms were not as significant a problem due to fuel diversity across thermal generators (large fleets of nuclear, coal, and gas), and with limited electrification of heating. However, because the future resource mix will be more heavily impacted by winter events due to an increased reliance on natural gas, increased electrification, and potential for sustained low wind and solar periods, it is crucial to account for winter risks associated with fuel supply and weather-dependent outages.

It is worth also noting that while winter risk is the most prominent form, summer risk related to plant deratings and failures also exists. However, fuel supply risk during those conditions is less relevant than during winter.

Case Study Example

In the ERCOT case study [11], the system was evaluated with and without weather-dependent outages on the thermal fleet in order to isolate the impact of both extreme heat and cold temperatures on system reliability. This was done by adjusting outage rates for each generator daily across the same 40 weather years of historical data used for the wind, solar, and load profiles. Generators were assigned to one of eight weather zones across Texas and a unique outage rate profile was developed based on local temperatures in the weather zone. This replaced the annual average outage rate used in the Base Case, which was adjusted so that the annual average outage rate in the base case was the same as the annual average across the 40 years of daily outage rates. This ensured that comparisons were based on the *timing* of the correlated outage risk rather than just an increase in the total amount of outages.

The relationship between temperature and generator outages is ambiguous for three reasons. First there is limited publicly available data for unit-specific, temporal outage rates that can be compared against historical temperature observations [12]. Second, extreme heat and cold conditions are relatively rare, limiting the sample size available for historical observations.

Lastly, it is often difficult to separate weather-dependent forced outages and fuel supply limitations, both of which are elevated during extreme cold conditions.

To overcome this limitation, the ERCOT case study used technology-specific outage relationships published in [13], which were developed based on observations in the PJM territory (dark blue curve in Figure 9). After reviewing the data, it was clear that the temperature to outage rate relationship was not directly applicable to ERCOT generators, which had better performance during summer heat and worse performance during winter cold snaps relative to PJM generators. This is expected, as generators are designed to operate in the conditions most likely in their region.

To adjust for this, the analysis evaluated three different temperature relationships by shifting the curve to the right (increasing cold temperature outage rates and decreasing hot temperature outage rates) and extrapolated outage rates further to capture tail events (Figure 9). Estimates of Winter Storm Uri (February 2021) and Winter Storm Elliott (December 2022) are also shown for reference.

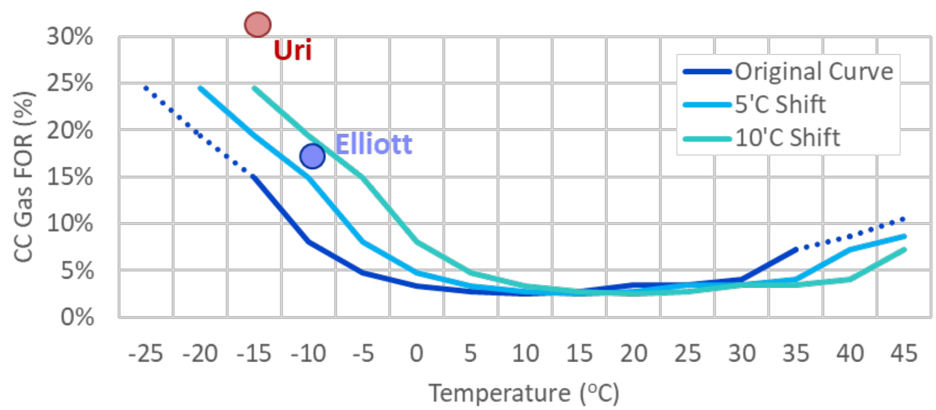


Figure 9. Temperature versus Outage Rate Relationship

The probabilistic resource adequacy analysis was run by adjusting daily outage rates across all 40-years of historical data. The results showed that LOLE (days/year) increased significantly when weather-dependent outages were included in the analysis, increasing from 0.19 days/year when using an average annual outage rate up to 0.53 – 0.82 days/year dependent on the temperature-outage rate curve assumed (Figure 10). In addition, the seasonality of the loss of load events also changes when weather-dependent outages are introduced, creating a large increase in winter loss of load events when a 5-degree or 10-degree shift in the temperature/outage rate curves are included.

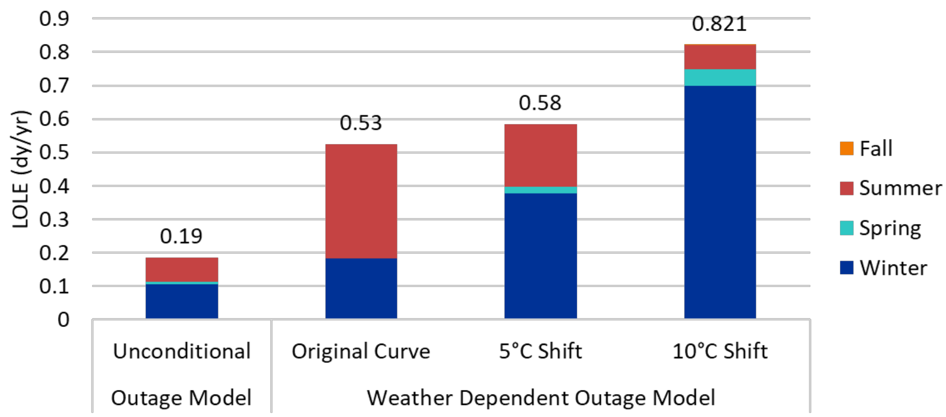


Figure 10. Seasonal LOLE with and without Weather-dependent Outages

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
8 Severe	1	2	1
	2	2	2
	3	2	3

Recommendations

To improve the modeling of winter risks associated with fuel supply and weather-dependent outages, several actions are recommended. First, better, and more detailed generator outage data that is spatially and temporally specific is needed. This information is needed to develop weather-dependent forced outage rate curves - either by technology type or for individual units - that can be used in resource adequacy modeling tools.

Second, for the more granular forced outage data to be useful, modeling tools must be capable of incorporating time-varying forced outage rates. Of the software tools evaluated in this study, most were unable to incorporate this feature, or required significant manual adjustment to do so. Recognizing temperature and time-dependent forced outage rates (which vary hourly or daily) is an important tool feature.

In addition to improvements in weather-dependent outages, increased visibility into the natural gas system is also required. At a minimum, this requires improved data on generator dual fuel capability, firm fuel supply contracts, and onsite fuel storage so that generators' fuel supply can be accurately modeled.

To properly capture the fuel supply risk in resource adequacy models, there are two approaches. One option is to perform natural gas sector modeling exogenously to the resource adequacy models. The outputs of the natural gas sector models would be used to identify maximum fuel offtake for the system or a given pipeline during certain periods or outage rates for specific natural gas pipelines. Both properties could then be mapped to the generators in the resource adequacy models.

A second approach to fuel supply constraints would be to model the natural gas sector endogenously within the resource adequacy tool. This would be much more data intensive and computationally challenging but may provide a better representation of the fuel supply constraints. Finally, metrics should be developed that show loss of load events by month and season to provide a better understanding of the impacts of winter risks on power systems.

By implementing these recommendations, the modeling of winter risks associated with fuel supply and weather-dependent outages can be improved, leading to more accurate reliability assessments and improved planning for winter events. By addressing this gap with better data, improved tools, and better modeling of the interactions between the natural gas and electric power systems, planners can better understand the risks associated with winter events and prepare accordingly. Failure to address this gap may lead to a significant underestimation of reliability risk as electrification increases and the resource mix shifts towards a greater reliance on natural gas and renewables.

7 GAP 6. INTERREGIONAL COORDINATION

Gap Description

Current practice for many resource adequacy studies is to assume limited or no availability of imports from neighboring regions unless a firm capacity contract or agreement associated with import availability exists. However, power can and does flow across the interconnected grid, even during tight margin events. While each utility, balancing authority, and ISO/RTO may be required to have resources to serve its own load, there is value to interregional coordination for resource adequacy. In addition, inter-regional resource adequacy coordination is increasingly important as power system resources and load become increasingly weather-dependent. Coordinating resource adequacy across regions increases geographic diversity of weather-dependent resources yielding a reduced risk of correlated weather events impacting renewable energy production and high electric demand.

Today, however, there is no standardized approach to modeling the broader interconnected power system in resource adequacy studies. Nor is there a standardized approach to determine how much a system can/should rely on neighboring systems for resource adequacy. Financial and contractual constructs to coordinate resource adequacy may or may not be aligned with the underlying ability of the power system to deliver capacity across a region, depending on the design.

For most regions, it is computationally intractable to model the entire grid and all interconnected regions at the high level of fidelity needed for a resource adequacy study. However, omitting models of neighboring systems entirely is not prudent either. Novel approaches could provide a method to incorporate a broader interconnected regional footprint, while keeping a detailed focus on a particular region.

Importance

Modeling a broad interconnection – spanning a continental scale – is not only computationally challenging, but it also introduces new questions related to accountability and responsibility when it comes to resource adequacy. Each region can and should determine the extent to which they may rely on neighbors or the wider interconnection for support during reliability events. Determining the appropriate scale in the underlying analysis and the RA-related decision-making has important implications for ratepayers.

However, as the system becomes more dependent on weather, increasing a power system's geographic footprint to span multiple weather patterns is likely to be beneficial for reliability. Geographic diversity in load, renewable availability, and fuel supply can yield significant reliability benefits. Wind and solar production droughts and electric demand spikes do not typically affect large regions simultaneously. Thus, incorporating neighboring regions with different weather patterns could significantly alter resource adequacy risk.

Resource adequacy studies that do not capture renewable generation, load patterns and emergency procedures for neighboring regions could be leaving a valuable mitigation for improved reliability off the table. This can result in overbuilding of systems when some studies/tools assume no imports, or vulnerability during extreme weather events when other studies assume imports are firm, but they are not fully available. Failure to properly account for geographic diversity and interregional coordination may also cause missed opportunities for increased investment in transmission, specifically interregional transmission, which can serve resource adequacy needs.

Case Study Example

Unlike the other case studies performed in the EPRI RA Initiative, the Western U.S. Case Study [14] was the only one to take a broad, interconnection-wide view of resource adequacy. To accomplish this, the case study explicitly modeled the load, generation, transmission across the entire western U.S. and across multiple weather years of synchronized wind, solar, and load data. The model topology is provided in Figure 11.

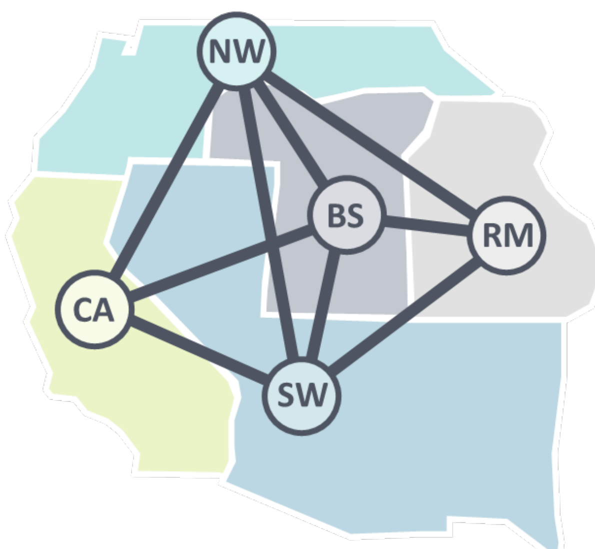


Figure 11. Western U.S. Case Study Topology [14]

While the focus of the case study was not specifically intended to explore the interregional interdependencies for reliability - which was evaluated in detail in previous research [15] - the model explicitly included the availability of imports, exports, and transfers of available resources across the interconnection. This approach captured the geographic diversity in wind, solar, and load, which is increasingly important for high renewable power systems.

Figure 12 provides an illustration of these transfers, which show the net imports for each region at times when a scarcity event occurs somewhere in the wider region. This allows planners to evaluate how much each region relies on operational coordination when the entire interconnection is short. Results show that these findings can change significantly depending on the portfolio as the resource mix changes. For example, net load duration curves are shown below for the California and Southwest regions *during loss of load events* at the WECC level, in both a near term and a high renewable and storage portfolio.

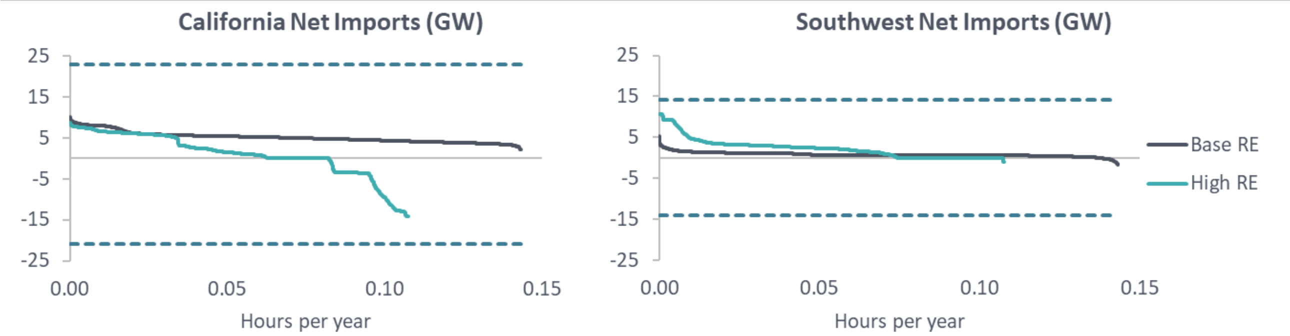


Figure 12. Net import duration curves during shortfall events by portfolio, by region

The main conclusion from these results is that - if allowed and included in the resource adequacy simulations - imports and exports are often available and leveraged significantly across the region. This highlights the importance of regional coordination, and it shows that as renewables are added across the West, the transmission flows will change significantly during risk periods. As a result, our intuition about imports during challenging events today may not hold tomorrow. While we cannot know for sure how those flows will change, as it is dependent on resource locations, the findings underpin the importance of regional planning and coordination, especially related to resource adequacy.

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
	1	1	1
6 Moderate	2	2	2
	3	3	3

Recommendations

There are several ways resource adequacy studies and planning processes can be updated to incorporate interregional coordination. First, there is a need for better representation of neighboring systems in resource adequacy modeling. This can be achieved by ensuring that external resources are accurately represented – with high fidelity, location-specific weather - and incorporating interregional flows.

To model interregional flows and location specific weather, common methodologies and datasets should be developed to reflect resource availability across wide geographies and interregional flows during tight conditions. While each ISO/RTO, balancing area, or utility will likely still evaluate their own resource adequacy, common approaches to modeling neighbors can facilitate the process of developing correlated weather data sets.

For example, an interconnection-wide or pan-national study – similar to the European Resource Adequacy Assessment - could be conducted on a continental scale, the results of which could be used as an input into regional, sub-regional or local studies. Results from a pan-national study would allow local resource adequacy studies to simplify large external regions without sacrificing accuracy. This would enable a more comprehensive and accurate evaluation of interregional coordination in resource adequacy studies.

This process would also require a robust, consistent, continental dataset for weather variables (see next gap). This dataset would ensure wide-region studies are using consistent weather data and maintain correlation with local analyses.

Lastly, regulatory frameworks can be revisited to provide clear guidance on how neighboring regions can be used to meet resource adequacy needs in lieu of locally sited generation. This framework could provide guidance on the extent to which neighboring regions can be relied upon to meet resource adequacy needs.

8 GAP 7. INCORPORATING CONSISTENT AND CORRELATED WEATHER DATASETS

Gap Description

As the previous gaps discussed, any resource adequacy modeling for a future power system requires accurate and consistent weather data. The weather and atmospheric dataset should cover a long historical record and be used to develop *consistent* wind, solar, load, and temperature datasets. However, many studies lack sufficient historical data to capture a long historical record of weather on wind, solar, and sometimes load. As a result, practitioners are often required to fill data gaps with statistical techniques and data bootstrapping. While this may allow for probabilistic analysis, it breaks the underlying correlation of atmospheric weather conditions, potentially leading to infeasible scenarios.

Moreover, wind, solar, and load datasets that do capture weather correctly frequently use disparate underlying atmospheric conditions. Even if the same weather years are evaluated for wind and solar, the wind and solar profiles are derived from different atmospheric variables. As a result, the data may not correctly evaluate correlations between the load, solar, and wind resources.

This lack of consistency in weather datasets introduces significant uncertainty in the assessment of weather-dependent power systems' performance. Additionally, datasets are not consistent across wide areas, with different regions using different weather data.

The gap in incorporating consistent and correlated weather datasets presents a significant challenge for power system planning and risk assessment. The power system is quickly transitioning to one that increasingly relies on weather-dependent resources such as wind, solar, natural gas, and other resources for reliability. However, there is a significant data gap of correlated weather data across multiple weather-dependent power system components (wind, solar, load) leaving grid planners with insufficient information and data to accurately model future power system events.

Importance

This shift towards a decarbonized system highlights the importance of accurately capturing weather risk, not just for normal conditions, but specifically for outlier conditions. Extreme weather events like heatwaves, cold spells, hurricanes, and droughts can significantly impact the performance of weather-dependent power systems. Therefore, accurately capturing the risks associated with weather is essential for power system planning and risk assessment.

If resource adequacy risk associated with a high renewable power system is to be accurately captured, it is crucial to have accurate and consistent weather data across long historical records. Weather events where there is a sustained low wind and solar event combined with high load and tight supply conditions could be missed if the data is not sufficiently comprehensive. Additionally, weather patterns follow physical conditions, and bootstrapping for statistical samples is not sufficient for evaluating weather details. To accurately capture weather events' risks, a long-term, comprehensive, and consistent dataset is significantly preferred.

It is also important to note that correlated datasets should be geographically large, spanning national or continental regions. This would provide a more diverse and accurate representation of the different weather patterns and trends across different regions. Climate trends should also be considered for both average temperatures and outlier events. These trends can help in identifying the potential impact of climate change on the system's performance and develop effective adaptation strategies.

Case Study Example

The ERCOT Case Study [11], for example, evaluated correlated, hourly weather variables across 40-years of historical data for wind, solar, load, and temperature-dependent outage rates. The historical record ranges from 1980 to 2019. Wind and solar profiles were developed by UL and historical weather observations were applied to existing and future wind and solar plants [16] Load estimates were developed by ERCOT based on historical temperature observations across Texas. This provided a long historical record of weather events spanning key drivers of reliability that can be applied to future system resource mixes.

The results of the analysis show that loss of load events can be highly dependent on the weather year evaluated and based on a confluence of factors. Figure 13, shows the winter and summer peak demand for each weather year (quantified as a percentage increase or decrease relative to the 40-year average) along with the corresponding loss of load expectation under 2023 and 2030 resource mix assumptions[1] These results indicate that in the 2023 resource mix, most loss of load events occur during weather years with higher-than-expected summer peaks (namely 2000, 2003, 2010-2012). More specifically, 30% of all loss of load events occurred during June 25-26 in weather year 2012. Interestingly, peak demand in 2011 and 2012 weather years are comparable (slightly higher in 2011), but LOLE is highest in 2012. This is because the time period also had lower wind and solar compared to 2011, showing the importance of evaluating correlated weather datasets.

Under the 2030 resource mix assumptions, however, resource adequacy risk shifts to the years with higher-than-normal winter peak demand (1982,1985, 1989). More specifically, nearly 50% of all events occurred during three days of the historical record, December 22-23 during weather year 1989 and January 11, weather year 1982. This suggests that winter risk increases as the system transitions to higher levels of variable renewables. This occurs for two reasons;

[1] In the results shown here, weather-dependent forced outages are *not* included in the analysis but were evaluated separately in sensitivity analysis.

because the increase in solar effectively reduces summer mid-day resource adequacy risk, and because a high renewable system can experience multi-day low wind and solar events that are more likely in the winter. This analysis shows the importance of using a long-historical record for probabilistic resource adequacy studies, and to capture the correlation across wind, solar, load, and generator outages as a function of the underlying weather.

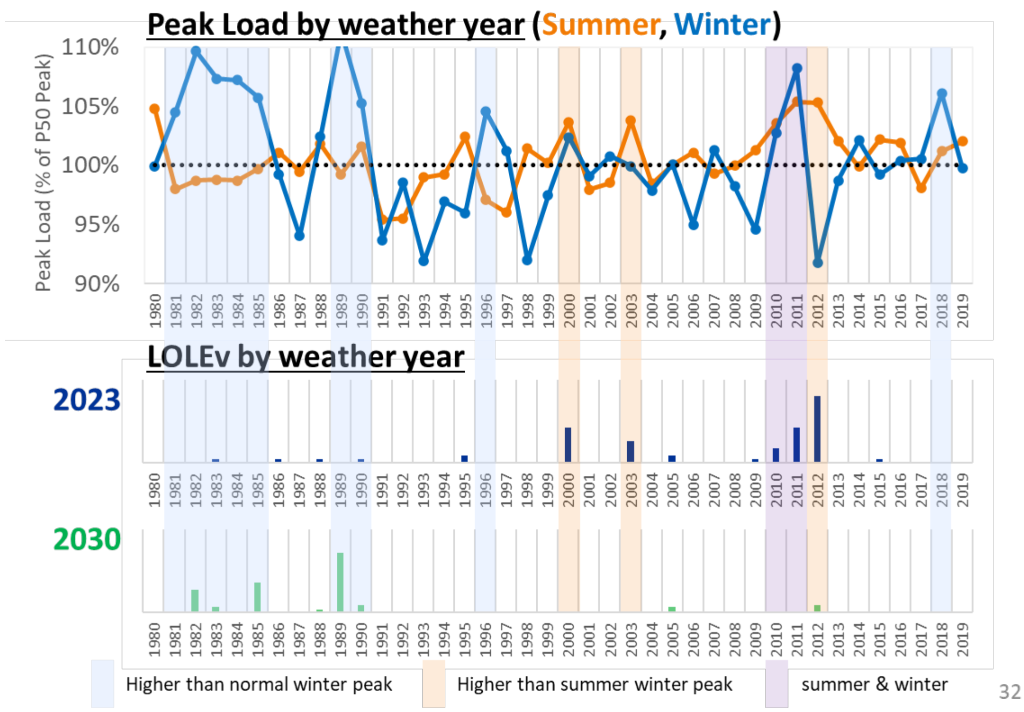


Figure 13. Winter and Summer Peak Demand and Loss of Load Expectation by Weather Year

How Big of a Gap is it?

	Recognition	Known Solutions	Impact
	1	1	1
5 Low	2	2	2
	3	3	3

Recommendations

If we want to accurately capture risk associated with renewable energy sources, it is crucial to have accurate and consistent weather data across long historical records. A consistent North American resource adequacy weather dataset should thus be developed to provide consistent wind, solar, and temperature data across broad geographies. The Energy Systems Integration Group previously identified desirable attributes of such a dataset, including [17]:

- Necessary variables at sufficient spatial-temporal resolution with sufficient accuracy and fidelity to produce meteorological fields representative of actual conditions,
- Represent multiple decades with consistent methodology, periodically extended ,
- Coincident and physically consistent across weather variables,
- Validated against real conditions with uncertainty quantified,
- Documented transparently and in detail, including limitations and a guide for usage,
- Periodically refreshed to account for scientific and technological advancements so the data does not become irrelevant,
- Publicly available and easily accessible.

For adequacy assessments over the mid to long term, application of transparent adjustment to account for the changing climatic conditions that may be expected in a future time is recommended. Methodologies to achieve this on a consistent basis are being explored as part of EPRI's Climate READi initiative. Overall, incorporating consistent and correlated weather datasets is critical for accurate power system planning and risk assessment. It is essential to accurately capture the risks associated with weather, not just for normal conditions but also for outlier events.

9 CONCLUSIONS AND NEXT STEPS

In conclusion, resource adequacy remains a critical and pertinent subject within the electric power industry, particularly in light of the ongoing energy transition. Conventional metrics, methods, and tools will continue to evolve with higher levels of renewable energy adoption, increased energy storage, thermal retirements, end use electrification, and climate change.

Fortunately, modeling and resource adequacy analysis have made significant progress in recent years, yielding valuable advancements. Simulations now often encompass multiple years of correlated weather-dependent demand, wind generation, and solar generation. Simulation of these correlated factors enables a more comprehensive understanding of system dynamics. Sequential Monte-Carlo analysis spanning the entire 8760-hour duration of the year has also become the norm, ensuring the proper inclusion of energy-limited resources and time varying risk. Moreover, resource adequacy models have begun to integrate the gas network to more accurately consider weather-dependent outages of thermal resources and fuel supply risk.

Despite these notable advancements, there is still significant room for improvement. This report aimed to identify major gaps pertaining to resource adequacy analysis and data, proposing potential solutions to address them, and outlining future research and development. The importance of these identified gaps was assessed by the advisors to EPRI's Resource Adequacy for a Decarbonized Future Initiative, through a voting process, which ranked the importance of the gaps outlined in this report (Table 4).

Note that the scores in Table 4 varies from the Gap Severity described in the body of this report. The scores in the report focused not just in the importance of the issue, which is what the survey was based on, but also how the gap is understood and can be filled. As such, while the metrics gap is seen as most important in the industry, the gaps for understanding and addressing the issue are not as significant when compared to others.

Table 4. EPRI Stakeholder Ranking on the Importance of Resource Adequacy Gaps

Rank	Resource Adequacy Gap	Score	EPRI Severity scale
1	Need for improved and more detailed resource adequacy metrics	5.8	Moderate
2	Improved load forecasting considering weather impacts and electrification	5.3	Severe
3	Capturing winter risk associated with fuel supply and weather-dependent outages	5.3	Severe
4	Incorporating consistent and correlated weather datasets	4.8	Low
5	Holistic integration of resource adequacy with other planning activities	4.8	Moderate
6	Interregional Coordination	4.5	Moderate
7	Identification and analysis of outlier, high-impact, low-probability, events	4.4	Severe

Ongoing initiatives within the industry are underway to bridge these gaps and enhance resource adequacy analysis. These initiatives encompass a wide range of activities and collaborations, demonstrating a collective effort to advance the understanding and management of resource adequacy. A selection of these ongoing activities is listed below:

a. New metrics and reliability criterion are being considered in several projects. A DOE-funded project led by **ESIG, NREL, EPRI, and Telos Energy** is developing best practices and guidelines on new resource adequacy criterion through a broad industry-wide Task Force. **PJM** is currently switching to EUE as a reliability criterion [18], **NWPCC** is developing a four-part reliability criteria that includes EUE, and maximum risk tolerance on size, frequency, and duration of individual events [19], and **ERCOT** is also developing a new multi-criteria framework [20].

b. Load forecasting efforts are also being improved to capture weather impacts and electrification. **EPRI's** Climate READi initiative is developing new tools and processes to develop multiple end-use, economy-wide load forecasts across different weather patterns and climate change scenarios. A similar approach is used by **Evolved Energy Research**, **NREL**, and others in ongoing research activities [21], [22].

c. The identification and analysis of outlier, high-impact low-probability, events is being addressed across many ISO/RTOs and utilities in response to recent extreme weather events and power system disruptions. **FERC** recently finalized two rules which requires **NERC** to develop a new or modified reliability standard to require transmission system planning for extreme heat and cold weather conditions over wide geographical areas. Further, NERC requires transmission providers to submit reports describing policies and processes for conducting extreme weather vulnerability assessments [23].

d. Winter risk, weather-dependent outages, and fuel supply disruptions are being continuously addressed. A **NERC** Standard Drafting Team is building off the work of the Energy Reliability Assessment Task Force (ERATF) to develop a standard on performing energy reliability assessment, which gives particular attention to fuel supply and winter risk [24]. **FERC** also approved new extreme cold weather reliability standards to evaluate extreme cold weather preparedness and operations [25]. Forthcoming research from **NREL** will also expand upon previous work related to weather-dependent outages of thermal resources to include data across the country [9].

e. Interregional coordination for reliability and resource planning is also gaining attention from key industry stakeholders. The recent U.S. Debt Ceiling bill requires **NERC** to conduct an Interregional Transfer Capability Determination Study [26]. **FERC** is also considering a new rule to develop minimum interregional transmission capability and reforms to interregional transmission planning [27]. **ESIG** is currently conducting an interregional transmission resilience and reliability study.

It is important to note, however, that there are still unaddressed issues across all of these gaps within the realm of resource adequacy. Most notably, in many parts of the country, there is limited attention currently placed on linking resource adequacy analysis with other planning efforts, namely transmission planning, and in many cases capacity expansion planning. In addition, significant data gaps remain related to high-quality, multi-weather year, spatio-temporal datasets on correlated wind, solar, and demand data. These gaps require further attention and research to ensure a robust and reliable electricity system that can effectively accommodate the evolving landscape of renewable energy, storage technologies, and changing demand patterns.

To improve comprehensive resource adequacy modeling, continuous research, development, and improvement efforts are crucial. The collaborative endeavors and industry-wide initiatives currently in progress demonstrate a commitment to overcoming these challenges and achieving a resilient and sustainable power system for the future.

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Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

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