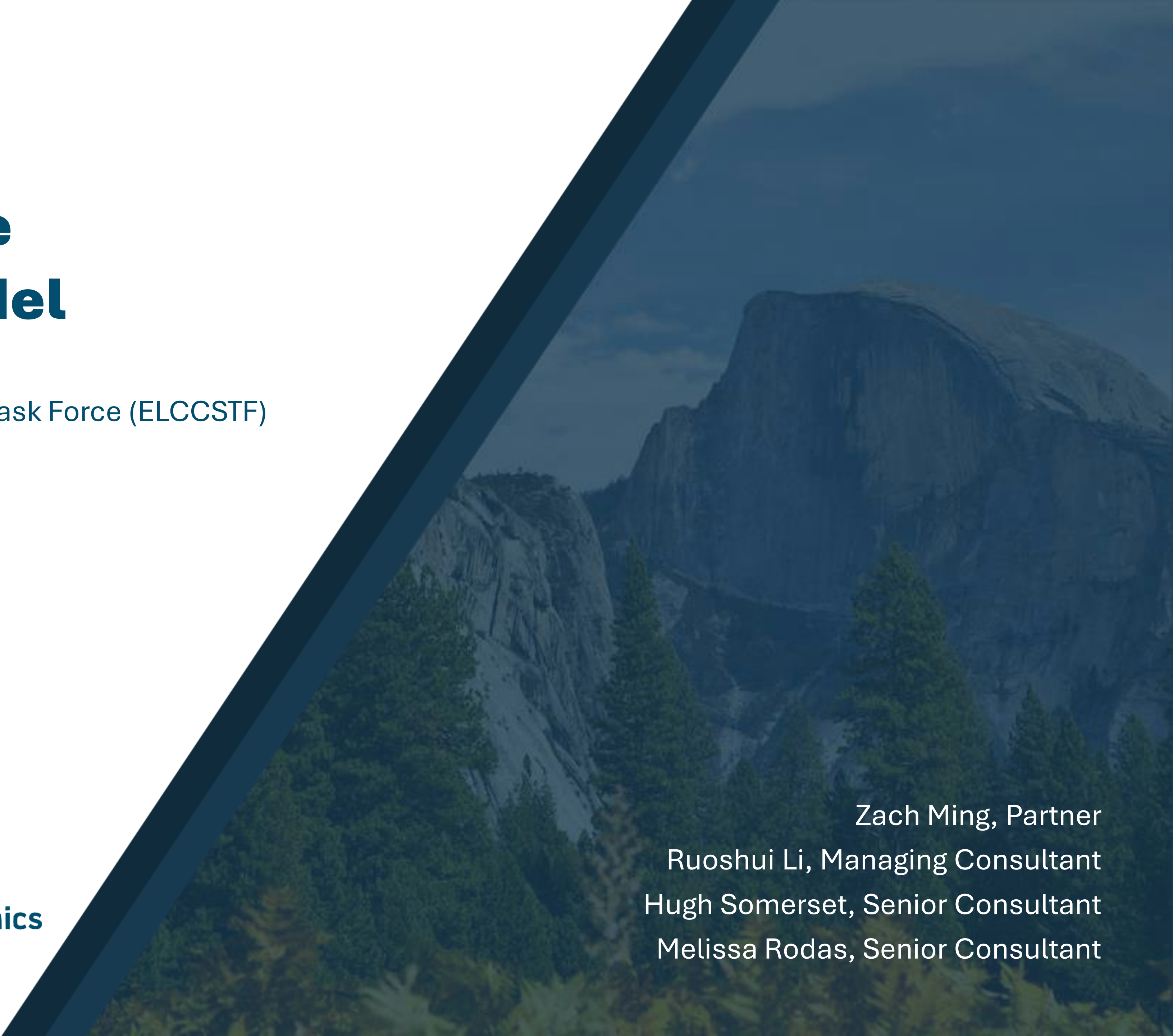
E3 Evaluation of the PJM ELCC/ RRS Model

Report Summary Presented to the
Effective Load Carrying Capability Senior Task Force (ELCCSTF)

December 9th, 2025



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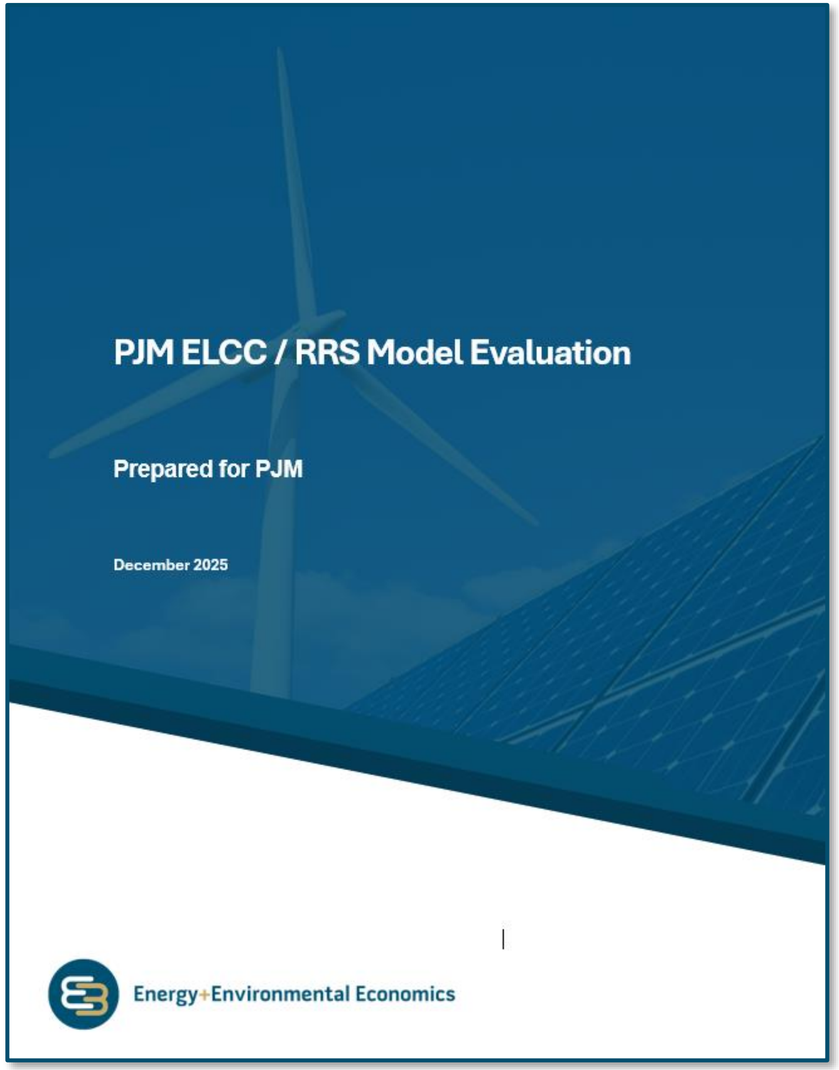
Energy+Environmental Economics

Introduction

- **Energy and Environmental Economics (E3) was retained by PJM to provide an independent assessment of the PJM Effective Load Carrying Capability / Reserve Requirement Study Model (ELCC/RRS Model) for alignment with industry best practices in loss-of-load-probability (LOLP) modeling**
  - This was the result of the Board’s August 2025 directive to PJM to “engage a consultant to identify additional recommended enhancements to discuss at the ELCCSTF or other similarly focused stakeholder group for implementation after the 2028/2029 BRA”
- **E3’s findings are publicly availably in a written report**



Agenda for Today

Agenda

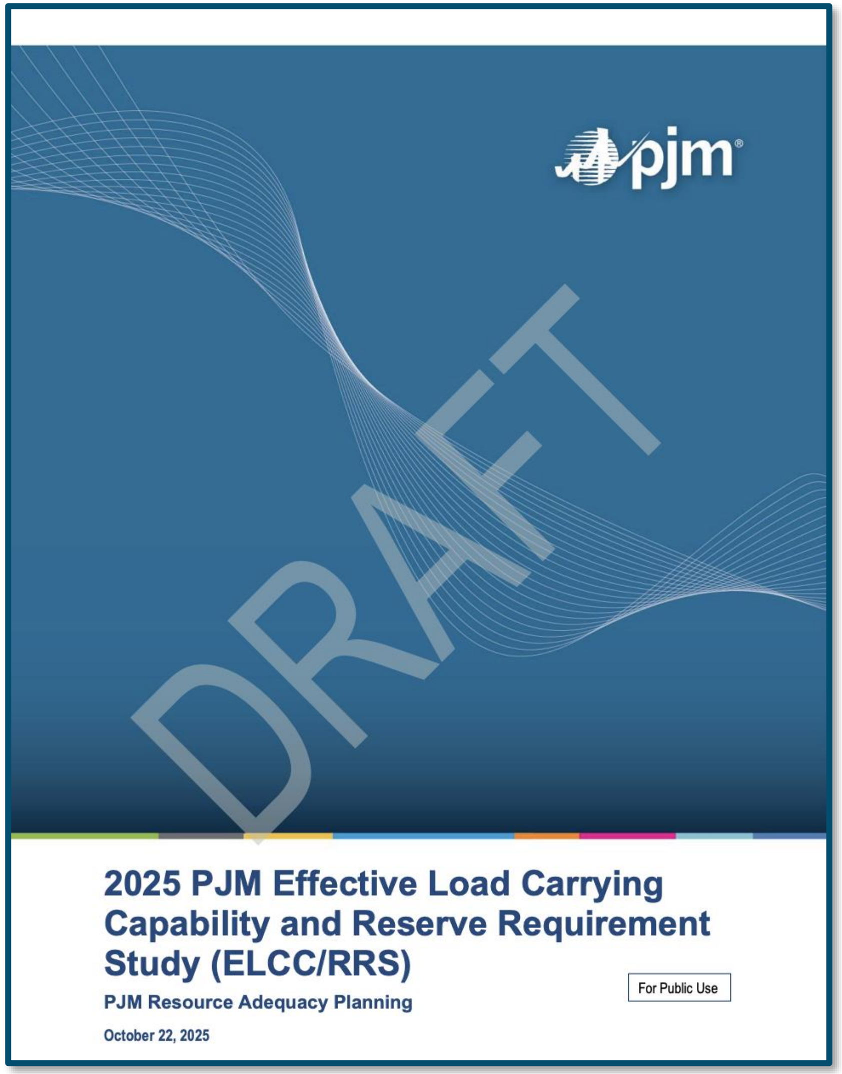
1.	Introduction	9 – 9:30a
2.	Overview of Loss-of-Load-Probability Modeling and Best Practices	9:30 – 10a
3.	E3 Evaluation of PJM ELCC/RRS Model	10 – 11a
4.	Considerations for Improvement	11-12p
5.	Buffer Time + Q&A	12 – 1:30p

Questions

+ We will pause periodically for questions, but may defer longer conversations to the end of the presentation in dedicated Q&A time

Brief Background on the PJM ELCC/RRS Model

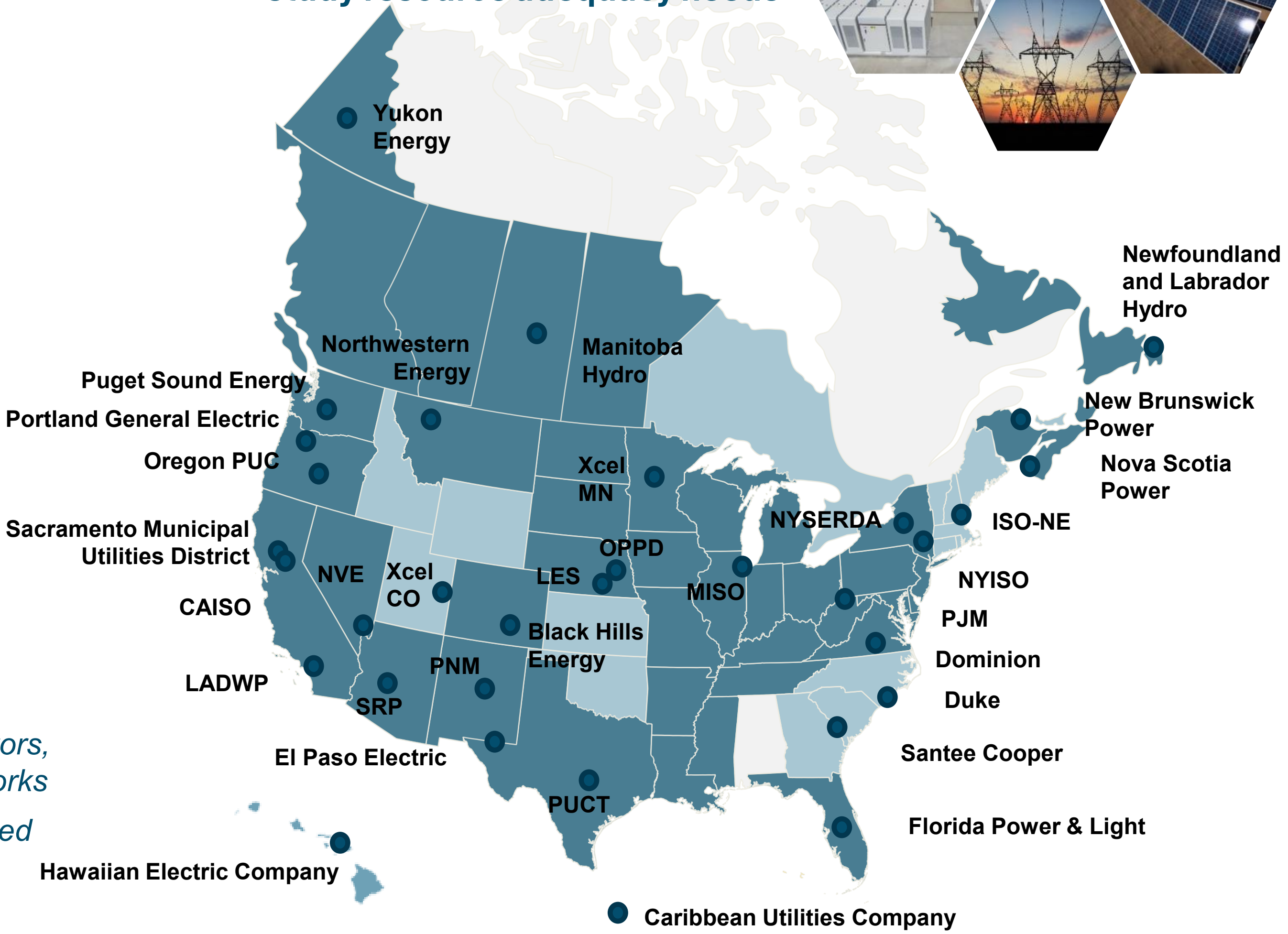
- **The PJM Effective Load Carrying Capability / Reserve Requirement Study (ELCC/RRS) Model is a model used by PJM to calculate specific capacity market parameters, namely:**
  - The "Reserve Requirement" or the total quantity of capacity (in MW) necessary to achieve the 1-day-in-10-year reliability standard
  - The "Effective Load Carrying Capability" values that quantify the contribution of each resource class toward the Reserve Requirements
- **The ELCC/RRS Model falls within a class of models referred to as "loss of load probability" (LOLP) models that are industry standard to perform these calculations**
- **PJM has published extensive documentation on the functionality of the model, available at: [2025 PJM Effective Load Carrying Capability and Reserve Requirement Study]**



E3's Resource Adequacy Experience

- E3 has performed dozens of resource adequacy studies across North America using RECAP, a loss-of-load-probability (LOLP) model developed and maintained in-house by E3
- E3 has published whitepapers on emerging resource adequacy topics such as the application of ELCC and critical hours
- E3 has advised ISO's and market participants on resource adequacy market design issues, submitting testimony to FERC on these topics

E3 has worked directly with utilities across North America to study resource adequacy needs



States where E3 has provided direct support to utilities, market operators, and/or state agencies to perform RA modeling or develop RA frameworks

Areas where E3 has worked with other clients to examine issues related to resource adequacy

E3's Scope

+ **E3 was tasked with two primary objectives:**
  1. Provide an assessment of reasonableness of the PJM ELCC/RRS model
  2. Provide potential considerations to enhance PJM's ELCC and risk modeling
+ **These findings were to be documented in a final report and stakeholder presentation**
+ **The materials were to illustrate and explain key features and methods for the purposes of stakeholder understanding and education**

Overview of Report

+ Overview of Loss-of-Load-Probability Modeling and Best Practices

- This section provides an overview of the importance and role of loss-of-load-probability modeling. It provides an overview of modeling best practices and how LOLP models are used to calculate values such as the total capacity requirement and individual capacity accreditation values

+ Evaluation of PJM Model Design

- This section provides E3's evaluation of the PJM ELCC/RRS model for alignment with industry best practices

+ Validation of PJM Model Performance

- This section tests inputs, methods, and outputs of the PJM ELCC/RRS to ensure that the model is working as intended

+ Considerations for Improvement

- This section provides a list of considerations for model improvement. E3 evaluates each consideration for improvement against the criteria of **accuracy, objectivity, stability, transparency, tractability, impact, and ease of implementation**

Overview of Loss-of-Load-Probability Modeling and Best Practices

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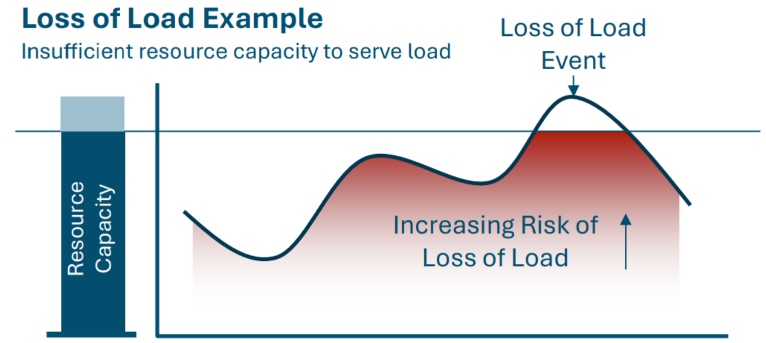
Overview of Loss-of-Load-Probability Modeling

- Loss-of-Load-Probability (LOLP) modeling is a means of assessing the resource adequacy of an electricity system – will sufficient generating resources be available when needed to meet demand?
- There are a number of LOLP models available
- Modern LOLP models typically simulate the performance of the electricity system on an hourly basis over the course of the entire year – these annual simulations are repeated hundreds or thousands of times, each iteration stochastically capturing a different combination of weather conditions and outages



Inputs

Load
- *Hourly load for many weather years*

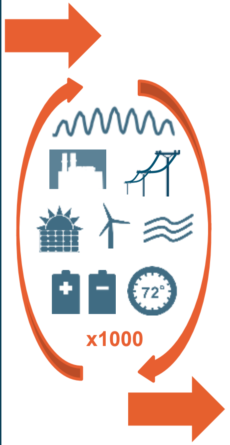
Dispatchable Generation
- *Capacity*
- *FOR*
- *Maintenance*

Renewables
- *Capacity*
- *Hourly generation profiles for many weather years*

Hydro
- *Hydro availability for many hydro years*
- *Max/min constraints*

Storage
- *Capacity*
- *Duration*
- *Roundtrip efficiency*
- *FOR*

Demand Response
- *Capacity*
- *Max # of calls*
- *Duration of each call*



Outputs

LOLE
- *Loss of load expectation*
- *days/yr of total expected lost load*

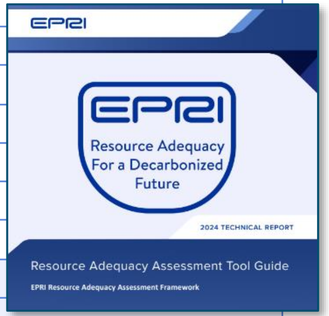
LOLH
- *Loss of load hours*
- *hrs/yr of total expected lost load*

EUE
- *Expected unserved energy*
- *MWh/yr of energy that cannot be served*

ELCC
- *Effective load carrying capability*
- *Equivalent quantity of 'perfect capacity' for a variable or energy-limited resource*

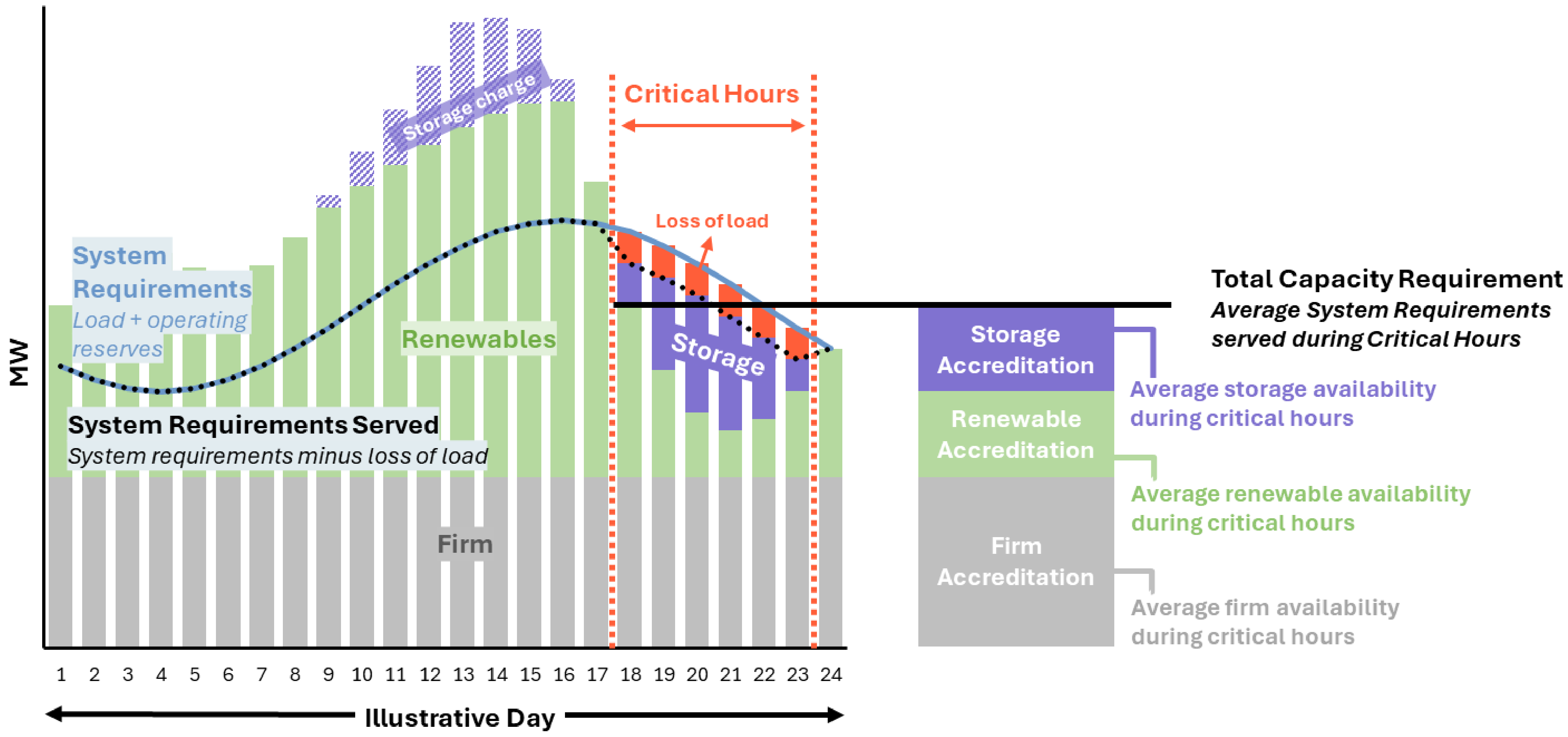
TPRM
- *Target planning reserve margin*
- *PRM required to achieve a specified reliability threshold (i.e. LOLE, ALOLP, or EUE)*

Tool Category	Tool Name	Tool Provider
Commercial	2-4-C	Ernst & Young (EY)
	Aurora	Energy Exemplar
	BID3	AFRY
	Crystal Super Grid	Artelys
	Enelytix	Polaris Systems Optimization and Newton Energy Group
	GridView	Hitachi Energy
	MARS	General Electric
	Plexos	Energy Exemplar
	PowerSIMM	Ascend Analytics
	PROMOD	Hitachi Energy
	SDDP	PSR
	SERVM	Astrape
Open source	Antares	RTE International
	GridPath	Blue Marble Analytics
	PRAS	National Renewable Energy Laboratory (NREL)
Custom	GRARE	Centro Elettrotecnico Sperimentale Italiano (CESI)
	MAVRIC	Western Electricity Coordinating Council (WECC)
	RECAP	Energy + Environmental Economics (E3)



Source: EPRI Resource Adequacy Assessment Tool Guide

Critical Hours

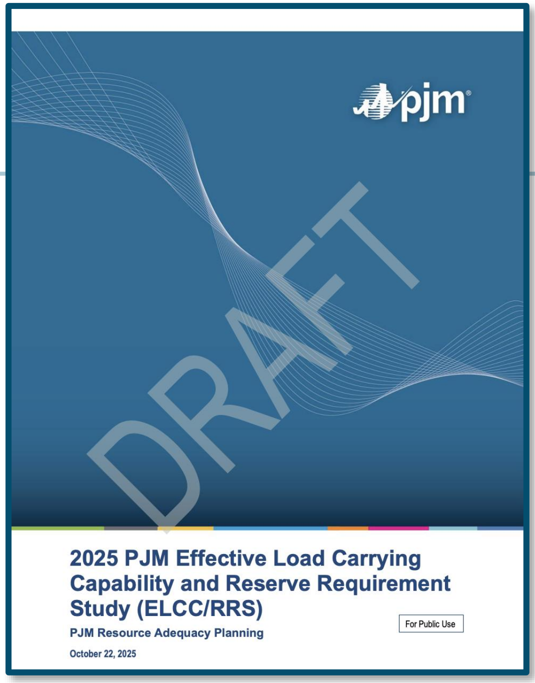


Loss-of-Load-Probability Best Practices

+ E3's experience with existing LOLP models, coupled with a review of ESIG's LOLP model review report highlighted several best practices in conducing LOLP modeling:

+ Capture a diverse range of load conditions that account for potential extreme weather
+ Simulate generator outages stochastically
+ Incorporate realistic profiles for renewable generation that capture correlation with load
+ Simulate dispatch of energy-limited resources on a time-sequential basis
+ Reflect actual expected system operations
+ Ensure statistical significance of results
+ Balance accuracy with tractability
+ Promote transparency

PJM’s Approach to LOLP Modeling



- **Many aspects of PJM’s Model are addressed in more detail throughout this presentation (as well as in PJM’s extensive documentation)**
- **Several notable features of PJM’s model include:**
  - **40,300 simulated years**
    - 31 historical weather years, 13 load rotations, and 100 resource availability draws
  - **12 years of historical resource performance data (2012 – 2024)**
    - Used to create resource availability draws
  - **Scrambling of load and resource performance using a temperature-based binning approach**
    - Each day is assigned to a specific “bin” based on a PJM-calculated temperature-humidity index (“THI”) - the model then stochastically pairs historical resource performance days with historical load days that occur within the same THI bin
  - **No scrambling of resource performance classes**
    - The model draws resource availability for all resource classes (e.g., solar, wind, thermal) from the same historical day to preserve correlation between resource classes
  - **Chronological dispatch**
    - The model chronologically dispatches energy-limited resources such as energy storage and demand response to meet the residual needs of the system that other resource classes (including thermal and renewables) could not meet. Any unserved energy is classified as loss-of-load

Questions

Evaluation of PJM ELCC/RRS Model Design

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Overview of E3 Evaluation

+ **E3 reviewed the PJM model through PJM documentation, discussions with PJM staff, the code base, and input and output files**
+ **E3 identified the following aspects of PJM's model for evaluation**
  1. Representation of Load
  2. Resource Forced Outages
  3. Resource Planned and Maintenance Outages
  4. Unlimited Resources Capability and Deliverability
  5. Variable Resource Availability and Deliverability
  6. Load and Resource Scrambling
  7. Dispatch of Energy Limited Resources and Demand Response
  8. Resource Accreditation
+ **For each aspect, E3 provided the following:**

1) Industry Best Practice   2) PJM Approach   3) E3 Evaluation

In totality, E3's review finds that PJM's ELCC/RRS model is reasonable and fit-for-purpose. E3's review also identifies several areas of the model where PJM may consider making future improvements

Representation of Load

Industry Best Practice

- **Include a diverse range of potential load (weather) conditions**
- **Use load profiles that accurately reflect the level and shape of expected loads during given weather and calendar conditions**

PJM Approach

- **Regression analysis to simulate hourly loads for 31 historical weather years** (June 1993- May 2024)
- **Additionally rotate each weather year pattern by +/- 6 calendar days to reflect that weather patterns from a given day could reasonably have occurred on nearby dates**

E3 Evaluation

Pros	Cons
+ Appropriately model wide range of potential weather conditions and load levels + Simulated loads levels in different weather conditions match historical observations + Simulated load shapes match expected seasonal and diurnal load shapes	+ 13 load rotations may result in six of the seven days of the week being simulated twice for a given historical weather day, and one day of the week simulated once

Figure 4: Daily Peaks of Simulated & Historical Load in Winter

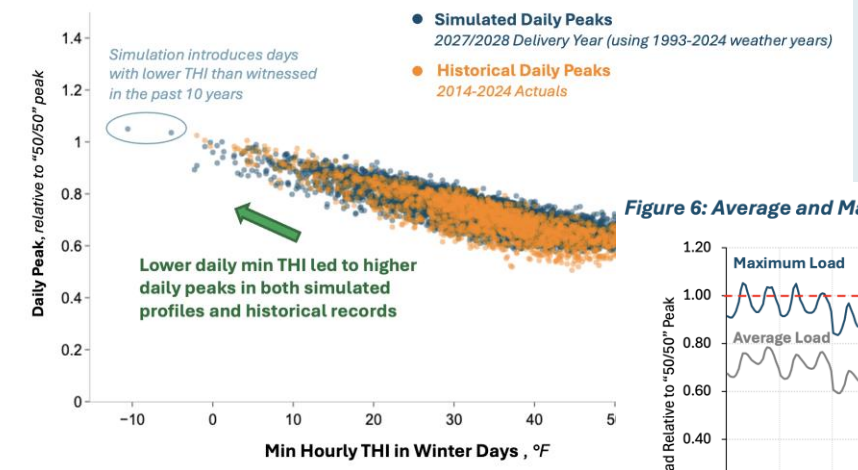
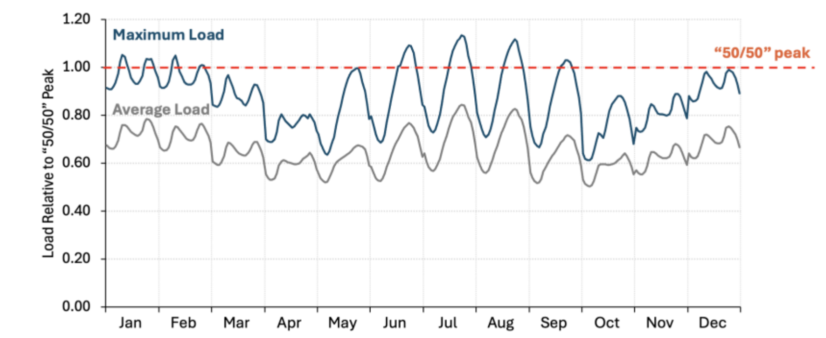


Figure 6: Average and Maximum Loads by Month-Hour



Resource Forced Outages

Industry Best Practice

+ **Simulate a diverse range of outage performance that reflects observed and expected performance**
+ **If historical data suggests a possible risk of correlated outages due to common mode issues, incorporate in the model to reflect these risks**

PJM Approach

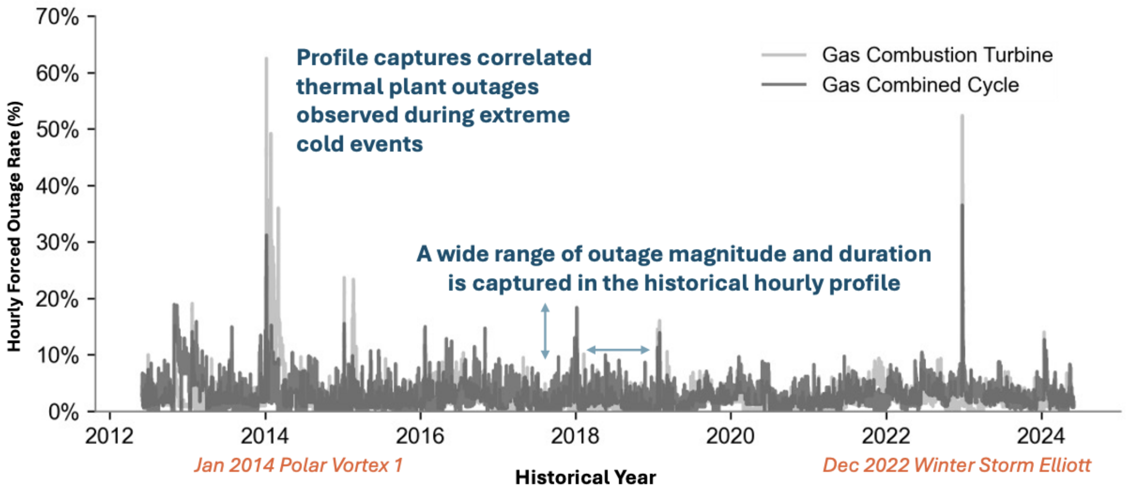
+ **Unlimited resources:** Uses historical forced outage profiles that capture variability and extreme events
+ **Variable resources:** Forced outages are embedded in historical availability data
+ **Battery storage:** Applies a static EFORd* derate that does not explicitly capture outage variability

* Equivalent Forced Outage Rate on Demand

E3 Evaluation

Pros	Cons
+ Simulates a diverse range of aggregate dispatchable performance, including periods of higher-than-normal outage conditions for unlimited and variable resources + Captures correlated outage events for unlimited and variable resources that are driven by common mode issues to the extent that these events are included in historical data	+ Static assumption of battery storage forced outages does not capture periods of higher-than-average forced outages and is inconsistent representation of unlimited and variable resources

Figure 7: Historical Forced Outage Record of Unlimited Resources



Resource Planned and Maintenance Outages

Industry Best Practice

+ **Schedule planned and maintenance outages in low-risk periods**
+ **Allow some maintenance during high-risk periods when inflexible scheduling or imperfect foresight make it unavoidable**

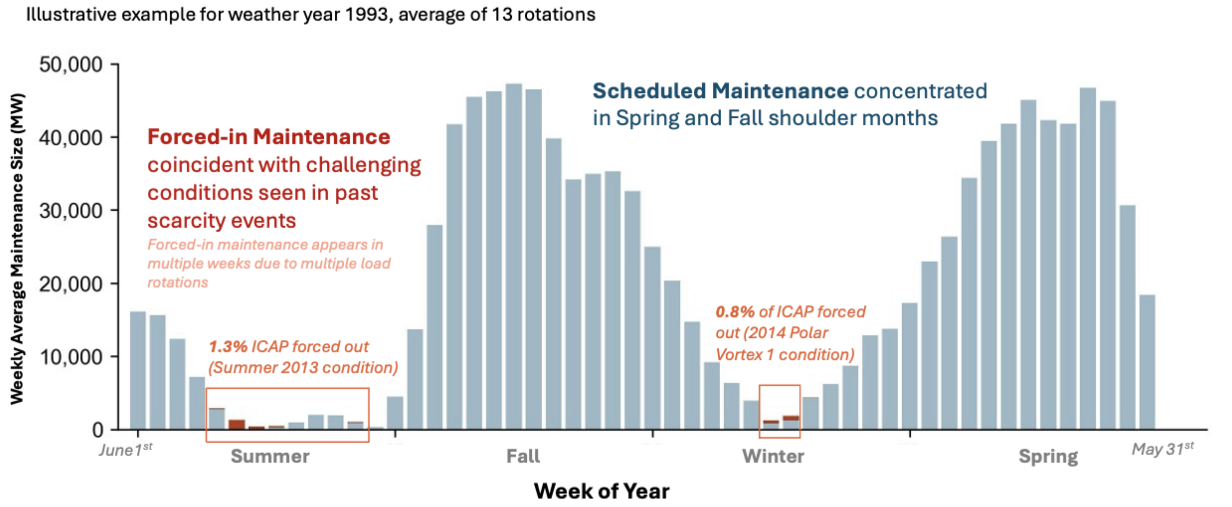
PJM Approach

+ **PJM models planned and maintenance outages for unlimited resources using "scheduled" and "forced-in" outages:**
  - **Scheduled** outages are scheduled into lowest gross load periods with a valley-filling method
  - **Forced-in** outages reflect a minimum quantity of resources being offline during seasonal peak load weeks, based on planned outages observed in past scarcity events

E3 Evaluation

Pros	Cons
+ Reflects expected real-world planned and maintenance outages by 1) smartly scheduling outages into periods of lowest risk and 2) recognizing that imperfect foresight will yield some minimum level of resources on maintenance during scarcity events	+ Use of gross load to define risk periods does not fully align with evolving risk patterns as variable and energy storage resource penetrations increase (although gross load is used to some degree in PJM operational practices)

Figure 8: Weekly Average Maintenance and Planned Outages for 1993 Weather



Questions

Unlimited Resources Capability and Deliverability

Industry Best Practice

+ **Represent changes to maximum potential generation capability** (e.g., outages, ambient derates) **based on real-time system conditions while recognizing tractability limitations**
+ **Represent key system network constraints, e.g., through resource deliverability constraints or zonal modeling**

PJM Approach

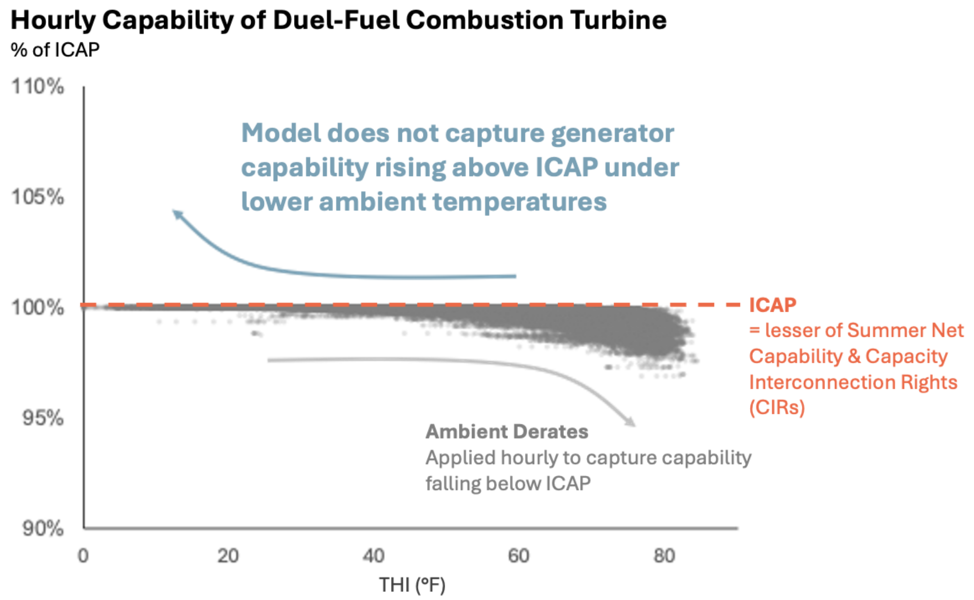
+ **PJM caps unlimited resources at their ICAP rating** (lower of Summer Net Capability or Capacity Interconnection Rights) **for all hours of the year**
+ **On an hourly basis, resource output are derated under high temperatures using ambient derate profiles from historical eDART* data and aggregated by class**

* electronic Dispatcher Application and Reporting Tool

E3 Evaluation

Pros	Cons
+ Ambient derates are applied to adjust resource capability when temperatures rise + Network constraints are incorporated through deliverability limitations	+ Generator capability is limited to potential capacity output in ambient summer peak conditions

Figure 9: Thermal Resource Capability Limited at ICAP



Variable Resource Availability and Deliverability

Industry Best Practice

- Use 5–10+ years of hourly availability profile to capture low, average, and high conditions
- Preserve correlations between electricity demand and variable resources
- Reflect key network constraints, e.g., through resource deliverability constraints or zonal modeling

PJM Approach

- PJM develops 12 years of hourly availability profiles for wind, solar, hydro, and landfill gas from settlement data or weather-based simulations
- Solar and Wind output is capped by deliverability constraints under three snapshots of system conditions: "Summer", "Winter", and "Light-Load"

E3 Evaluation

Pros	Cons
+ Sufficient number of years of historical variable resource availability data (12 years) to capture full spectrum of potential conditions + Aggregating time-matched individual profiles to develop resource-class profiles appropriately represents geographic diversity and correlations between variable resources + Deliverability constraints are applied to reflect network limits in a tractable (3 time-of-year periods) manner	+ Limited temporal granularity of deliverability constraints (summer deliverability, winter deliverability, light-load deliverability) limits overall granularity of variable resource representation. However, too much temporal granularity is intractable + "Time-of-year" methodology to assign deliverability constraints to hours in PJM Model does not directly reflect system conditions

Figure 10: Variable Resource Availability Reflected in 2012-2024 Weather Year Profiles

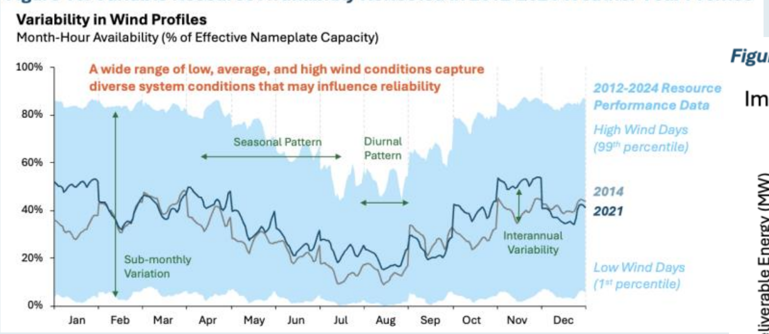
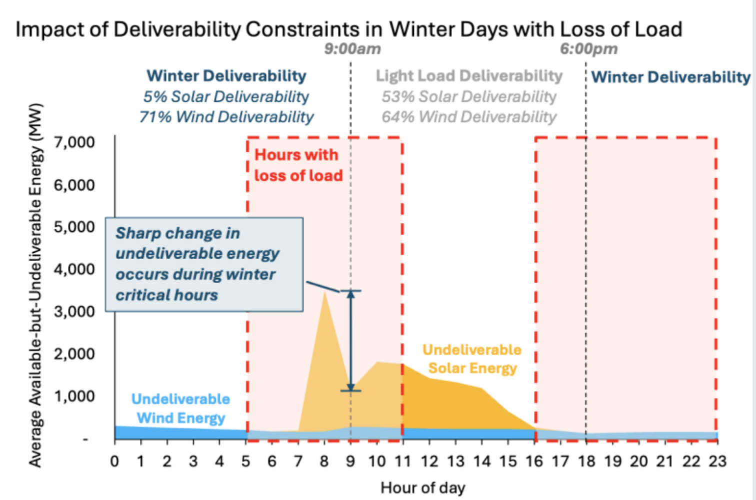


Figure 12: Average Undeliverable Energy in Winter Days with Loss of Load



Load and Resource Scrambling (1 of 2)

Industry Best Practice

- **Preserve realistic load–resource correlations by restricting scrambling to similar weather, load, and date**
- **Ensure that plausible high-risk events** (e.g., high load paired with low variable generation) **are represented**
- **Ensure sufficient scrambling replications so that model results are statistically significant**

PJM Approach

- **PJM implements a scrambling methodology by limiting scrambling to within a set of PJM-defined bins based on temperature-humidity index ("THI" bins) for both the summer and winter seasons**
- **PJM's approach scrambles, with equal probability, daily load profiles and daily resource availability profiles within each THI bin**
- **To ensure sufficient scrambling, PJM derives 100 unique resource generation profiles for each day within the 13 load rotations**

Figure 13: Seasonal THI Bins Used in PJM Model

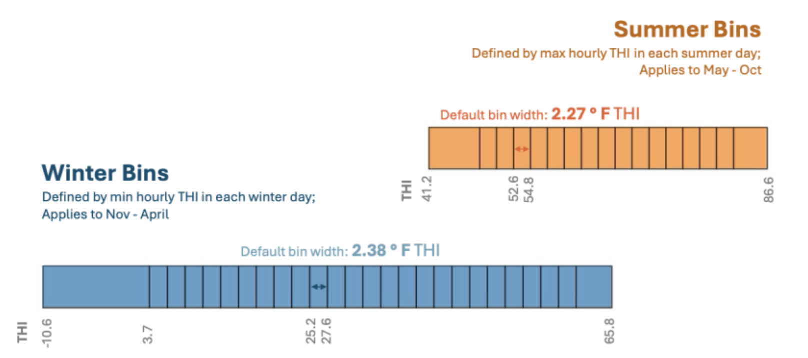
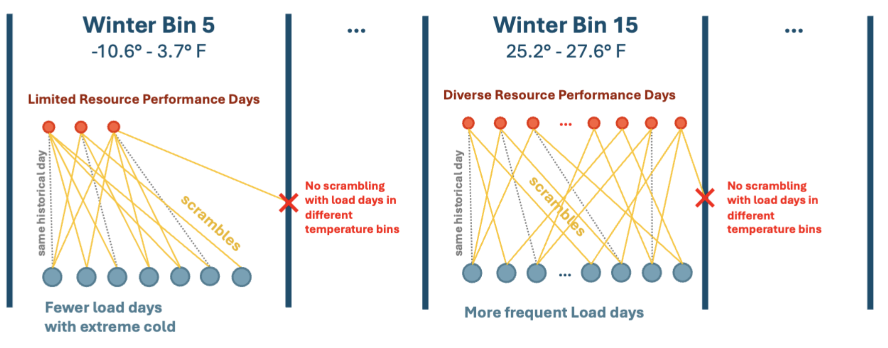


Figure 14: Illustration of Scrambling Process in ELCC/RRS Model



Questions

Load and Resource Scrambling (2 of 2)

E3 Evaluation

Pros	Cons
+ Aligns with industry best practice by scrambling load profiles and resource availability profiles in a way that introduces new plausible conditions while preserving correlation between load and resource performance by linking them through temperature	+ Weather for resource performance bins is not aligned with weather for load in “load rotations”, which fails to preserve realistic correlation between loads and resources
+ By not scrambling resource classes from different historical days, PJM’s approach preserves performance correlations between resource classes	+ Does not capture high or low multi-day resource performance events in ways that aligns with historical observations (unlikely to significantly impact model results until larger quantities of storage are present)
+ Bin sizes ensure sufficient resource performance observations in each bin	+ By assigning equal likelihood to recent resource performance days and those far in the past, PJM’s approach may not reflect the system “as is” if resources have undertaken improvements or enhancements
+ Number of resource performance draws ensure statistically significant results	

Figure 18: PJM 2027/28 BRA Simulated LOLE results by Load Rotation Scenario

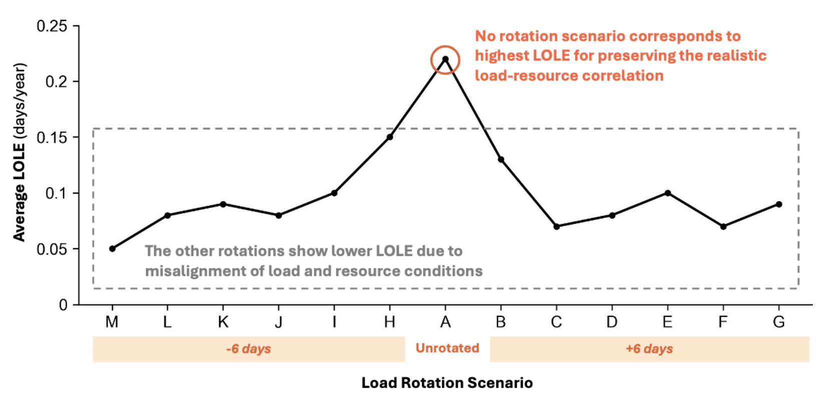
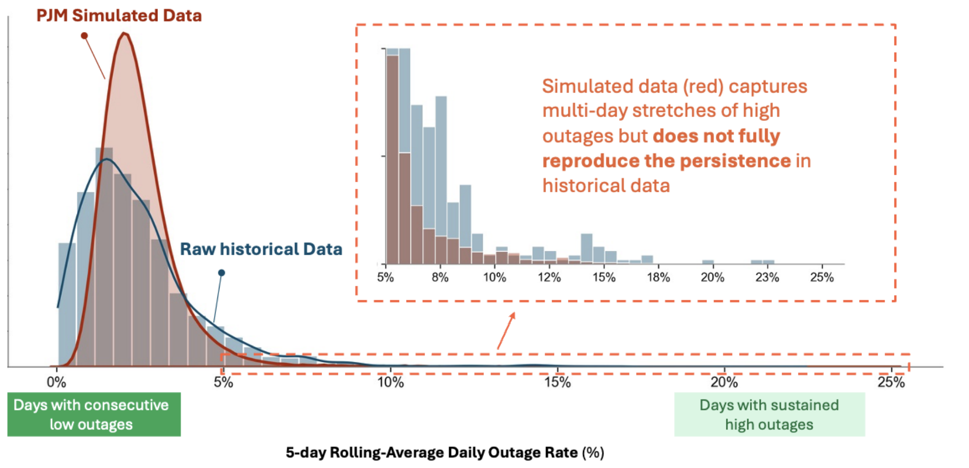


Figure 20: Consecutive-Day Average Forced Outage Rates Before and After Scrambling



Dispatch of Energy Limited Resources and Demand Response

Industry Best Practice

+ Use a tractable heuristic that approximates reliability-maximizing dispatch of energy-limited resources while accounting for imperfect foresight
+ Use time-sequential simulation to track state of charge, efficiency losses, and demand-response call limits

PJM Approach

+ Use a "more available resources dispatched first" methodology to first dispatch those with longer durations
+ Prohibits storage charging during demand response dispatch and charges energy-limited resources simultaneously at equal rates using excess unlimited/variable energy

E3 Evaluation

Pros	Cons
+ Hourly time-sequential dispatch of energy limited resources and demand response aligned with industry best practices in LOLP modeling	+ Dispatch of energy limited resources could be more optimal through an improved dispatch order. However, this would increase complexity and decrease tractability
+ Tractable dispatch heuristic reasonably approximates system operations and facilitates thousands of model simulations	+ Dispatch of energy limited resources could be more optimal by allowing energy storage to charge in hours where demand response is dispatched

Resource Accreditation

Industry Best Practice

+ **Implement a marginal ELCC framework that accredits resources based on their availability during critical hours**
+ **For practicality, calculate marginal ELCCs by resource class and differentiate individual resources based on a simpler heuristic**

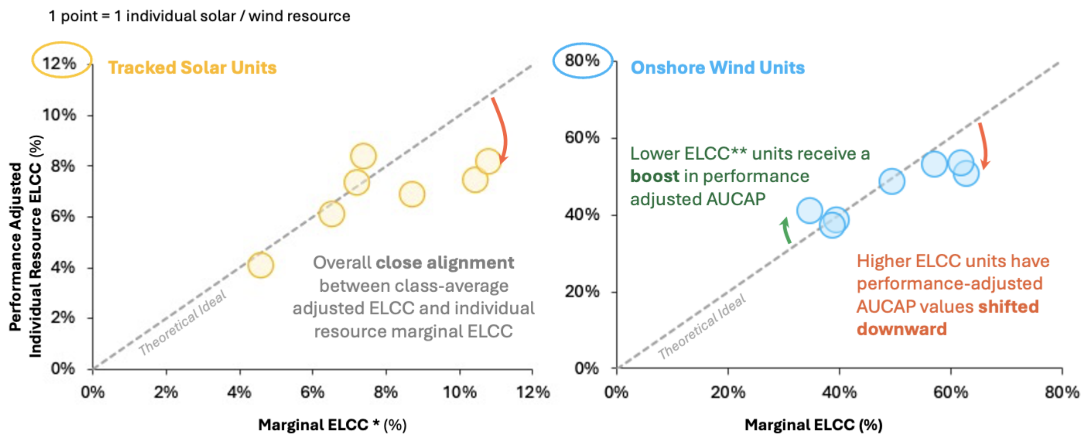
PJM Approach

+ **Calculates marginal ELCC for defined resource classes as the incremental reliability benefit** (in reduced EUE) **relative to a perfect resource**
+ **Assigns individual resource accreditation using "performance adjustment" factors based on average availability during loss-of-load temperature conditions**

E3 Evaluation

Pros	Cons
+ Accreditation founded on a marginal ELCC metric accurately and fairly accredits resource classes	
+ Individual performance adjustment approach yields Accredited Unforced Capacity (AUCAP) accreditation values that reasonably align with individual marginal ELCC values	
+ Performance adjustment approach flattens noise in historical data that may yield anomalous results	

Figure 24: Comparison of PJM Performance Adjustment ELCC with Marginal ELCC



* Marginal ELCCs are approximated with average resource generation during critical hours (more are discussed in the section b elow)
** Lower ELCC for certain units may reflect inherently low performance quality or over-penalization for unavailability during historical critical hours

Questions

Validation of Model Performance

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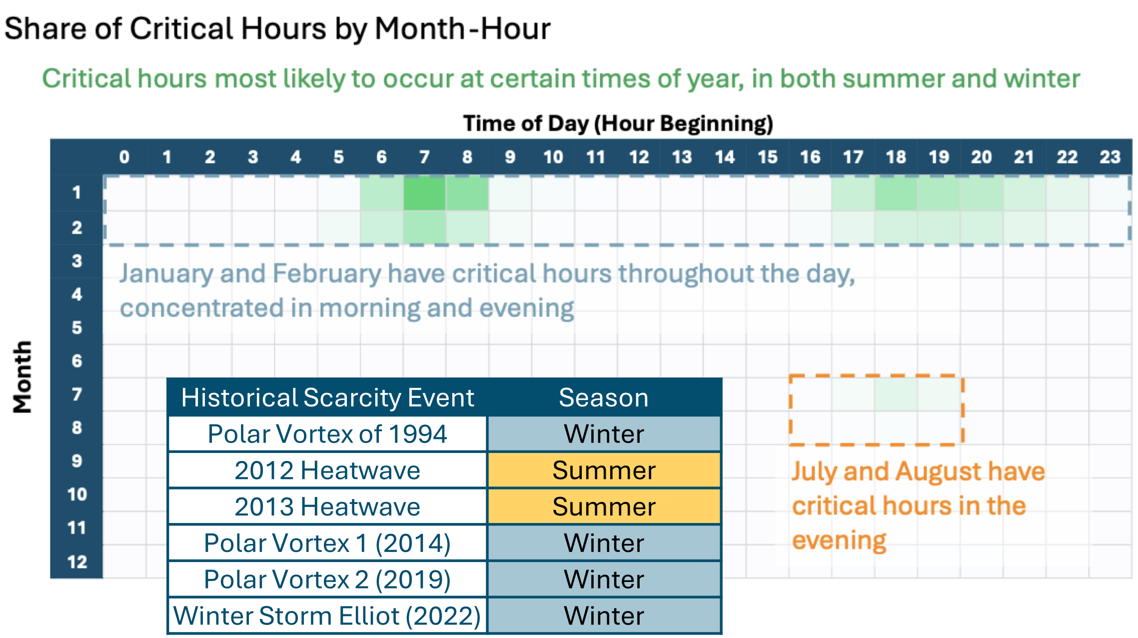
Validation of Critical Hour Timing

- Critical hours are the periods where extra energy or load reduction reduces unserved energy; load and resource availability during these hours fundamentally drive Forecast Pool Requirement (FPR) and resource class Effective Load Carrying Capability (ELCC) results
- PJM currently estimates critical hours in a post-processing step to the ELCC/RRS model. Specifically, PJM uses a heuristic method to approximately identify critical hours by identifying both “loss-of-load hours” and “energy benefit hours”, which are hours where additional energy allows energy storage to save charge for later in the day

Figure 25: Critical Hours Timing by Month-Hour



Historical Scarcity Event	Season
Polar Vortex of 1994	Winter
2012 Heatwave	Summer
2013 Heatwave	Summer
Polar Vortex 1 (2014)	Winter
Polar Vortex 2 (2019)	Winter
Winter Storm Elliot (2022)	Winter

The model identifies critical hours predominantly in winter** (with some in summer)**, aligning with historical scarcity events that have occurred in both seasons but more frequently during severe winter conditions. This additionally aligns with growing heating electrification and solar that is increasingly shifting more risk to winter

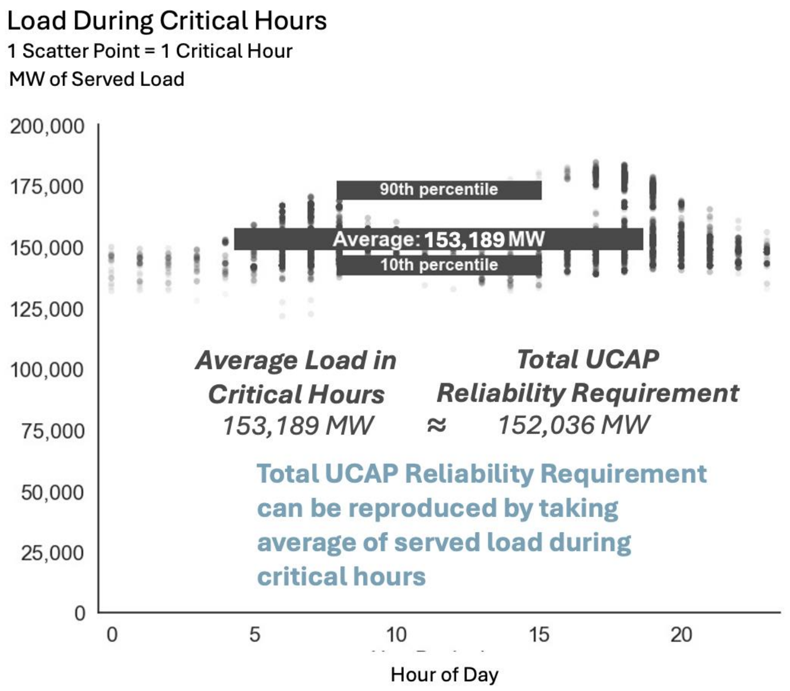
Validation of Forecast Pool Requirement Value

+ **The Total UCAP Reliability Requirement is theoretically equal to average* load during critical hours**
+ **As shown in the table, the relative alignment between these two values (<1% difference) indicates that the model is accurately calculating the reliability requirement**
    - The lack of exact alignment is due the post-processing heuristic approach used by PJM to identify critical hours that is not perfectly optimal

2027/2028 BRA Total UCAP Reliability Requirement vs Average Load During Critical Hours

Item	Value	Formula
Forecasted Peak	164,186 MW	[A]
Forecast Pool Requirement (FPR)	92.6%	[B]
Total UCAP Reliability Requirement	152,036 MW	[C] = [A] x [B]
Average Load During Critical Hours *Can be used to approximate Total UCAP Requirement*	153,189 MW *Within 1% of Total UCAP Requirement*	[D]

Figure 26: Load During Critical Hours



*for simplicity, assuming that all critical hours are equally critical

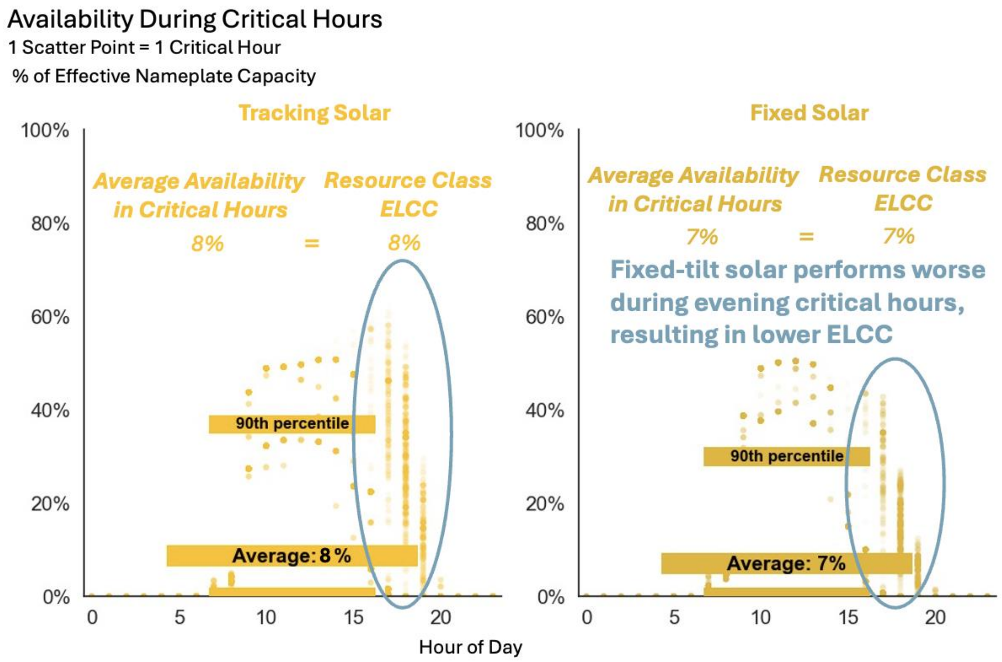
Validation of resource class ELCC value

- Marginal Effective Load Carrying Capability ("ELCC") values are theoretically equal to average* resource availability during critical hours
- Comparing PJM-calculated marginal ELCC values with average availability during critical hours, the very close alignment between these two validates that the ELCC values calculated by the model accurately represent the availability of these resource classes during the hours most critical to system risk

PJM 2027/28 BRA ELCC Results vs Average Availability in Critical Hours

Resource Class	Average Availability in Critical Hours (%)	Marginal ELCC (%)	Difference (%)
Onshore Wind	40%	41%	-1%
Offshore Wind	67%	67%	0%
Solar Fixed	7%	7%	0%
Solar Tracking	8%	8%	0%
4hr Storage	58%	58%	0%
6hr Storage	67%	67%	0%
8hr Storage	70%	70%	0%
10hr Storage	78%	78%	0%
Demand Response	92%	92%	0%

Figure 27: Solar Availability During Critical Hours



Validation of storage ELCC values

- As with all resources, the average dispatch of energy-limited resources during critical hours is equivalent to these resources' marginal ELCC
- Because the dispatch of energy-limited resources is controllable, the most relevant factor that limits the ELCC of these resources is the *duration* of critical events
- For example, a 4-hour duration battery would run out of charge during a 5-hour critical event and not be available for dispatch in the last hour
- The figure below shows the duration of critical events in the ELCC/RRS model – the prevalence of many long-duration critical events (particularly in winter) explains the ELCC values calculated by the ELCC/RRS model for energy-limited resources

Figure 28: Duration of Critical Hour Periods

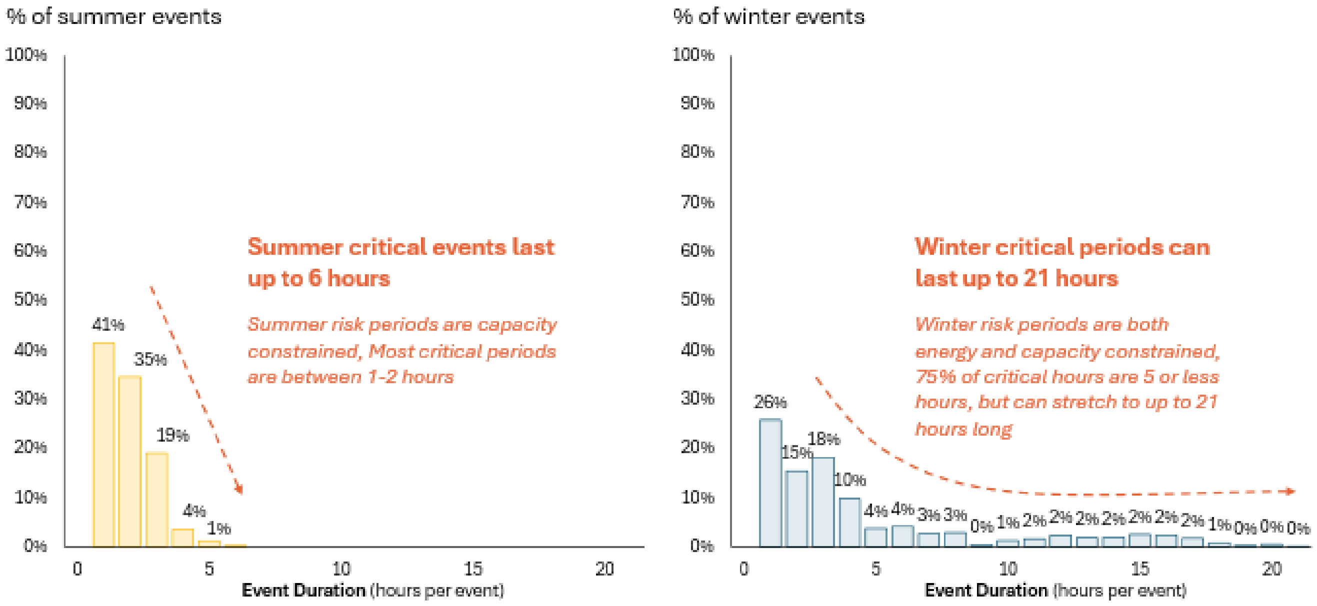
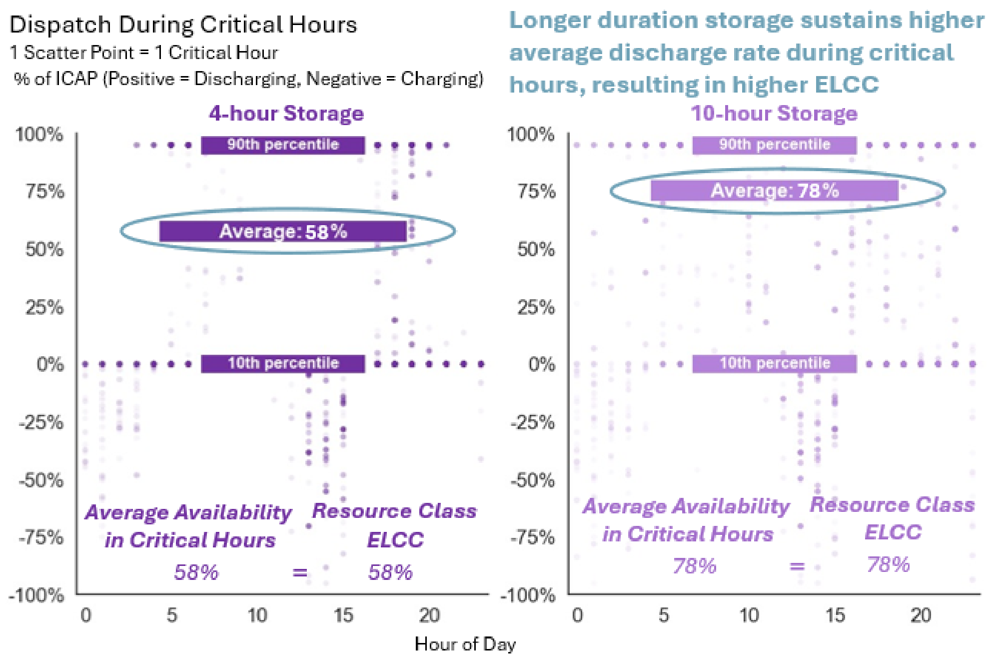


Figure 29: Storage Dispatch in Critical Hours



Other Model Validation Tests

- E3 further designed and performed a series of tests to further validate that the PJM Model is internally consistent and works as intended to produce transparent, explainable reliability results
- Specifically, E3 performed three validation "Test Types":
  - **Verification**: confirm that model inputs, intermediate data, and outputs align with PJM's documentation
  - **Replication**: reproducing selected model results using model inputs or upstream model components
  - **Assessment**: evaluating whether model inputs, intermediate data, and outputs fall within expected value ranges

Example validation tests conducted for "Load and Resource Scrambling" Design

Data Access	Test Type	Description of Test
Public	Verification, Replication	E3 tested and verified that applying Freedman–Diaconis rule to THI data replicates the same 31 winter bins and 20 summer bins published by PJM (pre-merge)
Public	Verification, Replication	E3 verified that assigning June 1, 2012 – May 31, 2024 resource performance days to summer and winter THI bins using hourly THI profile replicates resource performance days in each THI bin published by PJM
Public	Assessment	E3 validated that scrambling of renewable generation and thermal availability profile based on PJM published "Montecarlo by date" mapping file reproduces the scrambled profiles which are in the PJM model and published in "info for loss of load hours" file (for days with publish data)
Public	Verification	E3 verified that in the "Montecarlo by date" mapping file all of the 100 resource performance days come from the same THI bin as the load day they are matched to
Public	Verification, Assessment	E3 replicated and validated that scrambled net load profiles (gross load net of variable and unlimited resource availability) has a distribution of daily peak net load aligned with unscrambled net load profiles (see Figure 17: Daily Peak Load Net of Availability Resources Before and After Scrambling)

Questions

Considerations for Improvement

Evaluation Criteria to Potential Considerations for Improvement

- E3's review identifies several aspects of the model where PJM may consider making future improvements
- Rather than recommend specific changes to the ELCC/RRS model, E3 evaluates potential considerations for improvement according to the following criteria: accuracy, objectivity, stability, transparency, tractability, impact, and ease of implementation

Key Evaluation Criteria

1. **Accuracy**
   How well a model change improves the model's representation of system reliability risks or resource capacity accreditation?
2. **Objectivity**
   Does a model change increase or decrease subjective modeling inputs or methods?
3. **Stability**
   How well a potential model change improves the ability of the model to produce robust results that do not significantly change due to small input changes?
4. **Transparency**
   How clearly model methods, inputs, and results are documented and communicated?
5. **Tractability**
   Does a model change increase or decrease the computational and human effort to run the model ?
6. **Impact**
   The magnitude of impact on system reliability risks or resource capacity accreditation of a model change
7. **Ease of Implementation**
   The level of effort for PJM to implement a model change

Summary of Considerations for Improvement

Benefit of implementing a consideration
Caution of implementing a consideration
Drawback of implementing a consideration

Table to right summarizes E3's consideration for improvement and how each scores along the evaluation criteria

Each consideration is discussed in more detail throughout this section

higher — Approximate Prioritization — lower

Consideration *In order of approximate prioritization*	Accuracy	Objectivity	Stability	Transparency	Tractability	Impact	Ease of Implementation
1) Improve identification of critical hours		Benefit		Benefit	Benefit / Caution	Benefit	Drawback
2) Publish critical hours, including load and resource availability data during these hours				Benefit			Caution
3) Update the scrambling process to draw resource performance from the same weather condition used to synthesize load	Benefit					Benefit	Benefit
4) Use more temporal granularity to model capability and deliverability of unlimited resources	Benefit				Caution	Benefit	Benefit / Drawback
5) Schedule planned maintenance based on net load	Caution					Caution / Benefit	Benefit
6) De-weight historical resource performance events as new resource performance events under similar weather conditions occur	Benefit	Caution	Benefit		Caution	Caution	Caution
7) Increase the number of load rotations to balance days-of-week	Benefit					Caution	Caution
8) Calculate solved load by adding or subtracting "flat" load instead of scaling load	Benefit			Benefit		Caution	Benefit
9) Stochastically model hydro resources and extend hydro record	Benefit		Benefit			Caution	Caution
10) Stochastically model forced outages for storage resources	Benefit				Caution	Benefit / Caution	Caution
11) Evaluate improved mapping of deliverability constraints to system conditions	Benefit				Drawback	Caution	Drawback
12) Represent "Capacity Benefit of Ties" on a more time-granular basis	Benefit				Caution	Caution	Drawback
13) Study updates to resource performance sampling methodology to capture multi-day events	Benefit				Caution	Caution	Caution
14) More optimally dispatch energy storage, demand response, and hydro	Benefit	Benefit			Drawback	Caution / Benefit	Drawback

Consideration 1: Improve identification of critical hours

- PJM currently uses a heuristic method to approximately identify critical hours by identifying both loss-of-load hours and "energy benefit hours" through a heuristic approach
- While this is a reasonable method to identify critical hours, there is opportunity to improve accuracy, e.g., PJM's process identifies each hour as critical or non-critical, but does not measure the "criticality" of each hour
- PJM could refine its approach to identifying critical hours, e.g., through an optimization model that identifies the "shadow price" of energy in each hour
  - Ideally, the model would produce the criticality of each hour as a direct output without any post-processing or heuristic approximation

Consideration 1: Improve identification of critical hours	
Accuracy	N/A
Objectivity	More robustly identifying critical hours removes the need for a heuristic method to approximately identify critical hours
Stability	N/A
Transparency	Improved identification of critical hours supports a more transparent model by facilitating stakeholder vetting and understanding
Tractability	An automatic model process to identify critical hours (as opposed to a post-processing heuristic) reduces burden on the modeler and improves tractability
	Implementing optimization or a "brute force" method into the model increases computational requirements and decrease tractability
Impact Level	While identifying critical hours would not have any direct impact on results, identifying critical hours would improve transparency and have a significant impact on stakeholder understanding of the model and the ability to vet and check results
Ease of Implementation	More rigorously identifying critical hours through optimization requires a moderate to large implementation effort

Consideration 2: Publish critical hours, including load and resource availability data during these hours

- PJM currently publish the modeled loss-of-load hours to provide stakeholders with insight into the timing and duration of loss-of-load risk
- Publishing critical hours can greatly improve model transparency by allowing market participants, stakeholders, and policymakers to review the underlying data that drives FPR and ELCC values
- PJM could consider publishing all critical hours, including load and resource availability data during these hours. PJM could also consider publishing calculations demonstrating how model results (FPR and ELCC) align with load and resource availability during critical hours

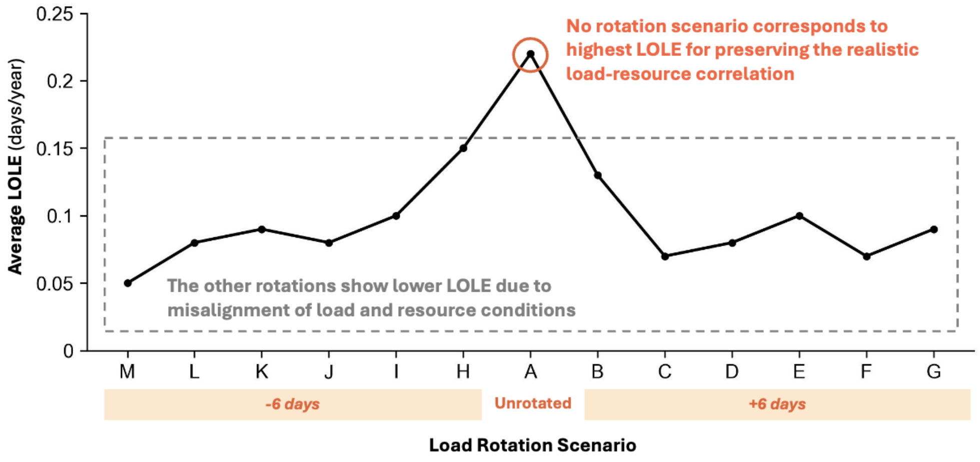
Consideration 2: Publish critical hours, including load and resource availability data during these hours	
Accuracy	N/A
Objectivity	N/A
Stability	N/A
Transparency	Publishing critical hours allows stakeholders to scrutinize and understand how FPR and ELCC results are derived, reducing the “black box” element of LOLP modeling. This is the single most important step PJM can take to increase model transparency
Tractability	N/A
Impact Level	N/A
Ease of Implementation	Small to moderate effort to publish critical hours and load and resource availability during these hours

Questions

Consideration 3: Update the scrambling process to draw resource performance from the same weather condition used to synthesize load

- The current PJM modeling approach samples resource performance values for each day from the weather bin associated with that particular date, even when rotates different weather through that day
- This leads to misalignment between the weather conditions reflected in the load profile and the weather conditions reflected in the resource performance assumptions, leading to over-stating system reliability
- PJM could instead consider drawing resource performance values from the same weather bin that was used to synthesize the load on each day to more accurately capture the correlation between temperature, load, and resource performance
  - *This consideration for improvement is aligned with PJM Package C, where PJM studied the impact of this change for 2026/2027 BRA inputs and determined that there is a measurable increase in overall system risk (IRM increases 3.3%) and decrease in accreditation for most resource classes*

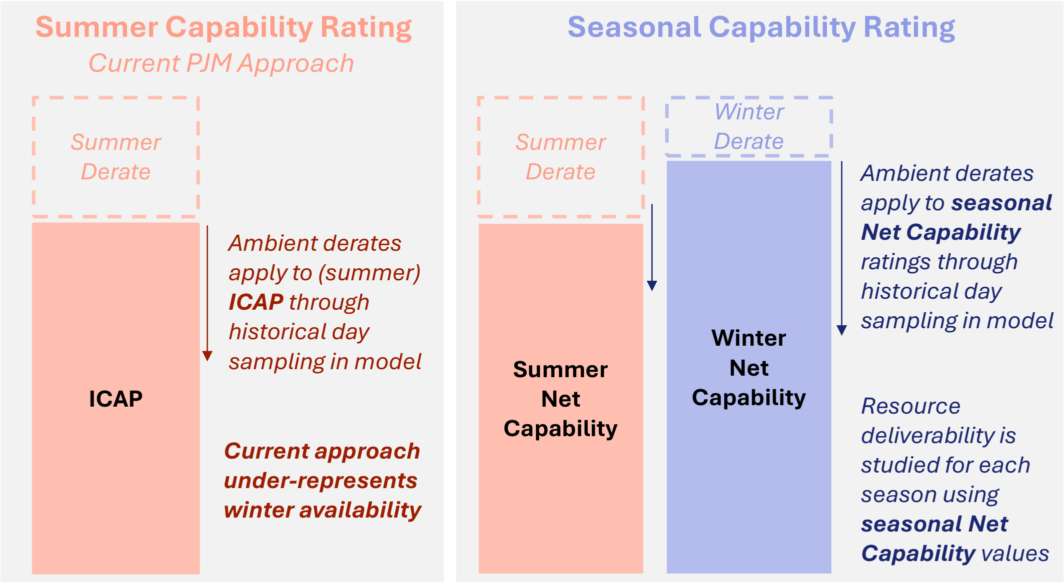
Figure 18: PJM 2027/28 BRA Simulated LOLE results by Load Rotation Scenario



Consideration 3: Update the scrambling process to draw resource performance from the same weather condition used to synthesize load	
Accuracy	Improved model accuracy by ensuring load and resource performance is drawn from consistent weather conditions to capture correlations.
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	N/A
Impact Level	Modest to high impact on IRM and ELCC values as indicated by PJM sensitivity analysis
Ease of Implementation	Low implementation effort given that PJM has already built this functionality to test impacts as part of Package C

Consideration 4: Use more temporal granularity to model capability and deliverability of unlimited resources

- PJM currently limits the availability of "unlimited" resources to their ICAP rating in all hours, with additional de-rates applied based on ambient conditions
- However, unlimited resources generally have higher availability outside of summer peak conditions due to colder ambient temperatures. Capping resource availability at ICAP therefore under-represents the availability of unlimited resources in periods outside of summer peak conditions
- PJM could consider representing availability with more temporal granularity, specifically on a "seasonal" or "daily" basis



Consideration 4: Use more temporal granularity to model capability and deliverability of unlimited resources	
Accuracy	Reflects resource capability changing with temperature conditions, increasing model accuracy
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	More granular data increases complexity of model
Impact Level	High impact. Approximately ~8 GW of additional unlimited resource capability in the winter months, ~1% IRM reduction.
Ease of Implementation	Low difficulty to implement a seasonal approach (which PJM has already done)
	High difficulty to implement daily approach

Questions

Consideration 5: Schedule planned maintenance based on net load

- PJM model currently scheduled planned and maintenance outages into lowest *gross load* periods, intending to both mimic actual operations and minimize system risk by concentrating maintenance during spring and fall shoulder seasons
- However, as renewable penetration increases and system risk patterns evolve, gross load may no longer serve as the biggest predictor of system risk
- Instead, PJM could consider scheduling maintenance into periods of lowest *net load*
  - In making any potential changes, PJM will need to ensure that its LOLP modeling is consistent with operational practices

Consideration 5: Schedule planned maintenance based on net load	
Accuracy	Scheduling planned maintenance based on **net load** rather than gross load improves accuracy by better aligning maintenance with periods of lower reliability risk. However, modeling maintenance inconsistently with operational practices could reduce accuracy.
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	N/A
Impact Level	Likely small to moderate impact level in the near-term Larger impact in the long-term as risk periods become increasingly dissociated with gross load peaks and more associated with periods of low resource availability
Ease of Implementation	Small to moderate implementation effort to model; dependency exists for operational practices

Consideration 6: De-weight historical resource performance events as new resource performance events under similar weather conditions occur

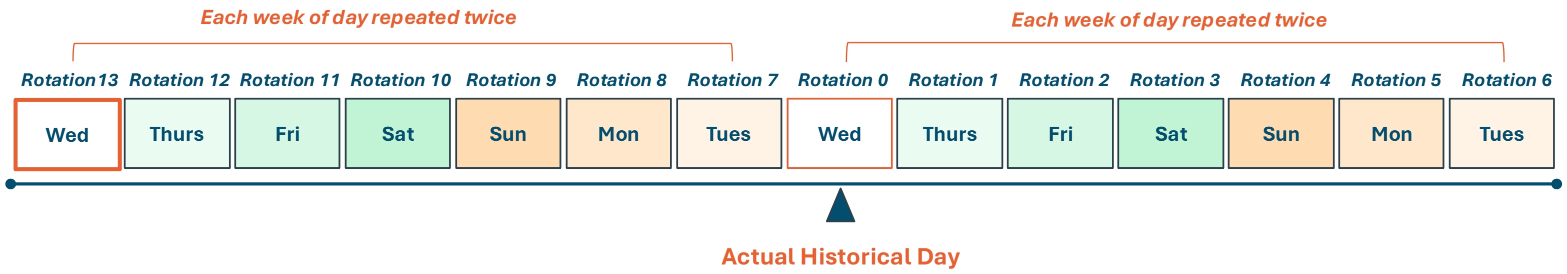
- **The current PJM model methodology draws resource performance profiles with equal probability from the weather bin this day falls into**
- **A potential concern with this approach is that it does not consider that more recent performance observations may be a better indicator of upgrades and enhancements that units can make to improve their performance over time - this is particularly important for incentivizing plants to undertake enhancements**
- **PJM could consider a balanced pathway to reflect performance enhancement measures by allowing recent unit performance to gradually replace old performance data**
  - *This consideration for improvement is aligned with PJM Package C, where PJM studied the impact of implementing different weights and determined that there is a minor impact on overall system risk (IRM increases by less than 0.4%, with the exact magnitude varying by*

Event	Year	Weight	
		Current PJM Approach	E3 Consideration
1 (most recent)	2024	1	α
2	2024	1	α
3	2022	1	$\alpha(1-\alpha)$
4	2022	1	$\alpha(1-\alpha)$
5	2018	1	$\alpha(1-\alpha)^2$
6	2018	1	$\alpha(1-\alpha)^2$
7	2014	1	$\alpha(1-\alpha)^3$
8 (oldest)	2014	1	$\alpha(1-\alpha)^3$

Consideration 6: De-weight historical resource performance events as new resource performance events under similar weather conditions occur	
Accuracy	Weighting more recent resource performance events likely improves accuracy by reflecting performance enhancement measures
Objectivity	De-weighting historical performance necessarily requires some level of subjectivity to decide how to de-weight these events
Stability	De-weighting historical performance as new events occur gradually phases out historical performance relative to removing specific historical events in a manner that is not clear or systematic. This has the potential to increase model stability
Transparency	N/A
Tractability	De-weighting historical performance is more complex than all performance days being equally probable, which decreases tractability
Impact Level	Modest impact on IRM as showed in Package C sensitivity analysis; higher impact on seasonal risk allocation depending on how much forced-outage observations in the most extreme historical bins are de-weighted.
Ease of Implementation	Moderate effort to develop appropriate weighting factors and implement in model

Consideration 7: Increase the number of load rotations to balance days-of-week

- **PJM currently develops load profiles using 30 years of historical weather data, and additionally "rotates" the weather forward and backward by 6 calendar days for a total of 13 load rotations**
- **An issue with PJM's approach is that rotating weather 6 days forward and 6 days backward means that each day of the week is represented twice *except* for the actual day of week for the historical date**
- **PJM could consider increasing the number of weather rotations to 7 calendar days forward and 6 calendar days backward for a total of 14 weather rotations, so that each day of week is represented twice**
  - Any adjustments to number of load rotations would need to remain consistent with the Load Forecast team



Consideration 7: Increase the number of load rotations to balance days-of-week	
Accuracy	Improved accuracy due to uniformly sampling the days of the week
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	N/A
Impact Level	Modest impact on reliability statistics and ELCC values
Ease of Implementation	Would require coordination with PJM Load Forecast team to ensure consistency

Consideration 8: Calculate solved load by adding or subtracting "flat" load instead of scaling load

+ **PJM's current approach to calibrating the system to the target reliability of 0.1 days/year loss-of-load-expectation is to scale load up or down**
+ **Scaling can shift critical hours more relative to an approach that adds or subtracts a "flat" load in all hours**
  - Adding flat load also better mimics the effect of adjusting firm generation, serving as the most neutral and non-interactive means of calibrating system reliability
+ **PJM could consider updating its methodology to calibrate system reliability by adding or subtracting flat load across all hours**

Consideration 8: Calculate solved load by adding or subtracting "flat" load instead of scaling load	
Accuracy	Improved accuracy by calibrating target reliability without shifting critical hours
Objectivity	N/A
Stability	N/A
Transparency	Flat load addition or subtraction is more transparent than a scaling factor
Tractability	N/A
Impact Level	Likely minimal impact on results
Ease of Implementation	Low implementation effort

Questions

Consideration 9: Stochastically model hydro resources and extend hydro record

- **PJM currently models hydro resources by matching each load year (1993 – 2024) to one specific hydro year (2012 – 2024); these parings are then used across all simulations**
  - For load years between 2012 and 2024, dedicated historical hydropower generation data are used; for load years without a corresponding hydro year, PJM selects a hydro year based on similarity of the peaks in the load years
- **The primary issue is that hydro and peak-load conditions are weakly correlated; pairing each load year with one hydro year can overlook plausible reliability risks, such as a drought year coinciding with an exceptionally high-load year**
- **Additionally, PJM's hydro dataset that includes years 2012-2014 may not capture the full range of potential interannual hydrological variability**
- **PJM could consider stochastically pairing hydro years with load years and extending the hydro record to capture a wider range of potential hydro conditions, if data is available**

Consideration 9: Stochastically model hydro resources and extend hydro record	
Accuracy	Stochastically representing hydro years and extending the hydro record would improve the accuracy of the model
Objectivity	N/A
Stability	Stochastically representing hydro years and extending the hydro record would increase stability of the model by reducing the influence of any single wet or dry year on reliability outcomes across simulations. For reference, the Northwest Power and Conservation Council utilizes an 80-year water record for use in reliability modeling
Transparency	N/A
Tractability	N/A
Impact Level	Likely a small to moderate impact given hydro's relatively small share of the resource portfolio
Ease of Implementation	Moderate implementation effort to develop extended hydro record

Consideration 10: Stochastically model forced outages for storage resources

- PJM's approach currently model storage resource outages use static de-rate that is always equal to the average outage level
  - This differs from unlimited and variable resource whose outages are modeled stochastically
- This static outage derate may miss periods where battery storage forced outages are higher than average, potentially overstating battery availability during stressed conditions
- PJM could consider enhancements to represent storage resource forced outages stochastically, consistent with the treatment of other resource classes
  - In the absence of extensive operational data, one potential enhancement is to develop generic assumptions to model storage forced outages stochastically

Consideration 10: Stochastically model forced outages for storage resources	
Accuracy	Stochastically modeling battery forced outages improves accuracy of the model
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	Stochastic modeling battery forced outages modestly increases model complexity
Impact Level	Low impact in the near term while batteries comprise a small share of the system portfolio
	Grows to moderate impact in the longer term once battery penetrations increase to a larger share of the portfolio
Ease of Implementation	Moderate effort, primarily due to gathering and developing battery forced outage data or making generic outage assumptions

Consideration 11: Evaluate improved mapping of deliverability constraints to system conditions

- **In PJM's current modeling, resource availability profiles are limited by deliverability constraints developed in PJM's Regional Transmission Expansion Plan (RTEP)**
  - For variable resource classes, deliverability constraints under three different conditions ("Summer", "Winter", and "Light-Load") are applied based on time of year; for non-variable resources, "Summer" deliverability constraints are applied to all hours of the year
- **Because congestion patterns depend on actual conditions (e.g., load levels, renewable output), time-of-year mapping may not best represent deliverability constraints in ELCC/RRS model**
- **PJM could consider improved mapping of RTEP deliverability constraints to hours in the model based on system conditions rather than "time-of-year"**
  - This will become more important as higher penetrations of variable and energy-limited resources increase the magnitude and volatility of congestion and shift critical hours beyond peak periods to an increasingly diverse set of hours driven by low generation availability

Consideration 11: Evaluate improved mapping of deliverability constraints to system conditions	
Accuracy	Improved mapping of deliverability constraints would more accurately represent congestion in the LOLP model.
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	Determining appropriate mapping of deliverability constraints to model hours would likely be a difficult and ongoing process, reducing model tractability
Impact Level	Medium impact from updating assignment of deliverability constraints to hours in PJM Model
Ease of Implementation	Medium to high implementation difficulty given large volume of data and cross-functional organizational coordination

Consideration 12: Represent "Capacity Benefit of Ties" on a more time-granular basis

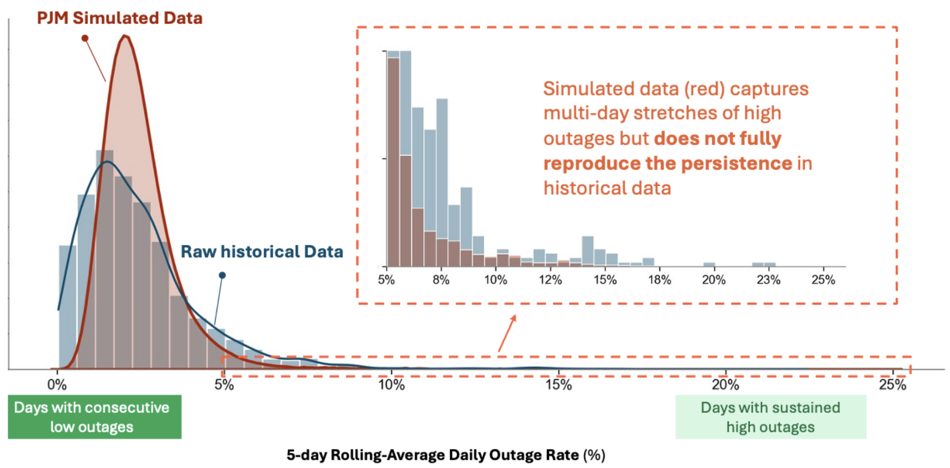
- **The Capacity Benefit of Ties (CBOT) is an assumption that is utilized in the PJM ELCC/RRS model that represents the ability of PJM to import uncommitted resources from external neighboring electricity systems during system stress**
  - The current CBOT value is administratively set to 1.5% of 50/50 peak load that is available in all hours of the year
- **However, levels of neighbor support during critical hours may vary, just as the availability of different resource classes varies on a time-granular basis.**
- **PJM could consider utilizing time-granular values for CBOT to more accurately capture these dynamics**

Consideration 12: Represent "Capacity Benefit of Ties" on a more time-granular basis	
Accuracy	Representing CBOT on a more time-granular basis would improve the accuracy of the model
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	Increasing time granularity of CBOT would increase complexity of model
Impact Level	Likely a modest impact in the near-term, but representing CBOT on a more time-granular basis could yield larger impacts over time as critical hours shift
Ease of Implementation	High effort to conduct study of external zones to understand ability to support PJM in different time periods

Consideration 13: Study updates to resource performance sampling methodology to capture multi-day events

- **PJM's current methodology draws resource performance for each day based on that day's temperature without taking into account the prior day's resource performance**
- **While this approach reproduces overall resource performance distributions, it fails to capture multi-day patterns where high or low performance tends to persist**
  - This may overstate system reliability, especially with higher levels of long-duration storage
- **PJM could consider studying an approach to capture multi-day resource performance events, e.g. by introducing the prior day's resource performance as a factor in drawing the resource performance profile for a particular day**

Figure 20: Consecutive-Day Average Forced Outage Rates Before and After Scrambling



Consideration 13: Study updates to resource performance sampling methodology to capture multi-day events	
Accuracy	Reflecting multi-day resource performance events increases model accuracy and exposes potential reliability risks and resource limitations in some resource portfolios
Objectivity	N/A
Stability	N/A
Transparency	N/A
Tractability	Implementing a persistence factor introduces some additional complexity
Impact Level	The potential impact is likely to be small at present due to limited quantities of long-duration storage. As storage penetrations grow, the impact is likely to become larger
Ease of Implementation	Moderate to high implementation effort. Capturing multi-day events will require study to identify different approaches and the performance and tradeoffs of those approaches

Consideration 14: More optimally dispatch energy storage, demand response, and hydro

- When dispatching energy-limited resources, current PJM model uses heuristic as "more available resources are dispatched first", where more available resources defined as those with longer durations
- While this is often a "smart decision", it may overlook factors beyond duration and misrepresent reliability, e.g., when longer-duration storage with lower round-trip efficiency requires more energy to recharge in an energy-limited system, or when demand response could be used to free generation to charge storage
- As portfolios include more storage and renewables, PJM could explore more optimal methods to dispatch energy-limited resources

Consideration 14: More optimally dispatch energy storage, demand response, and hydro	
Accuracy	Improved accuracy of model due to more optimal dispatch
Objectivity	Optimized dispatch is more objective than a heuristic approximation that requires estimations and subjective ordering of resource dispatch
Stability	N/A
Transparency	N/A
Tractability	Implementing optimization would likely increase computational requirements of the model and increase run-time. Maintaining tractability would require smart modeling strategies such as parallelization of different dispatch windows
Impact Level	In the near term, the impact of this change is likely to be small to moderate, as energy storage penetrations are still relatively low
	In the medium and longer term, the impact of this change is likely to be large as energy storage penetrations grow and coordination between demand response and storage dispatch becomes more important
Ease of Implementation	Implementing optimization would likely require significant effort to build the functionality and develop strategies to ensure it is tractable

Conclusion

- E3's independent evaluation concludes that PJM's Effective Load Carrying Capability / Reserve Requirement Study (ELCC/RRS) Model is a technically sound, well-structured, and transparent reliability modeling framework that accurately determines PJM's capacity requirements and resource capacity accreditation values
- The model aligns with established industry best practices for Loss-of-Load-Probability (LOLP) modeling and provides a robust foundation for ensuring that PJM is positioned to achieve its "one day in ten years" reliability standard
- E3's validation testing confirms that the model's core reliability metrics, including timing of critical risk periods, the Forecast Pool Requirement, and Effective Load Carrying Capability values are consistent with theoretical expectations and observed system performance
- E3 identified several areas of the model where PJM may consider making future improvements

Q&A

Thank You

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Energy+Environmental Economics