Outlook for Energy Storage in PJM

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The Role of Battery Energy Storage Resources in PJM

PJM has a critical near-term need for new cost-effective capacity to integrate large loads forecast through 2032. Dispatchable Resources such as Battery storage and Gas play a pivotal role in maintaining resource adequacy.

Issue: PJM is faced with several power supply constraints that raise Resource Adequacy concerns

Integrating forecasted data center loads and meeting states' clean energy goals require deployment of large amounts of firm capacity as well as intermittent renewable resources. **Tight supply availability, unresolved interconnection queue backlogs, and high resource costs are expected to limit capacity options to serve PJM's forecasted 19% peak load growth between 2025 and 2030.** The anticipated peak demand growth is so large that it may outpace available supply in the near-term.

Evaluation: Role of battery storage in addressing PJM's resource adequacy needs and state goals

This study evaluates the outlook for battery storage in PJM and the value that storage provides to PJM in reliably and cost-effectively meeting forecasted energy needs. We model the PJM system through 2045 under current forecast for load growth and cost expectations to estimate the cost-effective future resource mix in the region. We then quantify the resource adequacy implications to PJM via a hypothetical case study in which battery storage is an unavailable resource option.

Study Approach: Weather-Reflective Resource Adequacy and Capacity Expansion

We employ a state-of-the-art approach to capacity expansion by considering a wide range (of up to 25 years) of weather uncertainty, including cold snaps and heat waves, in evaluating **resource adequacy on an hourly basis wherein the PJM power grid is required to maintain reliability by meeting capacity needs in every hour, not just during peak conditions.** Within this framework, we evaluate how storage resources contribute cost-effectively to mitigate hourly resource adequacy challenges across 25 weather years.

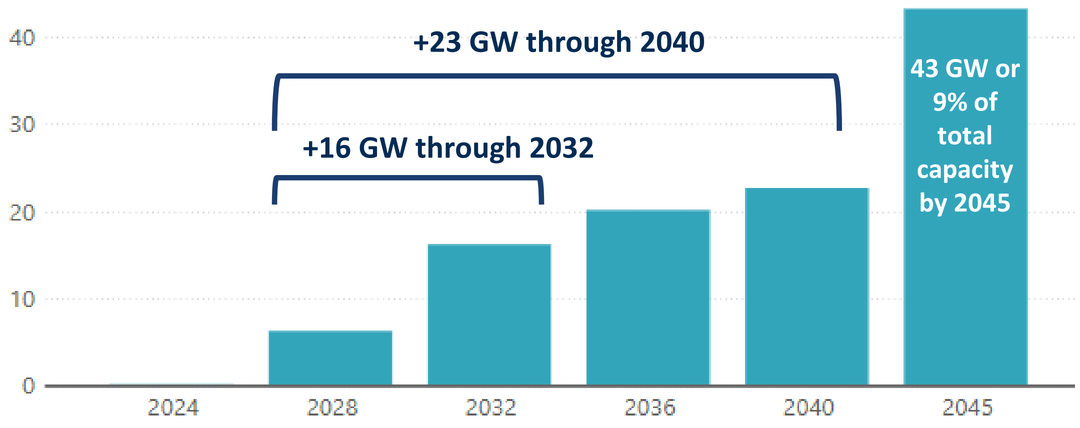
The Role of Battery Energy Storage Resources in PJM

Battery storage will play a pivotal role in cost effectively serving resource adequacy and clean energy targets

Our study projects that large quantities of dispatchable resources like storage and gas will be necessary to maintain resource adequacy and manage weather-risk in PJM.

- The demand for gas turbines is expected to exceed supply, while price pressures from trade barriers and supply chain uncertainty are adding additional cost risks across the supply ecosystem, including for gas, storage, and renewables.

Cumulative Storage Deployment in PJM (ICAP GW)



Within the next 7 to 15 years, PJM will require 16 to 23 GW of battery storage to address PJM's resource adequacy needs and state goals

- This assumes that **PJM will be able to integrate a minimum of 17+ GW of new gas resources by 2032, and delay almost all currently planned thermal retirements** to middle of the next decade
- **Slower gas resource deployment in the region would exacerbate resource adequacy challenges, necessitating even more battery storage** in the near-term
- Despite price pressures from uncertainty around trade barriers, **large quantities of storage remain active in PJM's interconnection queue, which could take up additional slack** if the projected amounts of needed firm gas capacity is not developed in time to integrate large loads by the end of the decade.
  - Importantly, storage facilities can be brought into service significantly faster as gas turbine supply rebalances to address backlogged demand.
- **In the near-term storage will be a key part of the solution for addressing critical resource adequacy needs in PJM**. In the longer-term, it will become even more cost-effective, providing resource adequacy benefits and meeting state goals.

PJM's Near-Term Challenges: Unprecedented Load Growth and a Tight Supply Outlook

A highly constrained near-term supply, including limited new gas resource outlook through 2030 is likely to exacerbate resource adequacy challenges in PJM as the region plans to serve unprecedented load growth

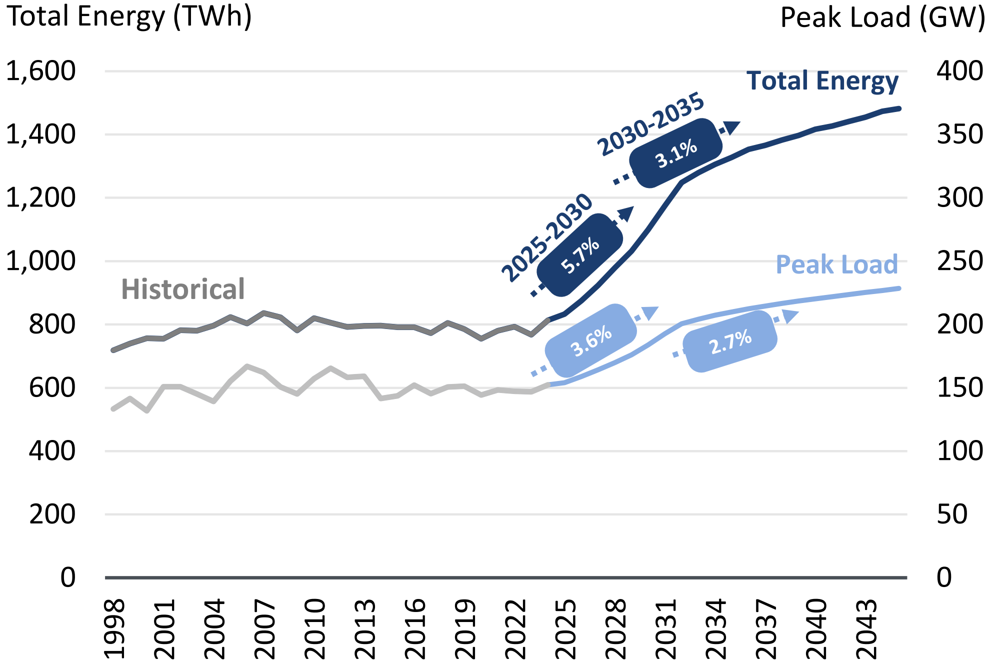
PJM is forecasted to experience unprecedented load growth over the next decade.

In this study, we assume all forecasted demand included in PJM's 2025 Load Forecast Report will materialize. By 2028, PJM's summer peak will increase by 16 GW, and by 2032, by an additional 30 GW, representing the fastest peak load growth in two decades.

Interconnection queue backlogs, protracted wait-times for new supply, especially gas-fired generation, and trade barriers for renewables and storage are likely to limit PJM supply through the early 2030s.

Despite recent efforts to increase available near-term capacity (e.g., via the RRI), PJM's interconnection process imposes a multi-year study wait-time. At the same time, demand for gas turbines exceed supply, leading to protracted wait times for fulfilling orders. In this study, we assume that all of the 7+ GW of new firm dispatchable capacity (gas and other fossil, including uprates) active in the PJM queue would be in-service in 2028, in addition to planned renewable and storage assets. We assume at most an additional 10+ GW of new gas facilities would be in-service by 2032. We allow economic builds of clean resources beyond planned additions.

PJM Historical and Forecast Projected Peak and Total Load



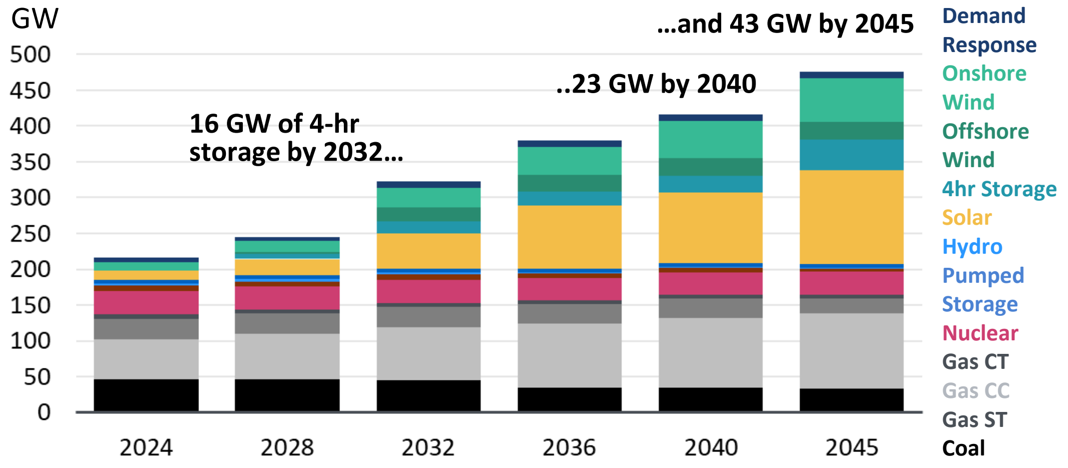
Note: Historical and forecasted peak demand sourced from PJM 2025 Load Forecast Report. 2025 – 2030 and 2030-2035 CAGRs shown.

PJM's Storage Outlook: Key Findings

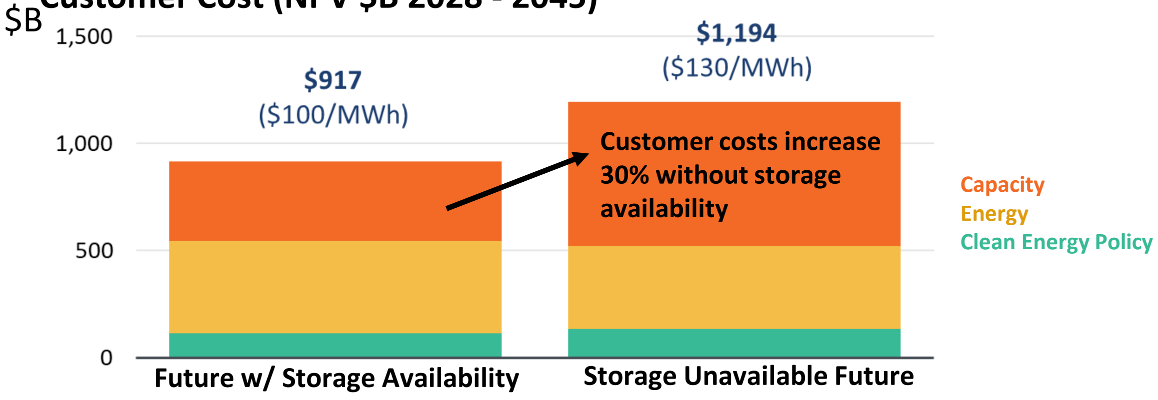
Significant amounts of storage capacity will be essential to serve new PJM loads and maintain resource adequacy in the near-term

- **Our simulations project that the PJM footprint needs to 16 GW of 4-hour storage by 2032 and 23 GW by 2040.**
- The 16 GW of storage capacity (along with 17+ GW of new gas resources, delayed thermal retirements, plus capacity contributions of the significant solar and wind resource deployment) is essential to integrate new loads, and meet state RPS targets amid interconnection backlogs and supply constraints that limit additional dispatchable resource availability in PJM .
- **With battery storage, PJM could avoid up to 15 GW of load shed risk during challenging system conditions in 2032**, such as extreme cold snap periods. Otherwise, this load shed results in a failure of planning standards, severe customer impacts, and an unreliable system.
- **Our simulations indicate that 4-hour duration storage will be deployed predominantly** to complement renewable generation and maintain resource adequacy. PJM will also need new gas and retain conventional firm resources through the 2040s; battery storage will support reliably serving growing demand in the coming decades.
- Importantly, the projected **storage deployment is primarily to address resource adequacy needs cost-effectively in PJM;** it is not just to address states' clean energy goals or storage mandates. Customer costs could increase 30% without storage deployment.

Capacity Expansion Results



Customer Cost (NPV $B 2028 - 2045)



Note: Customer costs are expressed in NPV $B 2028-2045 as of 2024 (in 2024 $s) discounted at a nominal 10%. T&D contributions to customer costs were not evaluated in this study. See appendix for additional assumptions.

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Purpose of the Study

The purpose of this study is to develop a battery storage outlook for the PJM region, and to evaluate the value that battery storage provides in maintaining resource adequacy in PJM

Key topics addressed by this report:

- **What is the role of storage in a supply constrained system?** Interconnection queue and supply bottlenecks create a difficult environment for new resource deployment to match large load growth over the next decade. Storage provides essential resource adequacy value to serve load growth while supply constraints are resolved for other firm resources.
- **A case study that assesses the RA implications of a hypothetical system without storage deployment in the PJM footprint.** Given the forecasted large demand growth and substantial supply-side limitations, storage deployment is crucial to serving all planned load and preventing resource adequacy violations.
  - This assessment is not meant to suggest a resource deployment roadmap of the PJM system without *any* battery storage, nor is it meant to suggest that such a system would be reasonable. Modeling a PJM market without storage resources is simply a useful hypothetical exercise to isolate the resource adequacy value of storage in a system with an evolving supply mix.
- **How does the value of storage evolve as the grid decarbonizes?** As PJM deploys more renewable energy to address states' RPS goals, the value of storage increases (due to energy arbitrage opportunities) while storage facilities synergistically also increase the resource adequacy value of intermittent renewable resources, thereby improving grid reliability.

Study Overview

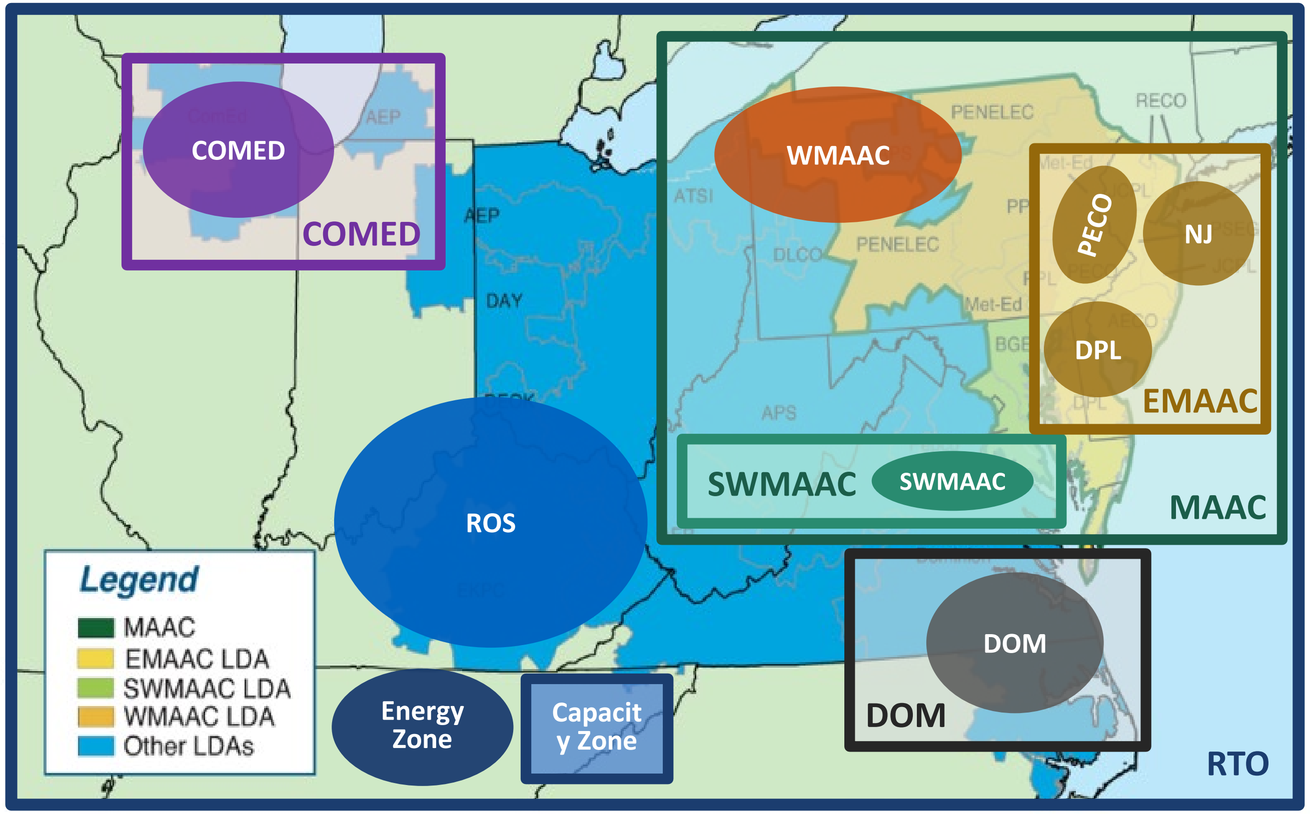
We employ GridSIM, Brattle's proprietary capacity expansion model, to optimize for the least-cost future grid mix to meet PJM's near and long-term demand for energy and capacity, considering 25 years of weather uncertainty, and subject to current policy and transmission constraints

We simulate capacity expansion and system operations for the entire PJM market on an hourly basis, considering conditions across 25 weather years. We model eight energy and six capacity zones to analyze reliability performance across PJM.

This study explores how much storage the PJM footprint could deploy cost-effectively (among other technology options and realistic near-term supply-side constraints) to address hourly resource adequacy ("RA") and current policy goals in PJM. To isolate the RA value of storage, this study also evaluates a hypothetical case study in which storage cannot be deployed in PJM and tracks the scale and severity of potential RA violations that result. Both cases rely on the same set of core modeling assumptions.

Modeling was conducted prior to passage of OBBBA tax credit repeals or recent OSW project stops. Storage results presented in this study remain relevant, if not more so, within PJMs constrained future. (*Modeling assumptions are described in detail throughout this section and in the Appendix)*

GridSIM Energy and Capacity Zonal Topology



Using GridSIM to Assess Value of Storage

Several key assumptions drives GridSIM's optimization results and assessment of battery storage in PJM.

Tight Supply Conditions

Interconnection queue backlogs, protracted wait-times for new gas turbines, and cost uncertainty due to trade barriers for renewables and storage exacerbate already tight PJM supply. In the near term, queue backlogs and gas turbine supply constraints are the most restricting factors for deploying new capacity throughout PJM.

Rapid Demand Growth

PJM will experience significant (and uncertain) demand growth over the next decade driven by data centers and electrification. We assume all demand must be served will existing and new resources or through load shedding. Demand response could reduce peak growth and complement storages' role. We model some limited DR growth beyond cleared DR capacity in PJM's recent RPM auctions.

Transmission Availability

GridSIM is a zonal model ("pipe-and-bubble") that assumes no nodal congestion within a zone. The zonal topology governs the energy and capacity interactions between zones. We do not assume any transmission growth beyond current levels through the study horizon.

Battery storage is likely to provide more value than our study captures due to persistent nodal level constraints .

Achievable State Clean Energy Goals

This study models a future that complies with all state mandates and clean energy goals (with some delays for offshore wind procurement targets). Storage resources help integrate renewables into the PJM grid as state RPS and carve-out goals mature in the later 2030s. We assume PJM states will continue to rely on alternative compliance payments for up to 25%, as well as imports, to serve RPS requirements until 2032 declining to 15% by 2045.

Overview of Demand Growth in PJM

Rapid demand growth over the next decade will require significant deployment of new resources to serve growing demand.

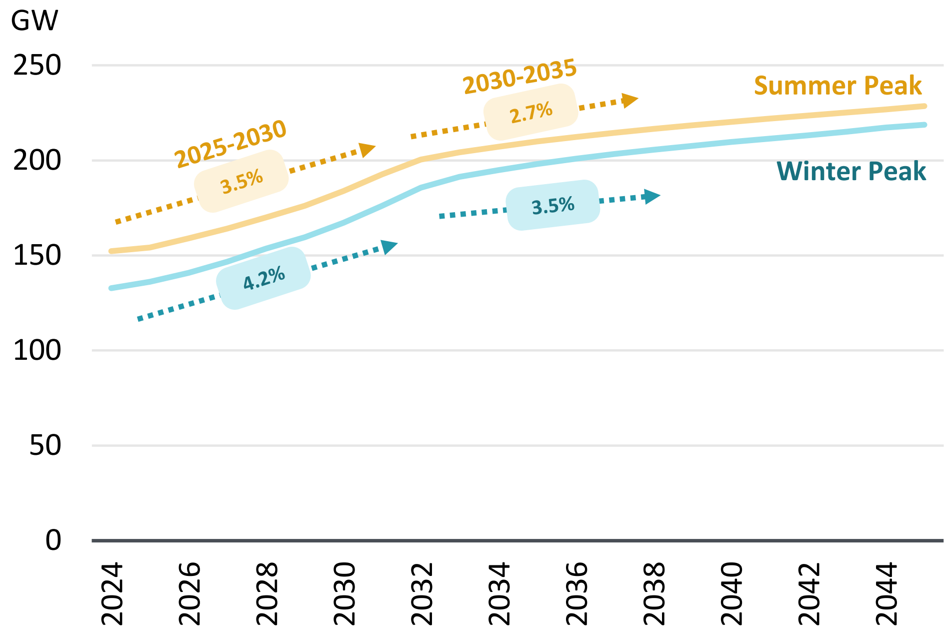
Data center and electrification driven load growth will increase summer and winter peak demand by 56 GW and 62 GW over the next decade.

PJM will remain a summer peaking system through our 2045 study horizon despite increased winter peak demand growth driven by heating electrification.

Near term load growth will create particularly challenging conditions during peak hours if deployable dispatchable capacity is limited.

The extent to which demand projections (on the wholesale grid) in the 2025 PJM Load Forecast Report materialize remains uncertain. This study assumes all demand will interconnect and must be served by available resources (including new facilities) or experience controlled and uncontrolled load shed.

Forecasted Peak Load Growth 2024-2045



Resource Availability

Supply tightness due to interconnection queue backlogs, limited supply of gas turbines, and global tariff uncertainty creates significant cost and availability uncertainty for new supply, especially in the near-term, when demand growth is projected to be steep, at 3.5% CAGR from 2025-2032.

The interconnection queue processing times severely limit available new capacity for the next decade.

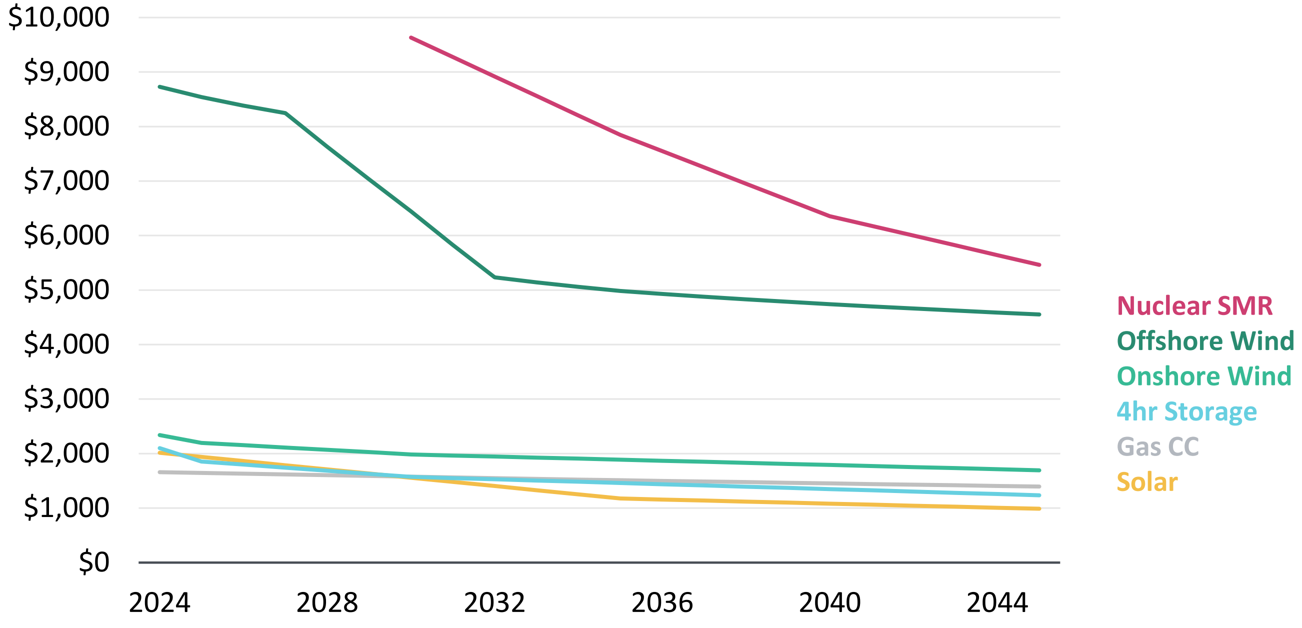
We assume that all new online capacity by 2028 is currently in the PJM interconnection queue, RRI, or uprate approval process. By 2028, up to 10 GW of storage, 3 GW of wind, 20 GW of solar, and 7.4 GW of gas capacity could be deployed in PJM. By 2032, an additional 10.5 GW of new gas capacity could become available. New onshore wind (~4 GW) and gas capacity (~17+ GW by 2032) is particularly limited by supply availability.

Resource costs assumptions are consistent with PJM's recent CONE study findings, reflecting tariff impacts and supply limitations

Cost assumptions informed by the recent Brattle 2025 CONE Report for PJM, and the NREL ATB.

See the Appendix for resource availability assumptions.

Candidate Resource Capital Costs ($2022/kW)



Note: CAPEX values shown before tax credits are applied. Model assumptions were developed before passage of One Big Beautiful Bill Act and assume storage ITC and renewable PTCs continue through modeling horizon. Storage results presented in this study remain relevant, if not more so, within PJMs constrained future.

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Resource Adequacy Value of Storage

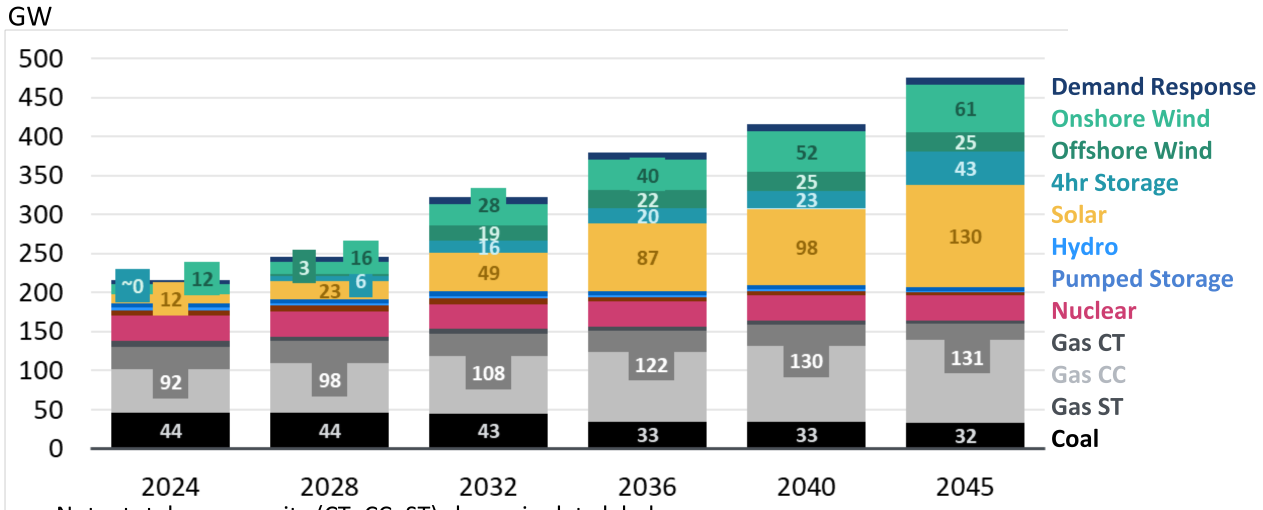
Peak load will grow at over 3% per year over the next decade and PJM is projected to deploy new gas, renewables, and storage to serve the projected 15+ GW peak increase by 2028.

- Around 20 GW of new solar, wind, and storage is needed by 2028. **By 2032, 16 GW of storage deployment is necessary and cost-effective.**
- **Despite protracted construction timelines, around 7.4 GW of new gas capacity is needed by 2028**; even more would be deployed if more were to materialize in the PJM queue. However, we note that deployment of 7.4 GW of new gas may already be aggressive given that it represents nearly the entirety of active gas projects and uprates in the PJM queue through early 2030s. **By 2032, all 17+ GW of new gas projected is necessary in PJM.**
  - We also assume that planned fossil retirements in 2028 will be delayed until 2033-36 to accommodate large near-term load growth.

By the next decade, over 30 GW of new storage and gas resources are critical to maintaining resource adequacy in PJM. Without the projected storage and gas deployment, and capacity contributions from renewable generation, PJM could face significant forced load shedding or fail to connect the projected demand.

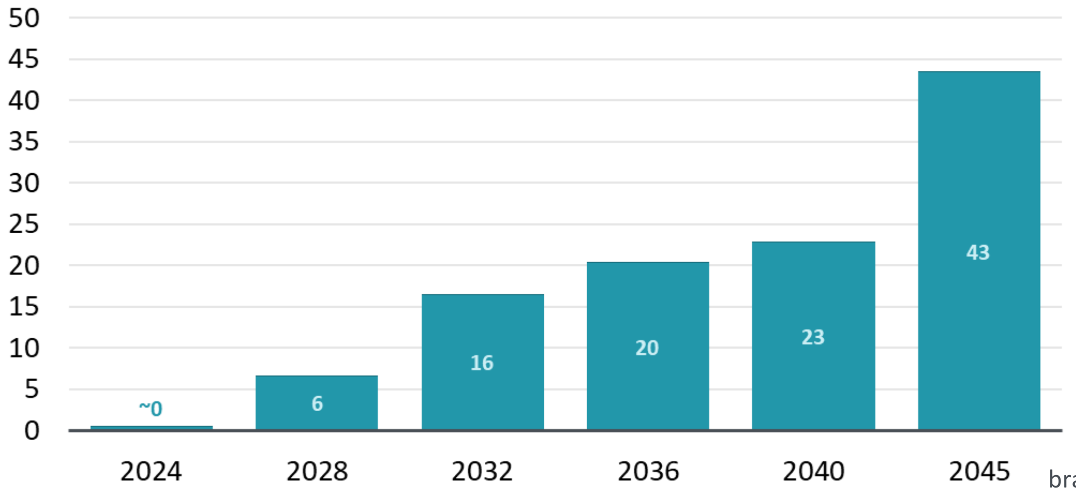
In the longer term, storage is the one of the most cost-effective technologies for addressing RA needs in PJM.

PJM Capacity Outlook for 2024-2045 (cumulative)



Note: total gas capacity (CT, CC, ST) shown in data labels

Cumulative Storage Deployments (ICAP GW)



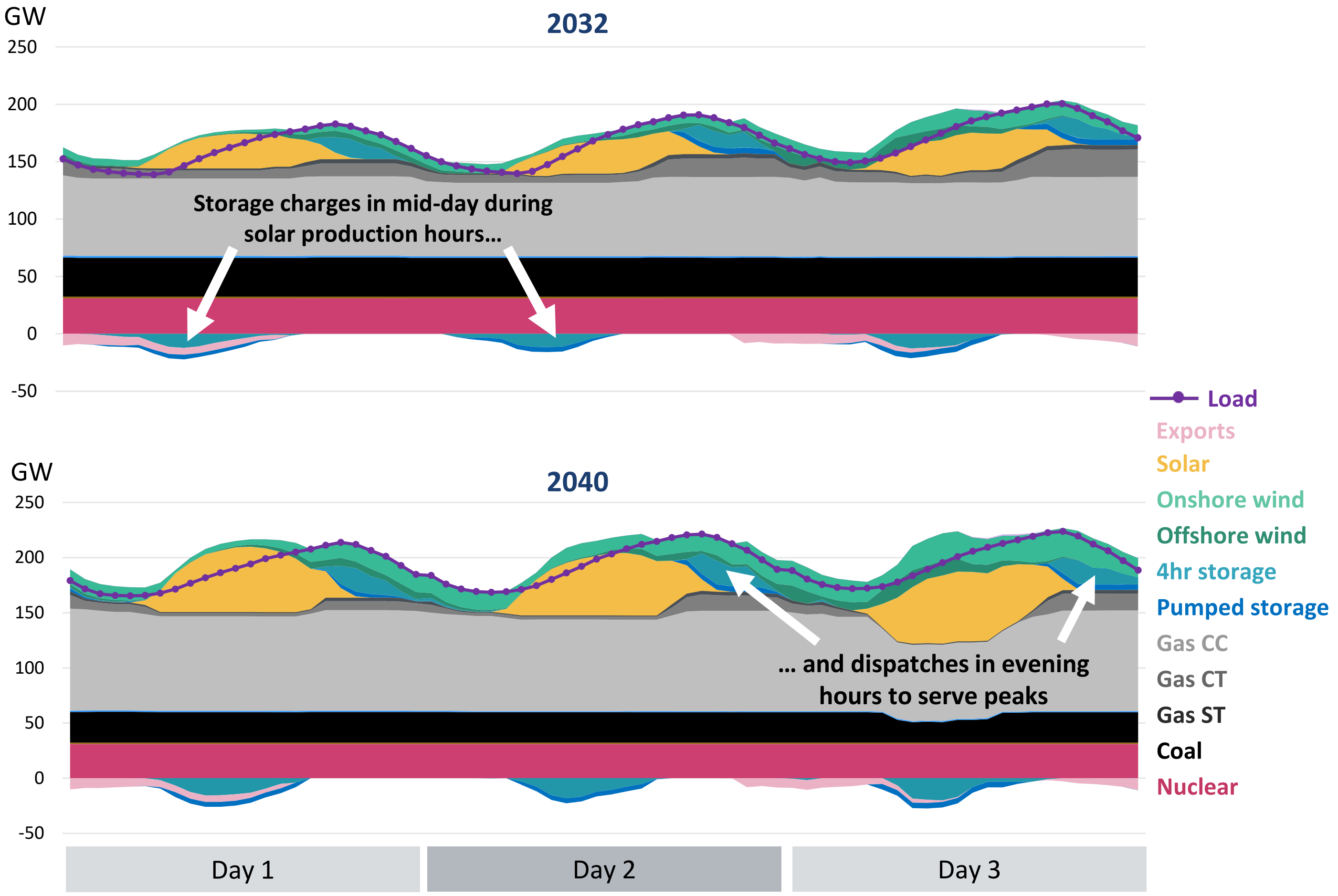
PJM Storage Dispatch during Extreme Summer Peak in 2032 and 2040

Battery storage is needed in PJM to address resource adequacy challenges during system peaks and extreme weather.

- **Within the next 7-10 years, 16-20 GW of battery storage could supplement the gap from limited supply of thermal and renewable facilities** to serve forecasted peak growth and weather-driver RA challenges in PJM.
- Battery storage provides capacity value and daily energy value when dispatched during net peak evening hours
- **Without storage, the projected fleet (of supply-limited new gas, renewables and retained existing capacity) would not be able serve evening net peak demand experienced during challenging weather conditions.**
- As more renewables (particularly solar) are deployed for RPS goals, storage's energy revenues grow (charging occurs during low-cost midday hours).

Without storage, there would be insufficient new resources available to mobilize in PJM to serve forecasted net peak loads during challenging weather conditions (e.g., cold snaps / heat waves). That is, the system will not meet RA needs (including operating reserves) and will not be weather-resilient without storage (see next slide).

72-hr Battery Dispatch Profile During Projected Summer Peak Conditions



Note: Small quantities of PJM resources such as biogen are modeled but not significant enough to visually distinguish within the supply stack.

KEY RESULTS

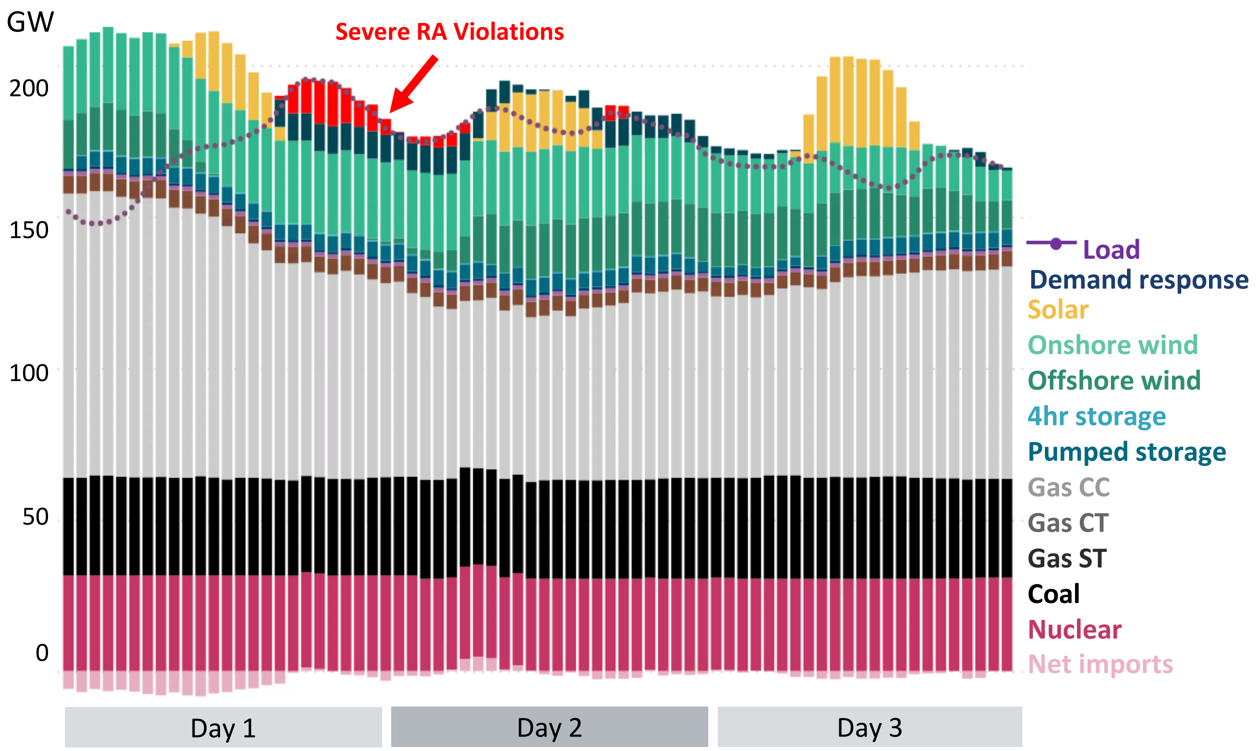
Projected Storage Deployment can Avoid Large-Scale Resource Adequacy Violations in PJM

Reliability Violations during a Winter Cold Snap in 2032

In the near-term, PJM has very limited resource options to integrate the forecasted 16-30 GW of large loads. **A case study illustrates the RA value of 16 GW of necessary storage in PJM during a 3-day cold snap event in 2032** (one akin to the Winter Storm Elliott of December 2022):

- **Without any storage, PJM will have insufficient total firm capacity in 2028-2032 to meet hourly RTO-wide demand (plus the hourly operating reserves that PJM must carry)**, leading to large-scale load shedding risks in PJM during cold snaps *(red stack bars show hourly load shed risks over 3-days in 2032).*
  - During challenging weather days with high net peaks and outages, storage can prevent PJM from depleting its operating reserves, which usually will trigger load shed to avoid uncontrolled cascading blackouts.
- **The scale of potential load shed may be more than 14,000 MW-h in 2032 during just 3-days of a winter cold snap.** Load shed risk of such scale would violate PJM's RA planning standards and reliability criteria.
  - Reliability standards protect public safety and economic security; they need to be met. This simulation quantifies the risks of failing PJM's RA planning standards.

Hourly Capacity Provision in PJM During a Coldsnap in Winter 2032 (without Storage)



Note: Small quantities of PJM resources such as biogen are modeled but not significant enough to visually distinguish within the supply stack.

Projected Storage Deployment can Avoid Large-Scale Resource Adequacy Violations in PJM (contd.)

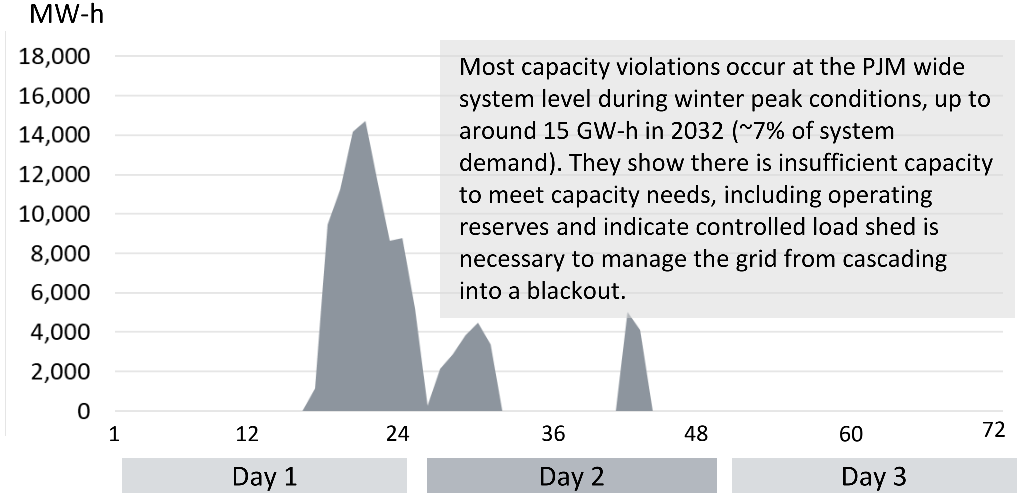
At least 16 GW of battery storage, 17 GW of new gas, delayed thermal retirements, and capacity contributions of the significant renewable generation deployments are necessary to manage 2032 resource adequacy challenges in PJM, especially during winter extreme weather events .

- Slower gas resource deployment in the region would exacerbate resource adequacy challenges, necessitating even more battery storage resources in 2028-2032 .

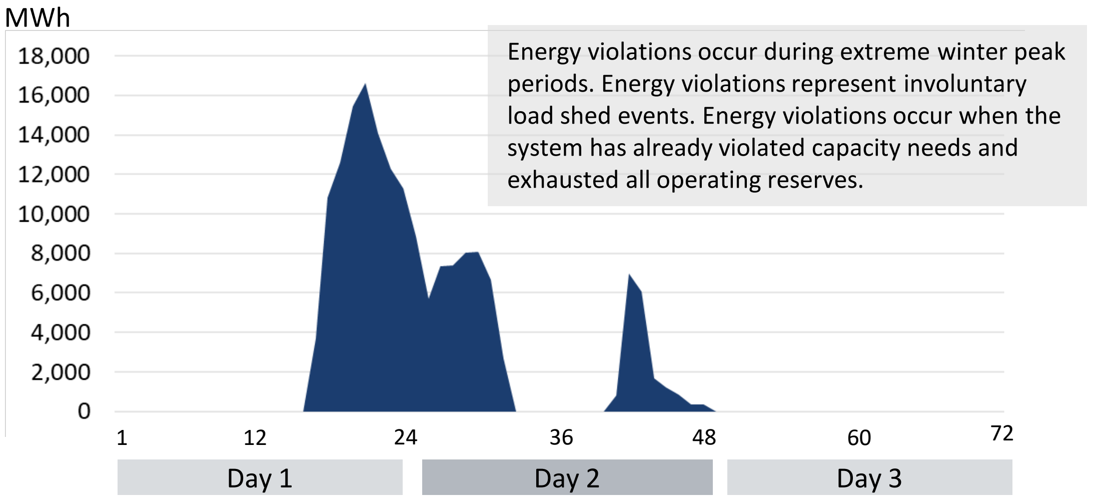
Without these 16 GW of storage, PJM will experience large-scale capacity violations, leading to forced load shed, of 10,000+ MW-h during a 3-day extreme winter weather event.

- A single cold snap event in 2032 (such as Winter Storm Elliot) could result in multiple hourly RA violations over 3-days, with hourly load shed risk of up to 14,000+ MW-h for several hours (top chart).
  - These load shed events could occur twice every 25 years and could result in **costs up to $0.4 to $1.2 billion** (valued at a VOLL of $3,500-$10,000) during a three-day event.
- Hourly RA violations (top chart) reflect the depletion of operating reserves below the levels required by PJM. These reflect controlled load shed necessary to manage the grid from potential cascading blackouts.
- Energy violations (bottom chart) represent involuntary load shed events, which occur when the system has insufficient generation and imports to meet hourly demand. When energy violations occur, the system has already exhausted all operating reserves and thus has already violated the hourly capacity requirements.

PJM Capacity Violations (2032 Winter Peak Day)



PJM Energy Violations (2032 Winter Peak Day)



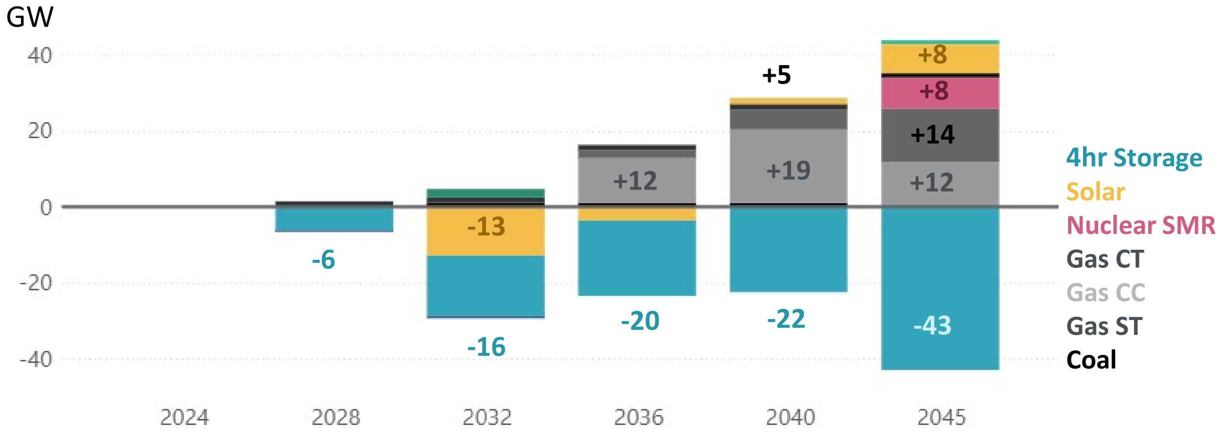
No-Storage Case Study: Resource Deployment in PJM Without Storage

Through the 2030s, PJM will face tight supply conditions such that without availability of an entire class of resources, in this case storage, there are simply few realistic replacement options.

In the absence of storage—assuming PJM must serve the forecast demand under the same supply limitations expectation—near-term load sheds become inevitable.

- Through 2032, additional onshore wind and limited available thermal capacity would supplant a portion of needed base case storage capacity in PJM. Despite that, large load shed events would occur in PJM. In this sensitivity, some of the solar deployment projected in the base outlook will be delayed until later years.
- In the mid 2030s, as supply-side limitations (especially for new gas resources) are resolved, additional new gas and renewables would displace energy and capacity contributions of storage.
- By 2045, the PJM system will continue to add additional thermal resources, nuclear SMRs, and renewables to meet clean energy goals, demand projections, and resource adequacy without storage.

Cumulative Installed Capacity Difference without Storage



Note: Nuclear SMR resources would be cost-effectively deployed in COMED by 2045 due to Illinois clean energy requirements.

A world without any battery storage is not a realistic characterization of PJM's market but this assessment serves as a useful modeling exercise to isolate the resource adequacy value that storage provides in PJM.

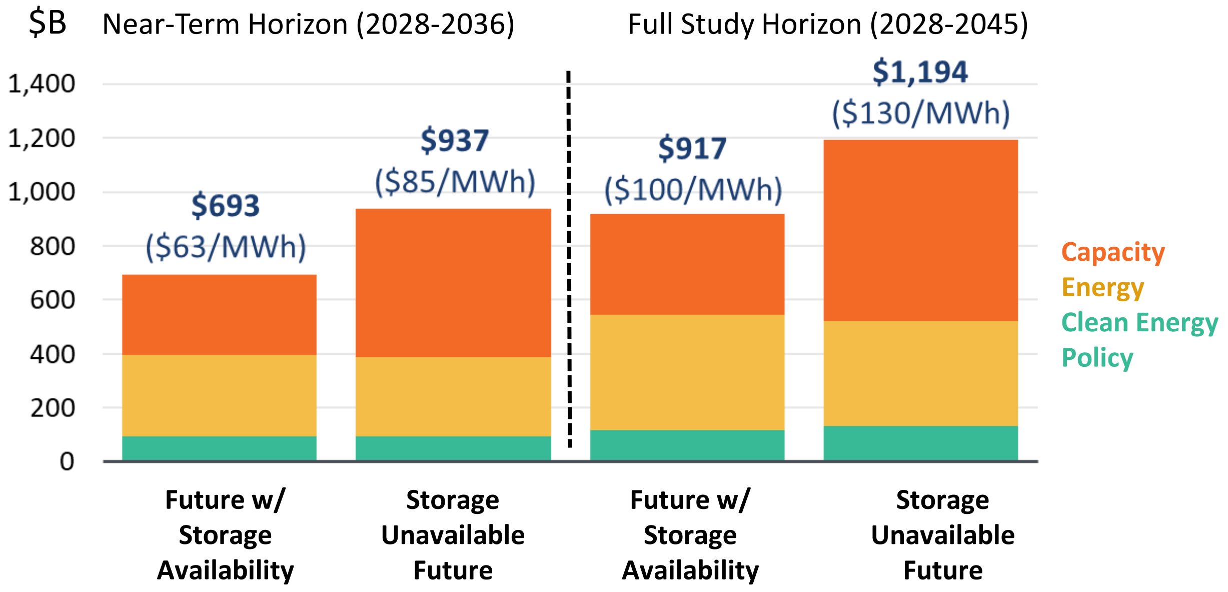
Quantifying Potential Cost to PJM Customers

To quantify the potential customer costs in PJM without storage as an available technology, we constructed a hypothetical analysis that compares simulated customer costs of needed storage (~43 GW) vs. a case without any battery storage, through 2045.

Without storage, we estimate that customer costs could be higher by 30% as the market deploys alternative, but more expensive resources, while resorting to large-scale resource adequacy violations (i.e., load shedding) in the near-term (2028-32) during challenging weather events. We reflect resource adequacy violations (capacity and energy) in the capacity component of the customer cost metric because these costs represent a failure in resource adequacy planning standards .

By 2045, over 40 GW *each* of new storage and new gas resources, along with the capacity contribution of the significant renewable resource deployments are projected to be necessary to maintain resource adequacy in PJM. Without this needed capacity, be it gas or storage, customer costs would be higher, as other alternatives are more expensive, and since 90 GW+ of new firm capacity is necessary to address resource adequacy needs in PJM through 2045.

Customer Cost (NPV $B)



Note: For this calculation, the assumed violation costs for unserved energy are $10,000/MWh and for capacity reserve depletion at $50,000/MW-h. Customer costs are expressed in NPV $B 2028-2045 or 2028-2036 as of 2024 (in 2024 $s) discounted at a nominal 10%. The impact of storage on distribution and transmission costs are not quantified. As a reference, current T&D costs in PJM roughly amount to under $50 billion per year from PJM IMM's Monthly Total Price reporting and EIA861 cost data for delivery only PJM utilities. The NPV $/MWh metric discounts the $ to effectively reflect a discounted weighted average rate impact placing more weight on near term years' impact but not necessarily discounting the result (e.g., if the impacts over time were a nominally constant X $/MWh per year, discounting both the numerator and denominator would result in the same X $/MWh as of 2024.)

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Large Scale Capacity Additions in PJM are Necessary to Maintain Reliability. And Storage is Key.

Battery storage is a key asset for PJM's reliable, cost-effective future. Our study projects that large quantities of dispatchable resources like storage and gas will be necessary to maintain resource adequacy and manage weather-risk in PJM.

Our analysis shows that up to **16 GW of four-hour batteries by 2032 (23 GW by 2040)** is the lowest-cost way to cover unprecedented load growth amid tight supply options, assuming that PJM will be able to integrate only about 17 GW of new gas resources by 2032, and delay almost all currently planned thermal retirements to middle of the next decade.

Storage delivers outsized resource-adequacy value during extreme peak hours and complements limited new gas builds and intermittent renewables. Without it, PJM could face **>15 GW of forced load-shed risk** by the early 2030s.

Storage's value to the footprint evolves over time, increasing as costs decline and net revenues grow. As renewable penetration increases, batteries provide growing energy-arbitrage, reinforcing their cost-effectiveness beyond exclusively its capacity value.

Beyond the Study

- Storage procurement goals, accurate accreditation methodologies, and interconnection queue policies could support storage deployment to serve PJM goals
- Interconnection queue reform is necessary to ameliorate current supply-side bottlenecks to create more opportunity for storage and other dispatchable resources to come online faster.
- In later years, storage and other emerging technologies will be key to cost-effectively maintaining resource adequacy amid state RPS goal achievement

Additional Brattle Group Reading on Storage

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Newell et al. "PJM CONE 2026/27 Report," for PJM Interconnection, April 2022.

Pfeifenberger, Johannes and Roger Lueken. "The Evolving Landscape for Storage: Wholesale Market, T&D, and Customer Benefits," presented at The MIT Energy Initiative Electric Power Systems Center Spring Workshop, May 2020.

Hledik, Ryan and Roger Lueken. "Determining Optimal Storage Deployment Levels," presented at Energy Storage Association webinar, December 2018.

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The report reflects the analyses and opinions of the authors and does not necessarily reflect those of The Brattle Group's clients or other consultants.

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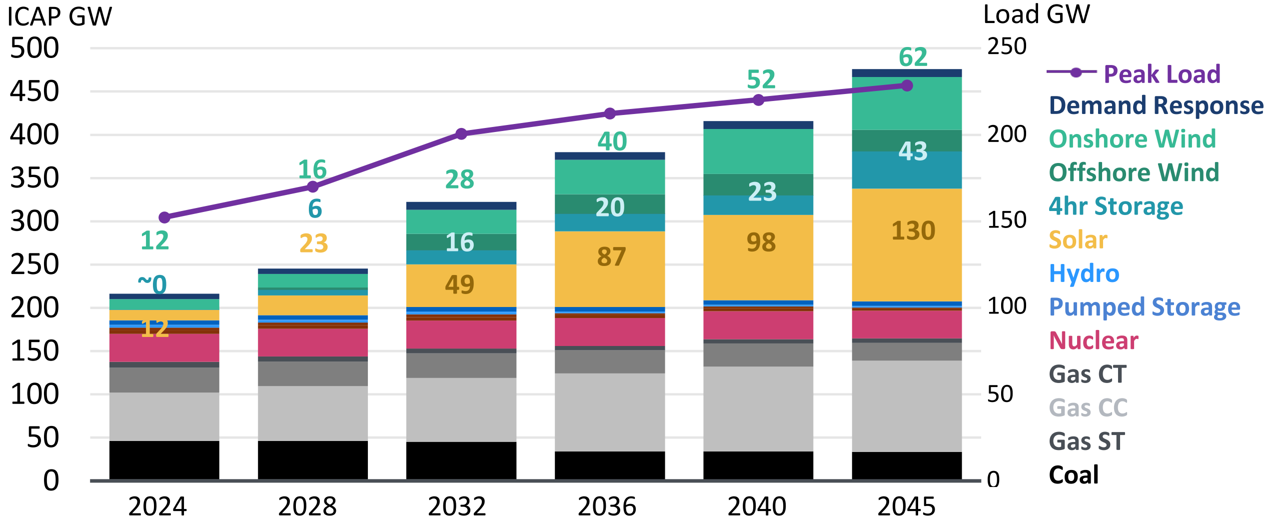
PJM Capacity Outlook

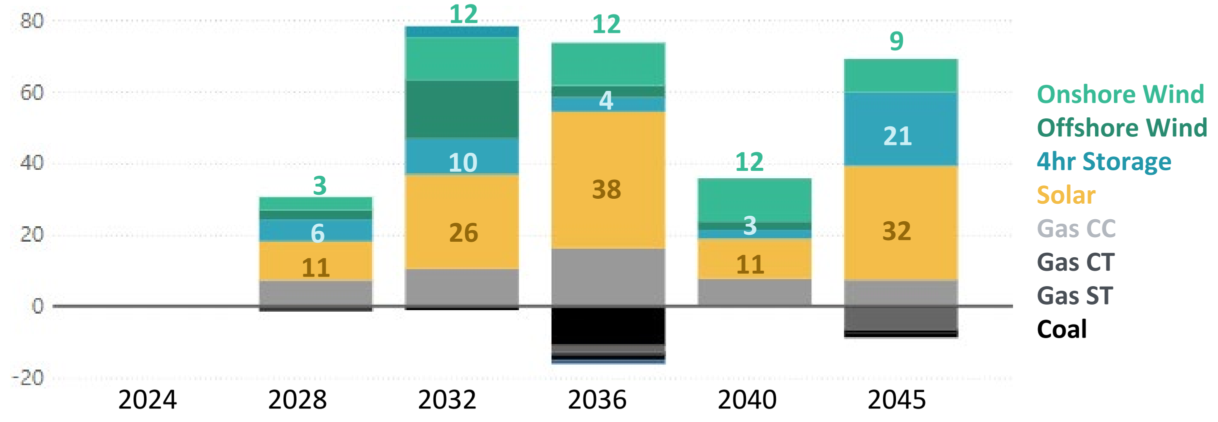
Peak load will grow 3% per year over the next decade and PJM will deploy available fossil, renewables, and storage to serve the over 15 GW increase by 2028.

- We estimate that 20 GW of solar, wind, and storage will deploy by 2028, with wind and storage severely limited by current interconnection queue applications (IQ limits by 2028: 10 GW of storage, 3 GW of wind, and 20 GW of solar – wind is binding)
- We assume that planned fossil retirements in 2028 are delayed until 2033-36 to accommodate large near-term load growth. Around 7.4 GW of new gas capacity is still needed by 2028. (Gas capacity is assumed to be limited to 7.4 GW by 2028 and an additional 10.5 GW by 2032 based on the current queue information)
- Offshore wind is deployed at policy targets but is not allowed in the modeling to be economically developed beyond the state procurements until after 2030.

Capacity Expansion Results (GW)



Capacity Additions and Retirements (ICAP GW)



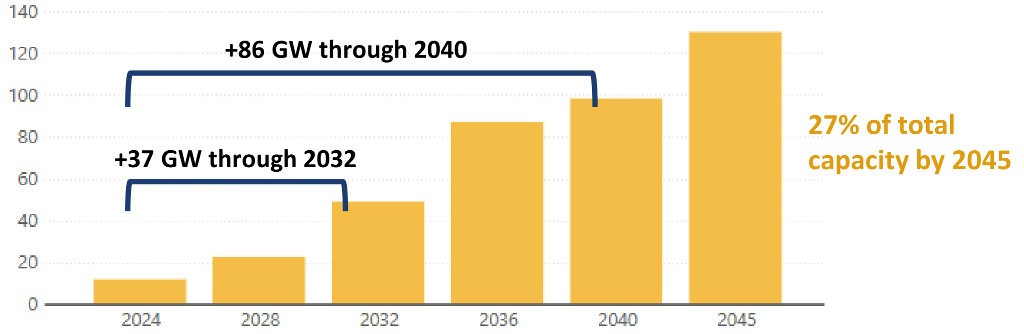
Note: "Annual" additions and retirements reflect all capacity added or retired between model years

Projected Renewable and Storage Deployment

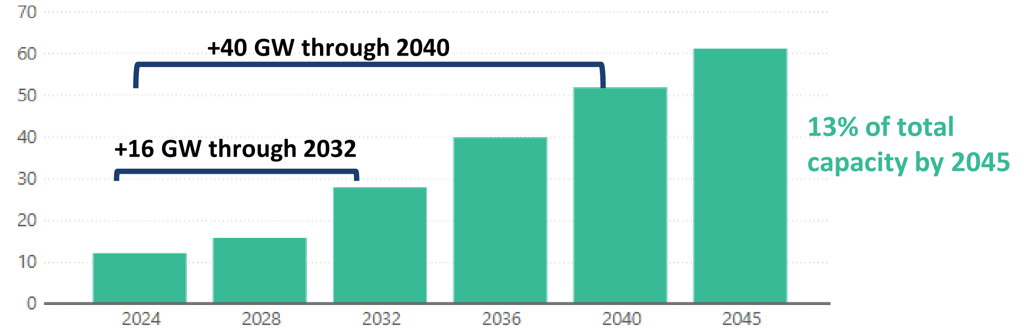
Storage is primarily deployed to meet resource adequacy needs while complementing renewables that satisfy clean energy goals.

- Wind will continue to be developed in the near term until solar dominates renewable market share.
- PJM will rely on up to 43 GW of battery storage by 2045 to maintain reliability and complement solar generation.
- 4hr storage is the only cost-effective duration. 6hr and 8hr are not valuable in a PJM system with < 50% renewable penetration. Longer-duration storage assets are not cost-effective candidates under current modeling assumptions.
- Our results are consistent with [PJM capacity expansion planning] (albeit outdated) with our estimates between their Policy and Accelerated scenarios for most resource types. We deploy more solar to meet additional load growth captured in recent PJM forecasts.

Solar (ICAP GW)



Onshore Wind (ICAP GW)



Storage (ICAP GW)

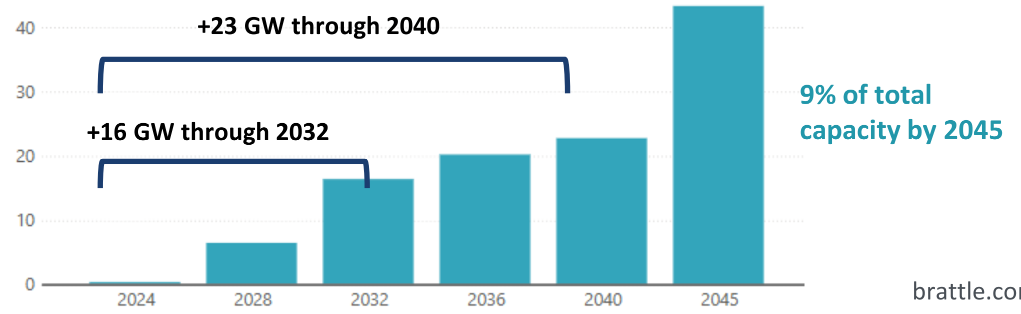
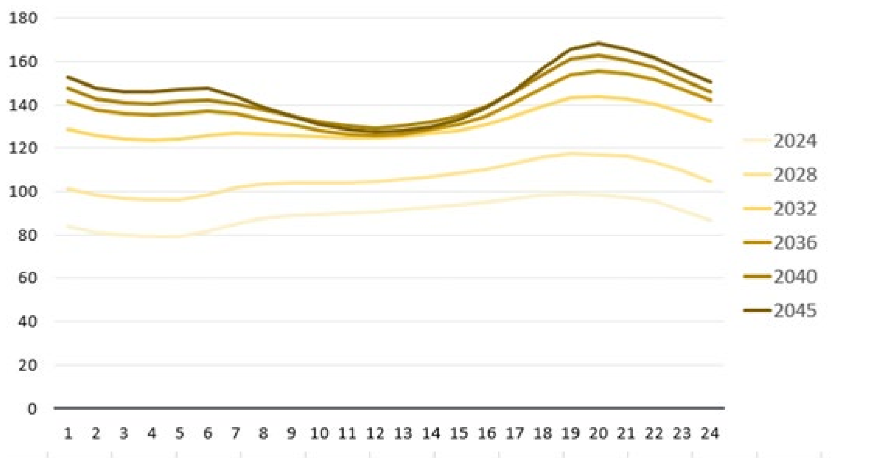


Illustration of Net Load Shapes

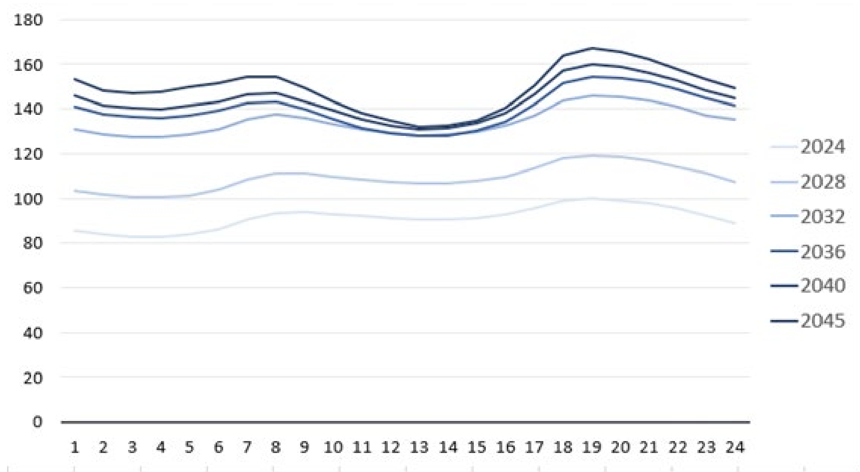
Through the early 2030's PJM has low solar deployment with relatively limited need for daily load shaping.

- In the near term, batteries are primarily added resource adequacy needs with some energy arbitrage value in DA RT energy imbalance and ancillary services markets.
- Beginning in the 2030s storage assets contribute to time-shifting of daily loads (via higher arbitrage opportunities), complementing solar generation patterns.
- PJM resource adequacy risk hours are concentrated in summer and winter early evenings in the near term and shift to late evenings with increased solar penetration

Summer



Winter



Note: Net load consists of hourly demand less solar, onshore, and offshore wind generation – before any battery storage dispatch. Figures are shown as seasonal average daily shapes.

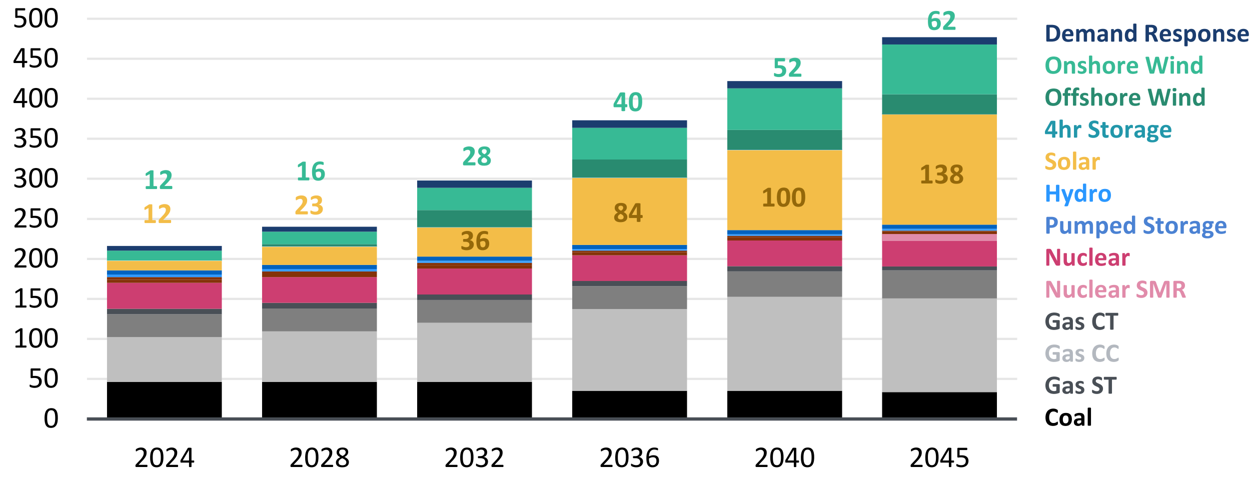
PJM Capacity Outlook (without storage case study)

We model a hypothetical case study without storage as an available candidate resource to isolate the value that storage provides to the PJM system. We maintain the same interconnection queue, supply chain, and cost limitations in this scenario.

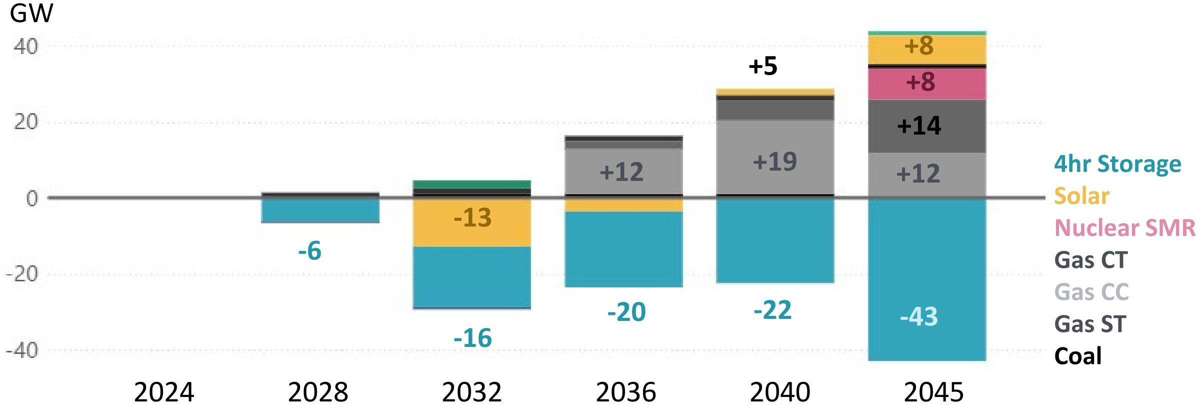
All else equal, without storage, load cannot be met in all hours and potential load shed conditions will occur (due to depletion of operating reserves) beyond LOLE standards. These events manifest on the extreme winter peak day and can scale up to around 15 GW across all zones.

Without storage, less solar is built in the near term, while more fossil capacity is retained. Additional fossil capacity is needed through the 2030s to serve load growth. Nuclear SMRs also become a viable resource candidate by 2045 to serve demand in states with clean energy policies (IL). More solar capacity is also built in the long term to serve hourly demand.

Capacity Expansion Results w/out Storage (ICAP GW)

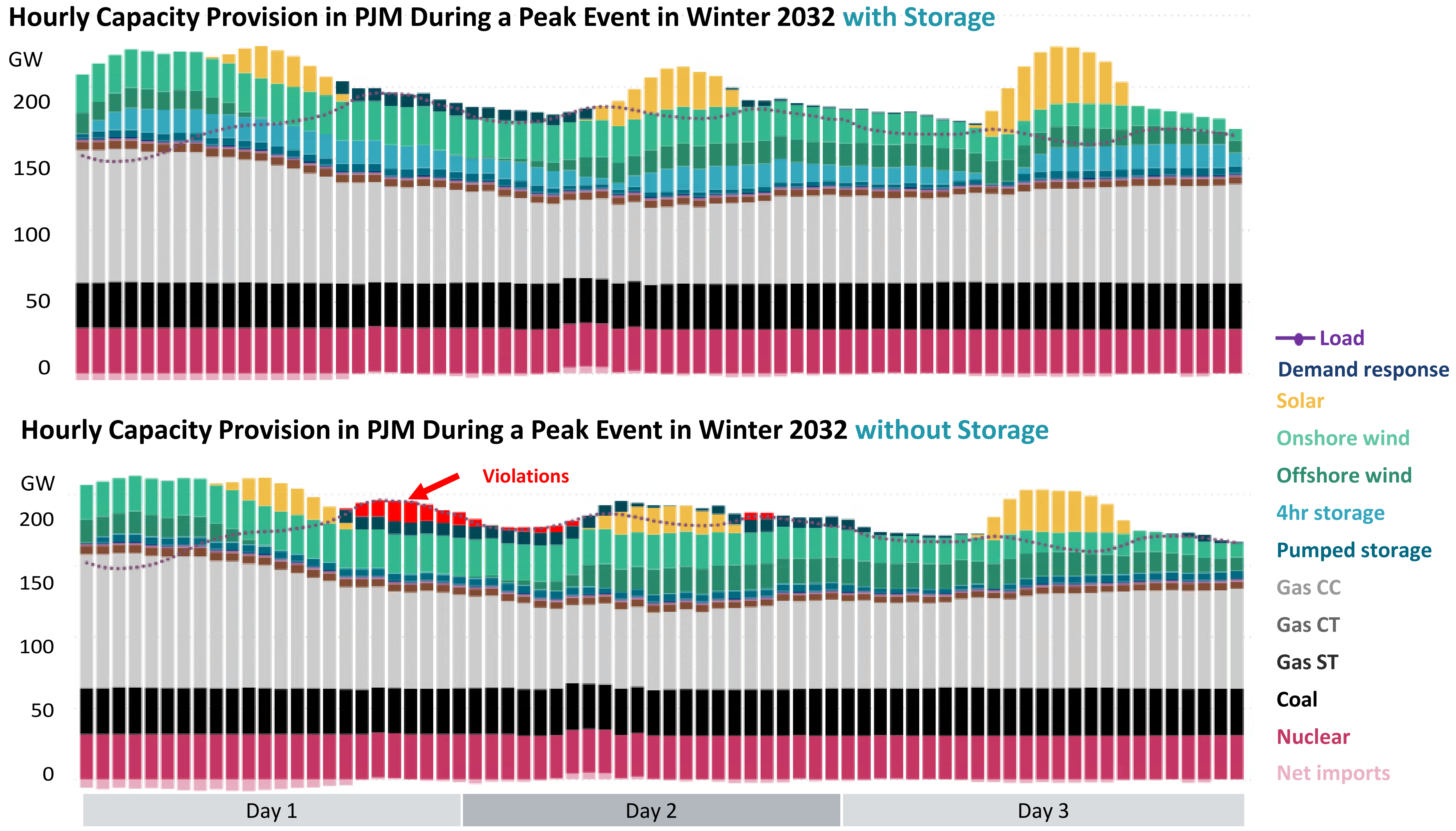


Cumulative Installed Capacity Difference without Storage



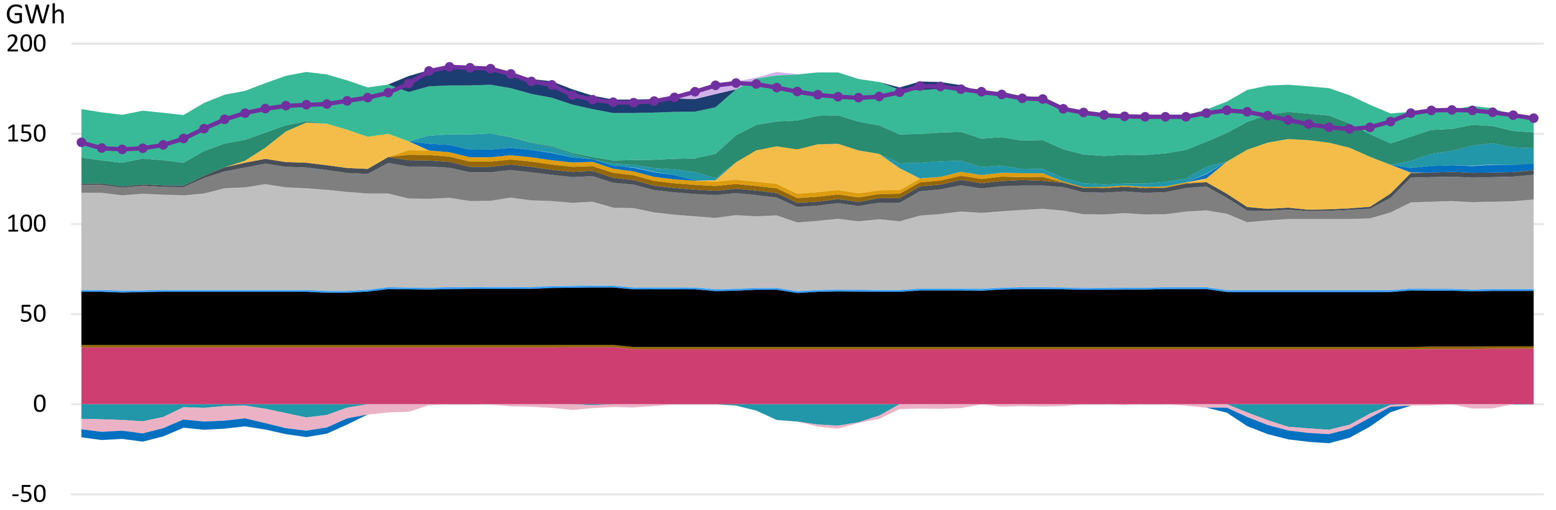
Note: Nuclear SMR resources would be cost-effectively deployed in COMED by 2045 due to Illinois clean energy requirements.

Capacity Violations (controlled load shed) in the Absence of Storage

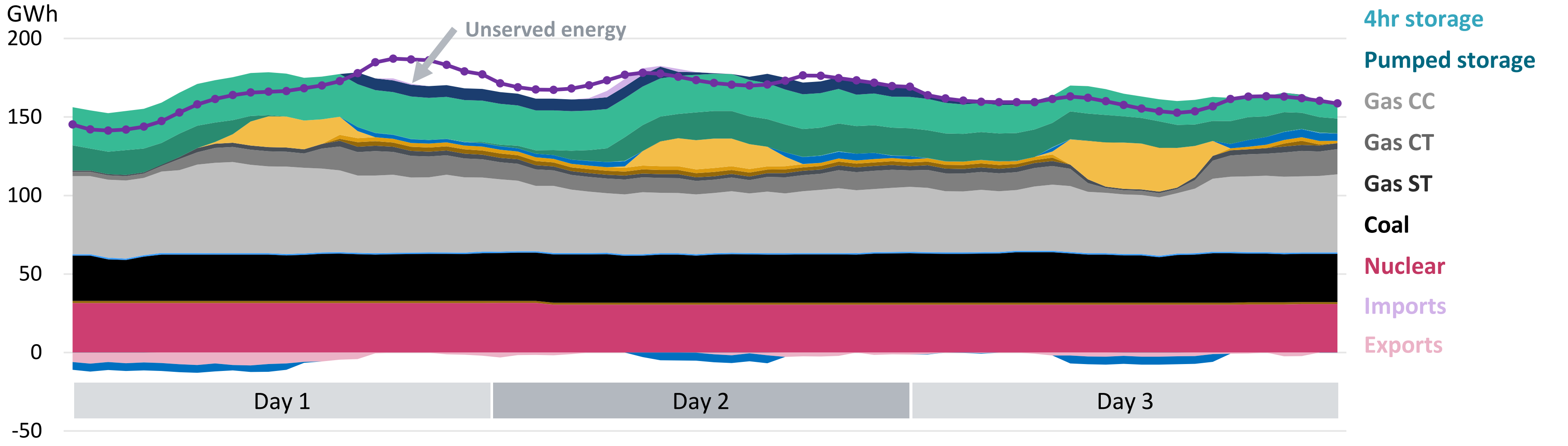


Energy Violations (uncontrolled load shed) in the Absence of Storage

Illustrative Dispatch in PJM During a Peak Event in Winter 2032 with Storage



Illustrative Dispatch in PJM During a Peak Event in Winter 2032 without Storage

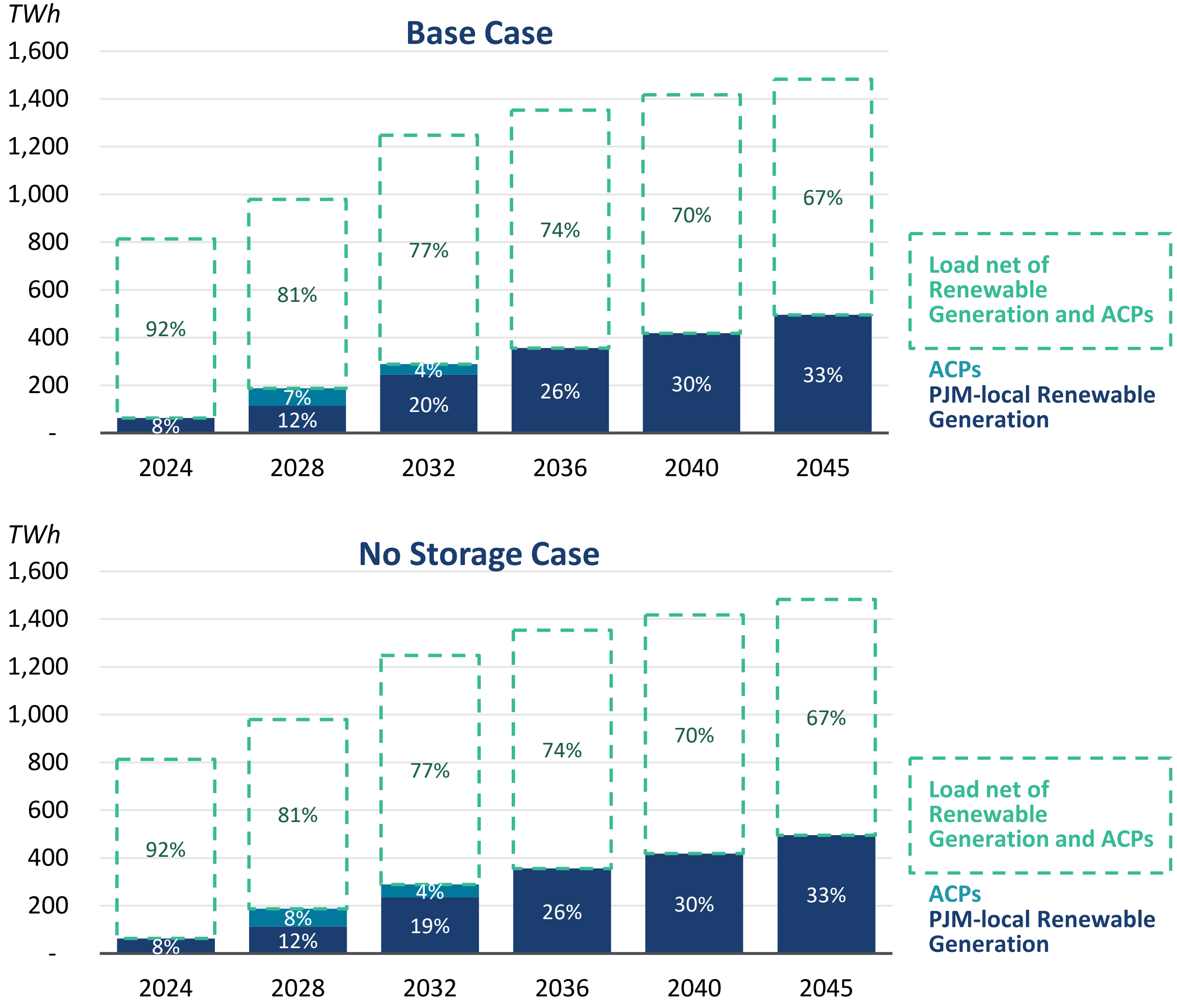


Alternative Compliance Payments

Much of new renewable development in PJM is driven by state RPS and clean energy goals.

- Today, PJM meets 46% of state targets with local generation, supplementing the rest with imports from MISO and Alternative Compliance Payments (ACPs)
- By 2032, we assume that all PJM state targets will be met with local generation or ACPs due to increased transmission costs between ISOs necessary to ensure RPS deliverability
- Without storage, PJM states rely on more ACPs to meet state RPS goals, particularly in 2028, than if storage was a resource option

PJM State Driven Clean Energy Standards



PJM Generation

PJM will meet most near-term load growth with increased fossil generation then rely on renewables to serve demand growth in the later 2030s.

- Today, the share of annual generation from renewables and nuclear is 39%. State RPS goals and carbon emission reduction targets will increase share of clean generation to 50% by 2045. In the near-term, by 2032, clean generation share decreases slightly (~37%) because of new gas development.
- Nuclear dominates the share of clean generation through the 2030s, but by the end of the modeling horizon solar, wind, and nuclear each contribute even shares of clean.
- Even by 2045, 50% of total energy demand is met by fossil generation despite state clean energy and carbon targets.

Annual Generation Results (TWh)

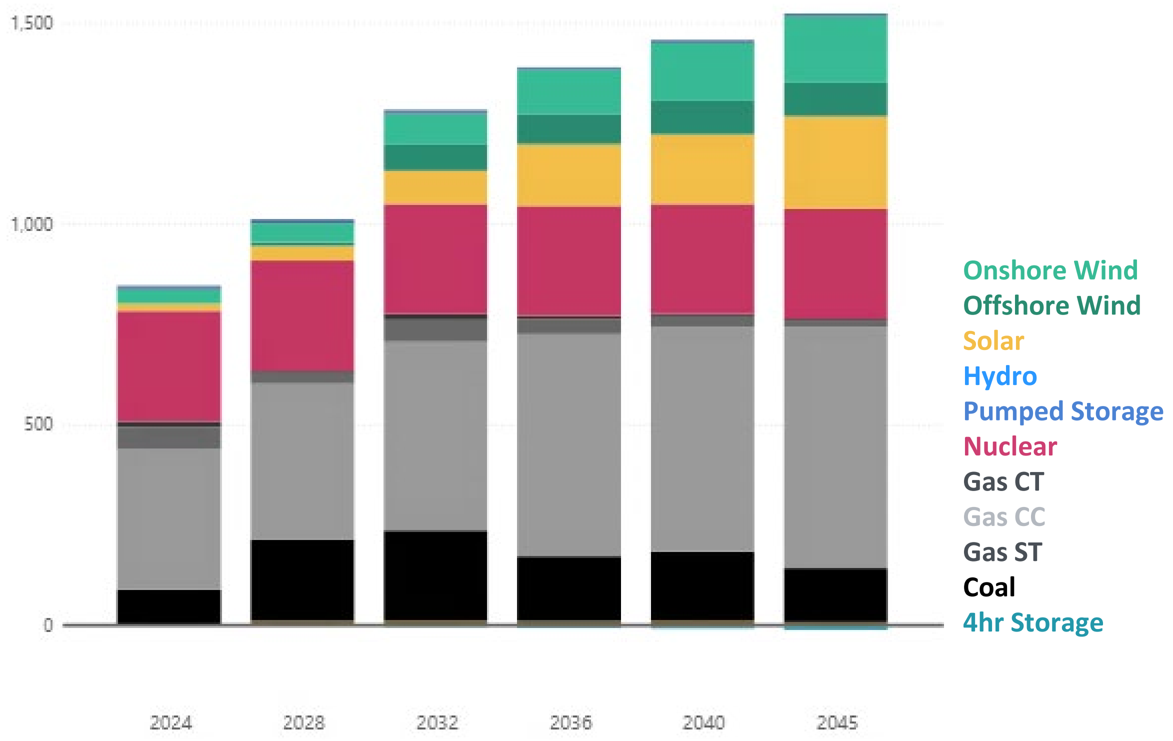


Table of Contents

Summary of Modeling Inputs

Category	Data Element	Description and Source Notes
Supply-Side Modeling Inputs	**Existing Generator Data**	Unit capacity, fuel type, prime mover, location, and heat rates (where applicable) from Velocity Suite, ABB Inc.
	Scheduled Additions/Retirements	Near-term planned additions and retirements sourced from Velocity Suite, ABB Inc. Planned fossil retirements are delayed until 2032-2036
	Cost Trajectory for New Generation	New resource costs, fixed and variable O&M sourced from NREL Annual Technology Baseline, adjusted for interconnection costs. New resource costs for gas and storage resources from Brattle 2025 CONE Report for PJM
	Hourly Renewable Generation	Hourly renewable generation by resource type for 25 weather years, from Renewables.Ninja and NREL SAM
	Hourly Thermal Outages	Hourly temperature and weather-based forced outages, and planned and maintenance outages by resource type from PJM 2025-2026 BRA Files and 2019-2023 System Operations Reports, extrapolated for 25 weather years using regression analysis
	Fuel Prices	Monthly fuel prices from S&P Market Intelligence Forwards and EIA AEO 2023
Demand-Side Modeling Inputs	**Load Shapes and Load Growth**	From PJM 2025 Load Forecast Report for 25 weather years
	Representative Periods	28 3-day periods created using k-means clustering algorithm on 25 weather years of demand and supply data
Market and Policy Inputs	**Resource Adequacy Framework**	Hourly resource adequacy requiring available capacity to be equal to or exceed hourly load plus operating reserve margin. Operating reserve margin from PJM Reserve Certainty Senior Task Force 2024 workshops.
	Tax Credits and Clean Energy Policies	IRA-based PTC for solar and wind and ITC for battery storage, SMR, and OSW – assumed to continue through end of modeling horizon based on national emissions reductions trajectory. Clean energy policies from literature review of PJM state-level targets
Transmission Modeling Inputs	**Zonal Topology**	'Pipe-and-bubble' model set-up with 8 uncongested energy zones with interzonal transmission flow limits. Flow limits consistent with NREL ReEDS and NERC ITCS data.
	Imports and Exports	Hourly energy flows to and from NYISO and MISO based on historical interchange data. Capacity import capability from PJM 2025-2026 BRA data on zonal CETL

GridSIM Inputs, Optimization and Constraints, and Outputs

INPUTS

Supply

- Existing and planned resources
- Fuel prices
- Investment/fixed costs
- Variable costs

Demand

- Representative day hourly demand
- Representative day hourly capacity needs

Transmission

- Zonal and intertie limits
- Capacity import limits

Regulations, Policies, Market Design

- Carbon pricing
- State and federal energy policies and procurement mandates

GridSIM OPTIMIZATION ENGINE

Objective Function

- Minimize NPV of Investment & Operational Costs

gridSIM

Constraints

- Market Design and Co-Optimized Operations
  - Energy
  - Capacity
- Regulatory & Policy Constraints
- Resource Operational Constraints
- Transmission Constraints

OUTPUTS

Annual Investments and Retirements

Energy Prices

Hourly Operations

Emissions and Clean Energy Additions

Revenues

Topology and Model Years

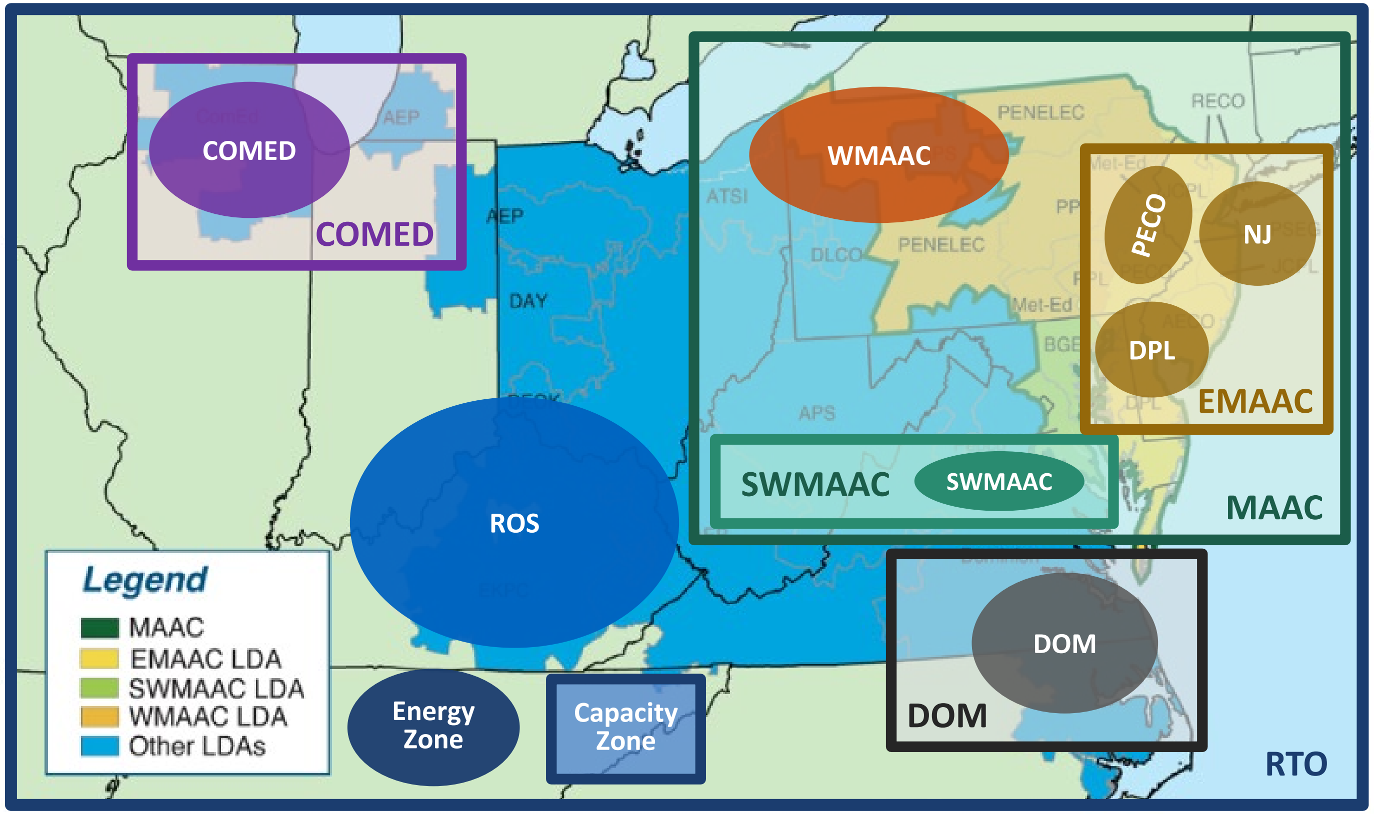
gridSIM is a “pipe-and-bubble” model. We model the PJM region as 8 energy bubbles nested within 5 capacity zones and an RTO wide target.

Each zone is connected to applicable neighbors via transmission “pipes” with limits informed by PJM transmission reports, NERC ITPS, NREL ReEDS, and/or other public data sources.

We model PJM conditions for select years: 2024, 2028, 2032, 2036, 2040, and 2045

We model simple connections between PJM and neighboring regions (NYISO, MISO) based on historical interface flows.

GridSIM Energy and Capacity Zonal Topology



Approach to Estimating Electric Customer Costs

- We evaluate PJM customer costs as the net present value of energy, capacity and any REC charges for the period between 2028-2045. We exclude model years prior to 2028 since build decisions are pre-determined.
- The impact of storage on distribution and transmission costs are not quantified. As a reference, current T&D costs in PJM roughly amount to under $50 billion per year from PJM IMM's Monthly Total Price reporting and EIA861 cost data for delivery only PJM utilities.
- The gridSIM model solves for a least-cost solution in each run. The model will build the lowest cost portfolio of resources that meets state RPS, energy and capacity needs, subject to resource availability constraints.
- Without storage available as a resource option, our model finds the lowest cost resource mix to meet state RPS and resource adequacy – sometimes resorting to costly load shed during the most extreme hours.
- We reflect the customer costs on an NPV $/MWh basis over 2028-2045. Rate impacts will vary year to year over this period.

Adjusted Customer Cost Approach

Customer Costs = **Capacity Costs** + **Energy Costs** + **Clean energy policy costs**

Capacity Costs: Hourly capacity obligation (MW) * hourly capacity cost ($/MW) summed over all nested PJM capacity zones

Energy Costs: Hourly load (MW) * hourly energy price ($/MWh) summed over all modeled PJM energy zones

Clean energy policy costs:
- RPS obligation (MWh) * REC price ($/MWh) for all state policies
- Procurement targets (MW) * procurement price ($/MW) for all state procurements

Customer costs are expressed in NPV $/MWh 2028-2045 as of 2024 (in 2024 $s) discounted at a nominal 10%. The NPV $/MWh metric discounts both the $ and MWh to effectively reflect a discounted weighted average rate impact placing more weight on near term years' impact but not necessarily discounting the result (e.g., if the impacts over time were a nominally constant X $/MWh per year, discounting both the numerator and denominator would result in the same X $/MWh as of 2024.)

GridSIM's Resource Adequacy Approach

GridSIM uniquely assesses the value of storage through an hourly resource adequacy framework.

gridSIM

gridSIM is Brattle's in house capacity expansion model

- **Optimization model** that minimizes system investment and operation costs
- Provides cost-effective power system **build-out** and **dispatch** solutions for given scenario conditions
- Represents the PJM market through **energy** and **resource adequacy** zones
- Applies market, policy, and technology **constraints** that mimic real life power systems and markets

WRAS

GridSIM employs the Weather and Resource Adequacy Sampling (WRAS) Tool to:

- Represent weather conditions occurring over **25 years** in a **single proxy year**
- Endogenously determine the capacity value of renewable and storage resources (and their co-dependencies) based on **hourly resource availability**
- Replace overly simplistic representations of resource capacity contribution (e.g. weather normal conditions and planning reserve margin)
- Efficiently capture renewable and load conditions over a 25+ year weather sample

Overview of WRAS

Brattle's capacity expansion modeling employs the **Weather and Resource Adequacy Sampling (WRAS) Tool** to create a weather-reflective proxy year with appropriately probability weighted multi-day periods:

- The tool selects probability-weighted proxy year periods based on multi-variable "k-means clustering" algorithm for gross load, net load (adjusted for weather-correlated forced fossil outages), and solar/wind profiles
- The proxy year is comprised of (e.g. 25 or 50) multi-day periods (or proxy weeks). Each period is weighted based on the frequency of periods with similar conditions during the entire 15+ year sample to capture multi-day events
- Weather representative proxy year eliminates the need for planning reserve margin and allows for hourly approach + operating reserve margin

This approach is computationally efficient, while representing the spread of renewable and load conditions that unveil the value of storage.

Weather and Resource Adequacy Sampling (WRAS) Tool

Brattle's WRAS tool creates a weather-reflective proxy year with appropriately probability weighted multi-day periods reflecting the range of load, renewable, and generation outage conditions that are expected to occur over the course of 20+ weather years. WRAS greatly enhances the representation of resource adequacy issues (and how to address them) in deeply decarbonized capacity expansion and production cost simulations.

INPUTS

20+ weather years of system-wide and zonal data:

- Load forecasts for weather years
- Wind, solar, and hydro profiles (including multi-day renewable droughts and variable hydro conditions) for weather years
- Planned and forced generation outages (including high hot/ cold weather outages)

OUTPUTS

- Proxy year composed of multi-day proxy periods (or proxy weeks)…
- … that reflects the renewable, load, and generation outage conditions that are expected to occur over many weather years
- Load and renewable/hydro generation profiles for each of the multi-day proxy periods
- Weights for each proxy period that reflect the expected frequency over entire weather sample

Model Years and Representative Periods

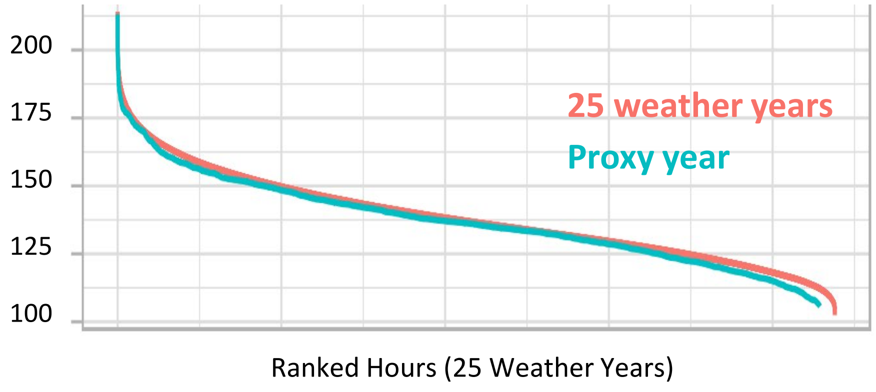
We model one historical year, 2024, every 4 years through 2040, as well as 2045.

Representative periods:

- gridSIM models representative 28 three-day periods instead of 8760 hourly observations to represent a model year
- Representative periods are selected from 25 years of historical weather, load and renewable generation data to simulate a 'proxy year' that captures a large range of weather uncertainty
- Our 28 period 'proxy year' represent 6 'typical' periods from each season, as well as two summer peak periods and two winter peak periods

The figures to the right illustrate an example of how closely our 'proxy year' data align with our 25 weather years.

Annual Generation Results (TWh)



Thermal Outages

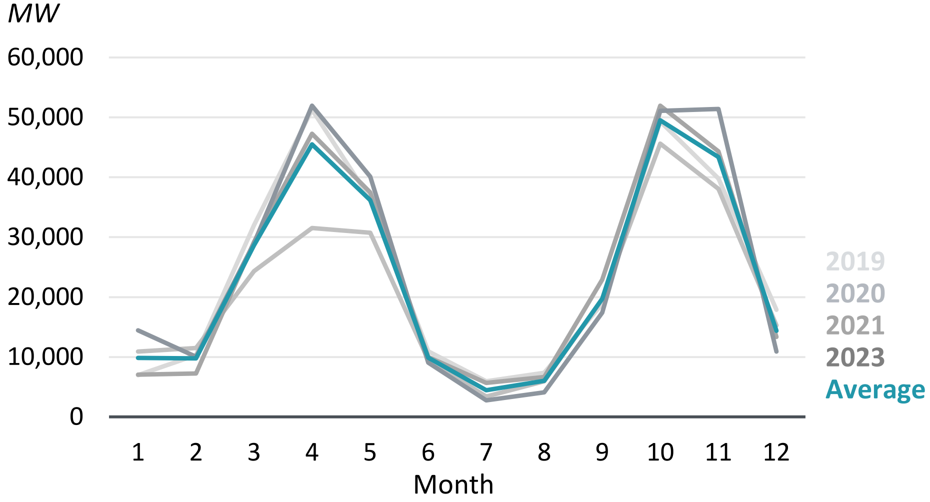
Representative periods also reflect unavailability of thermal plants due to planned and forced outages:

- Thermal capacity is frequently decommissioned during shoulder months for routine maintenance
- Extreme high or low temperatures can also lead to operational difficulties for thermal plants and therefore to forced outages (e.g. extremely high outage rates during Winter Storm Elliott)

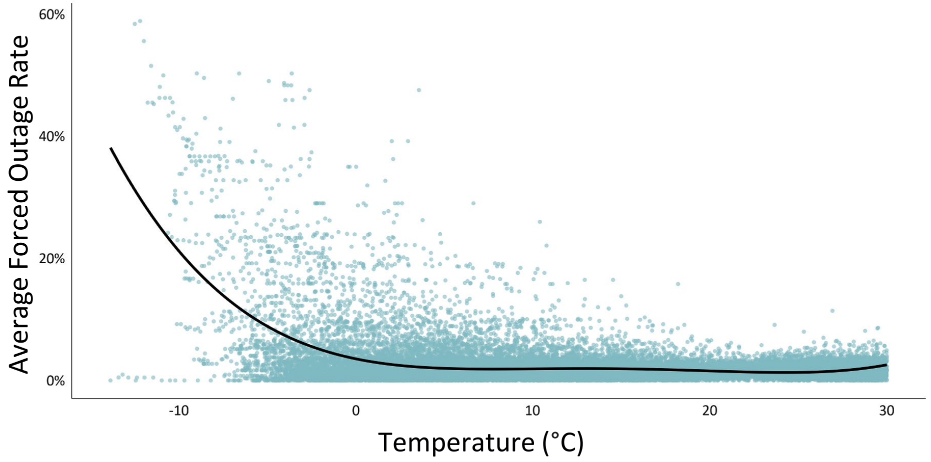
gridSIM reflects both planned and forced outages:

- Planned and maintenance outage data is sourced from PJM's Systems Operations Reports
- Temperature forced outages are sourced from PJM forced outage data or derived through a polynomial regression on historical forced outage rates during extreme temperatures

PJM Thermal Planned and Maintenance Outages from Systems Operations Report



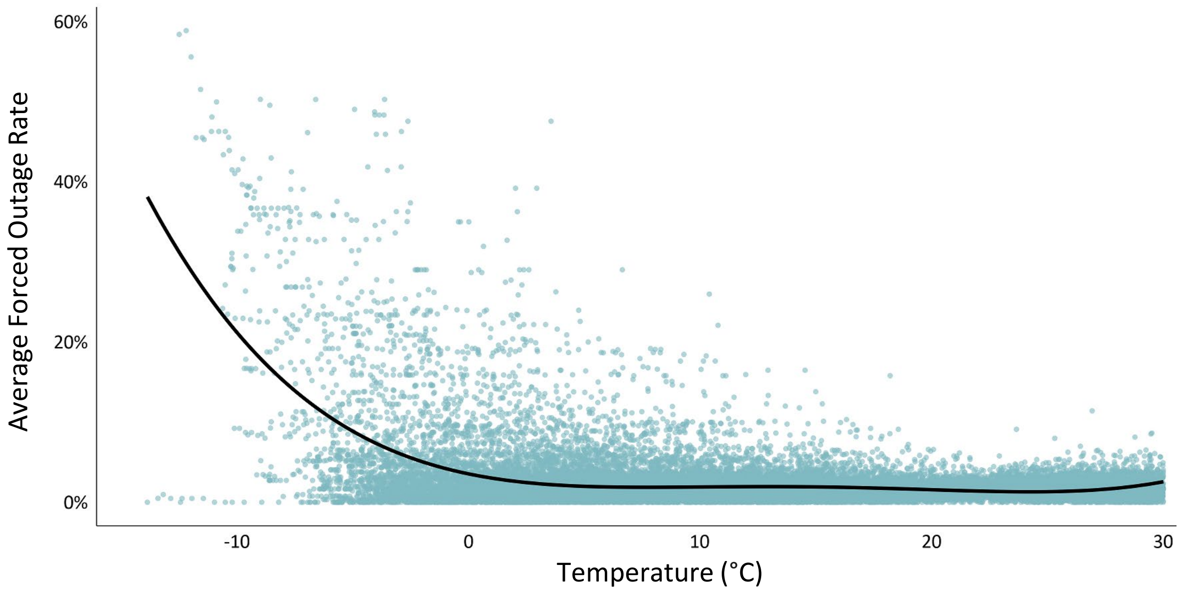
Forced Outages by Temperature for Gas CT



Prediction of Thermal Outages from Temperature

- A polynomial regression is applied to the average forced outage rate by temperature. The fit is varied by resource type to best capture the relationship between outages and temperature. An example relationship for Gas CTs is shown left.
- For gas CT, gas CC and coal, outage rates are adjusted to capture high outage rates during extreme weather events. In each predicted year, the top 1% of hours with the highest outage rate across the historical period (2012-2022) are scaled by the average difference between the predicted and historical outage rate.
- The polynomial is fit using PJM hourly forced outage rates from 2012 to 2022 by resource type[1].
- Hourly temperature data from 2009 to 2022 applied from Open-meteo.
- The polynomial estimate is applied to 2009-2011 weather data to estimate forced outage rates for years without historical data.

Forced Outages by Temperature for Gas CT



1. PJM - Effective Load Carrying Capability (ELCC)

Candidate Resources

We model the following candidate resources:

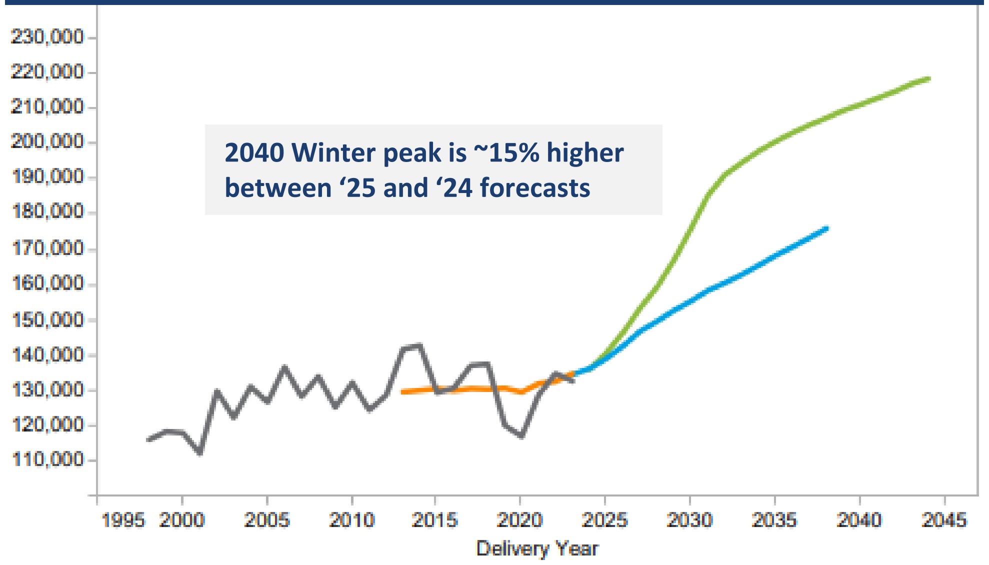
- **Renewables**: solar, onshore wind, offshore wind
  - Existing hydro and pumped storage units are also modeled
- **Battery storage**: 4hr, 6hr, 8hr (NREL ATB provides cost estimates up to 10 hours)
  - Existing 1hr and 2hr storage are modeled but are not offered as a candidate for capacity expansion due to lack of capacity accreditation by PJM for shorter duration storage resources
- **Thermal**: gas CC, gas CT
  - Existing biogen, gas ST, coal and large nuclear are modeled but are not considered as candidates for capacity expansion
- Additional resource types:
  - Nuclear SMR: NREL ATB provides cost estimates, although the cost and technology uncertainty remain high
  - Thermal CCS retrofits: coal CCS, gas CC CCS
  - Coal to gas fuel conversion

Demand Forecast

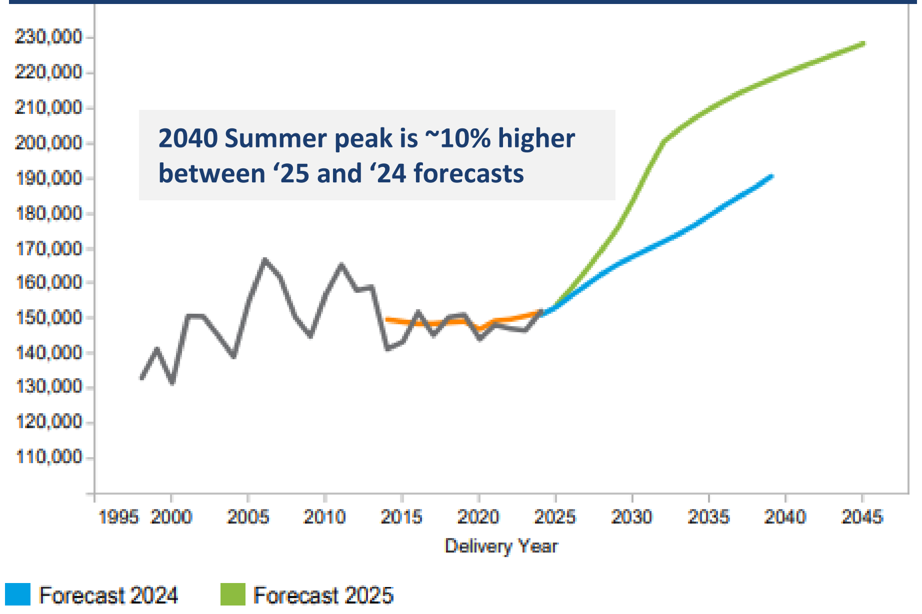
We use the recent 2025 PJM Load Forecast and weather years of data to capture weather related uncertainty and impacts on resource adequacy and capacity needs. Peak growth has increased significantly relative to 2024 forecasts.

PJM RTO

Winter Peak



Summer Peak



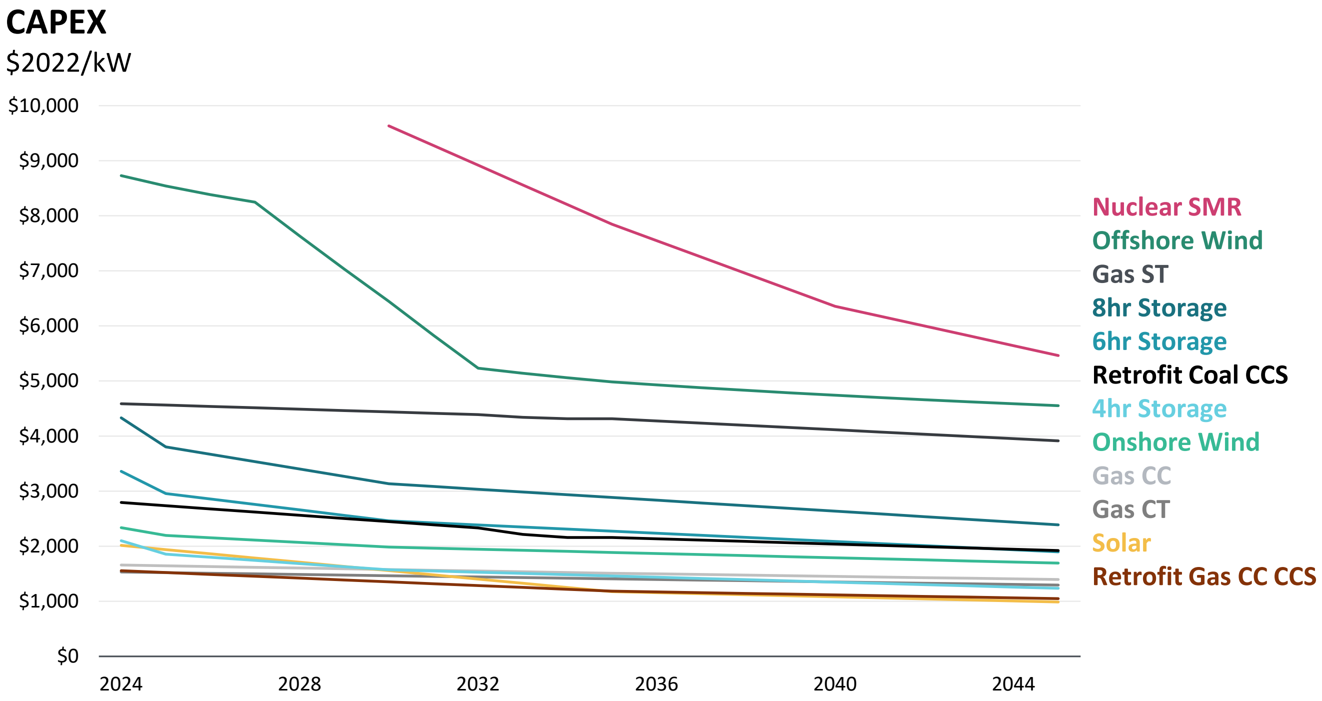
Resource Costs

For BESS, gas CCs, and gas CTs, we use recent installed cost forecasts by Brattle/S&L as part of the 2025 PJM Quadrennial Review.

NREL ATB occasionally understates costs of resources, particularly renewable resources subject to commodity price spikes and supply constraints. We adjust the assumed capital cost of other renewable resources based on component cost increases observed in Brattle's Quadrennial Review for PJM.

Table at right shows Brattle's estimates (published April 2025) and scaled NREL estimates in the chart.

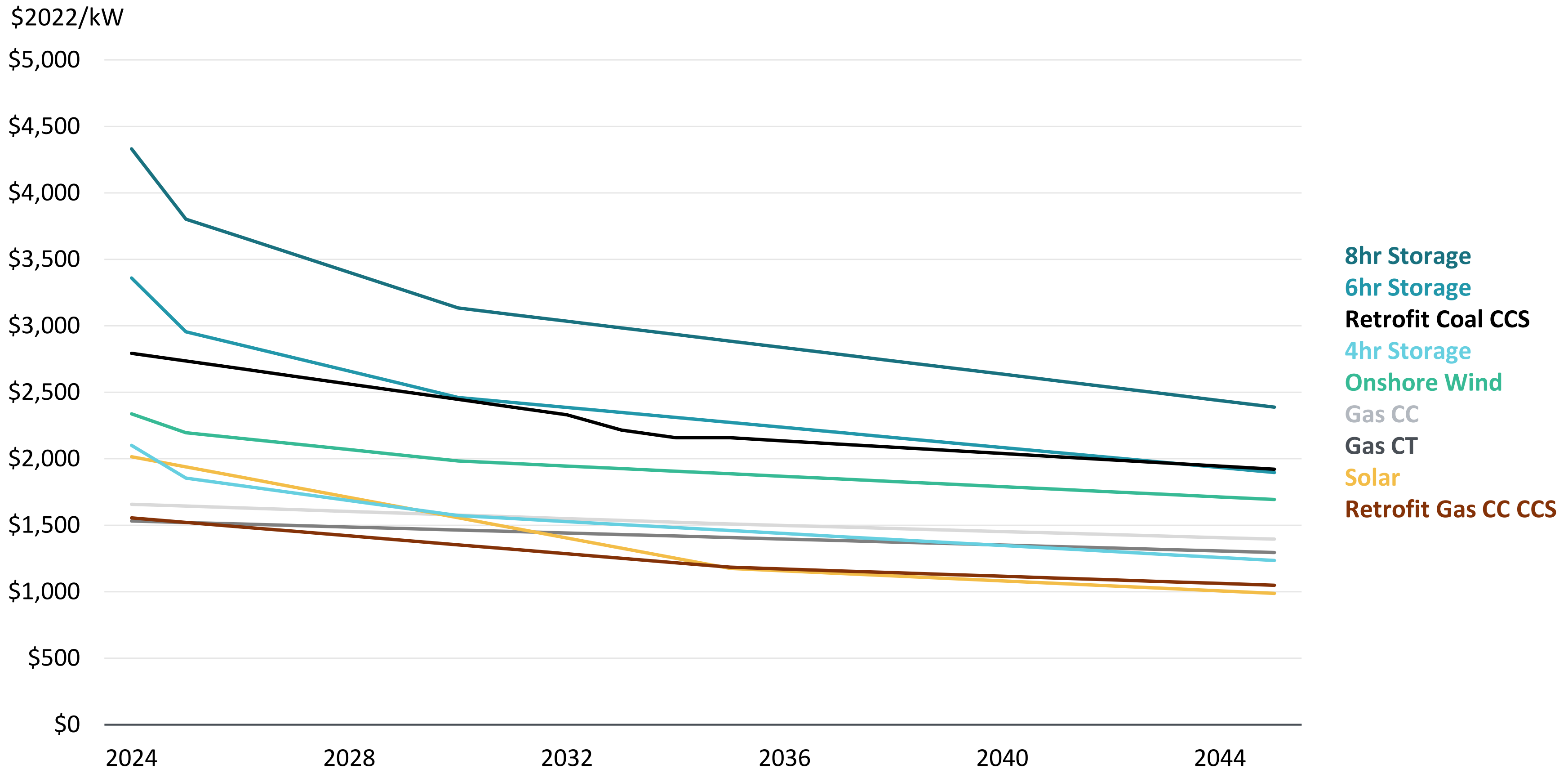
	Installed Cost (2028$/kW)	
	PJM CONE (Rest of RTO)	NREL ATB
Natural Gas CT	$1,674	$1,482
Natural Gas CC	$1,806	$1,639
4 Hour Storage *(pre-ITC)*	$1,898	$1,787



Note: CAPEX excludes tax credits.

CAPEX Costs – Close Up

CapEx by Resource



Note: Select resources shown for closer presentation.

Real-Time and Ancillary Service Revenue Adders

GridSIM does not capture revenue from real time and ancillary services markets that comprise a significant portion of peaker and storage unit revenues. These may make storage assets a more attractive investment option relative to other resources.

Brattle's advanced battery storage optimization model, bStore, has found that PJM battery assets can earn $20-65/kW-yr in the real-time energy and ancillary service markets. We assume ancillary service revenues are comprised primarily of synchronized reserve revenues, as the regulation market will likely be too thin to provide much value to storage resources.

Using bStore modeling results and additional calibration between the bStore and gridSIM models, we determined a cost reduction of ~$55/kW-yr to reflect additional revenues not captured in our capacity expansion.

bStore Modeling Results for PJM

Year	Real-Time Energy ($/kW-yr)	Synchronized Reserves ($/kW-yr)	bStore to gridSIM Model Calibration
2019	$10	$15	$15
2020	$15	$5	$15
2021	$25	$20	$15
2022	$30	$35	$15
2023	$20	$10	$15
Average	**$20**	**$20**	**$15**

Clean Energy Policies

Today, PJM imports around half of their procured REC amounts (largely from MISO). This is not feasible in the long run due to transmission infrastructure costs that would be more costly than installing local generation.

Based on the locational requirements of state RPS', we assume that 100% of state RPS targets will be fulfilled in PJM by 2032, rather than through imported RECs from MISO or alternative compliance payments. We 'feather in' the RPS between now and 2032 based on current levels of renewable generation and the PJM-wide 2032 RPS target.

We model alternative compliance payments (ACPs) of $50/MWh for Tier I resources and $150/MWh for solar carveouts in NJ, MD and DC.

Additionally, we model state RGGI participation through an applicable carbon price. We do not model EPA 111(d).

State	RPS and Clean Energy Goals	Carbon Emissions Goals (2005 Baseline)	Geographic Requirements for RPS
DC	RPS: 100% by 2032. Solar 15% by 2040.	Carbon free by 2032 (dccouncil.gov)	PJM or PJM adjacent state
DE*	RPS: 40% by 2035. Solar carve out of 10% by 2035	50% reduction by 2030, 100% by 2050 (de.gov)	PJM or outside of PJM deliverable to Delaware
IL	RPS: 50% by 2040. CES: 100% by 2050.	Carbon free by 2045 (ilga.gov)	In Illinois, adjacent to Illinois, or deliverable to Illinois
MD*	RPS: 52.5% by 2030 (50% Tier I, 2.5% Tier II). Solar 14.5% by 2030.	60% reduction by 2031, net zero by 2045 (md.gov)	PJM or deliverable to PJM
NJ*	RPS: 52.5% by 2030 (50% Tier I, 2.5% Tier II). Solar declining from 5.1% to 2.2% by 2030. 100% by 2050		PJM or deliverable to PJM
OH	RPS: 8.5% by 2026		In Ohio or deliverable to Ohio
PA*	RPS: 18% (completed)		In PJM
VA	RPS: 100% by 2045 (Dom), 100% by 2050 (ApCo) – RPS is applied to load not served by nuclear	Note that we are not modeling GHG reduction targets for Virginia	75% in state for Dominion, otherwise in PJM

Sourced from a review of state RPS goals, CAPSTF modeling, and PJM documentation. RPS = renewable portfolio standards. CES = clean energy standard. Standards are applied to eligible load. *Notes RGGI states.

Procurement Targets

Modeled state procurement targets are shown in the table on the right.

Despite project delays, cancellations, and various states lagging behind their procurement target, we model offshore wind procurements as scheduled in all cases and isolate the impacts of storage between the base and no storage cases. This assumption and modeling occurred before the recent stop-work orders. We anticipate a greater need for storage in PJM to complement solar and onshore wind that would be deployed in greater quantities to meet state RPS targets without OSW availability.

We do not model the following tentative procurements and instead allow the model to optimize non-mandated procurements:

- IL HB 587 and HB 5856, due to uncertain forward procurement years and proposed legislation status
- VA pending storage procurement
- IN and MI storage goals that likely won't lead to PJM capacity

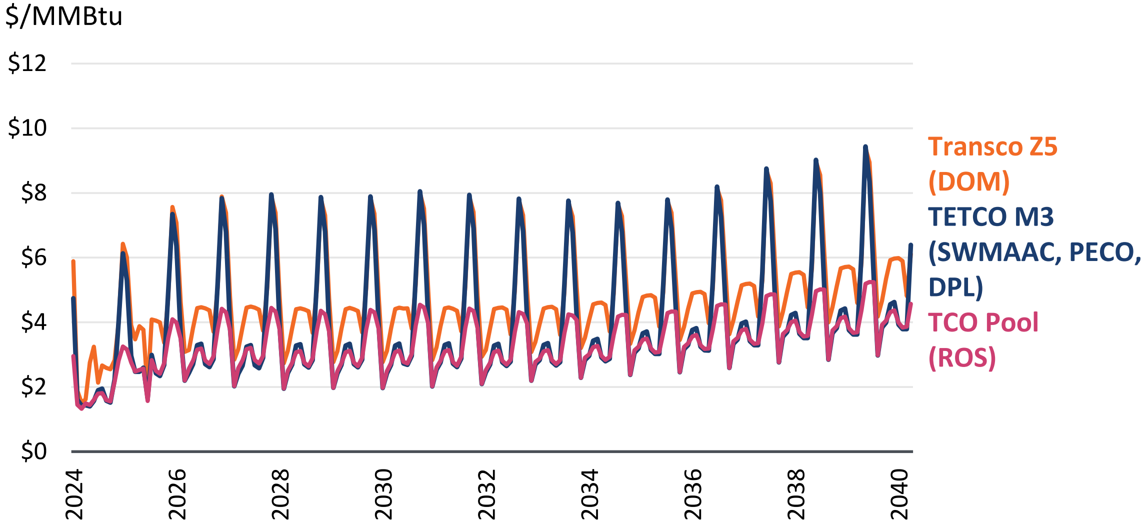
State	Storage Procurement Targets	Offshore Wind Procurement Targets
MD	3 GW by 2033	8.5 GW by 2032
NJ	2 GW by 2032 (1.4 GW by 2028)	11 GW by 2040 (6.4 GW by 2032, 8.7 GW by 2036)
VA	3.1 GW by 2035	5.2 GW by 2036 (with 2.6 GW planned by 2028)

Fuel Prices

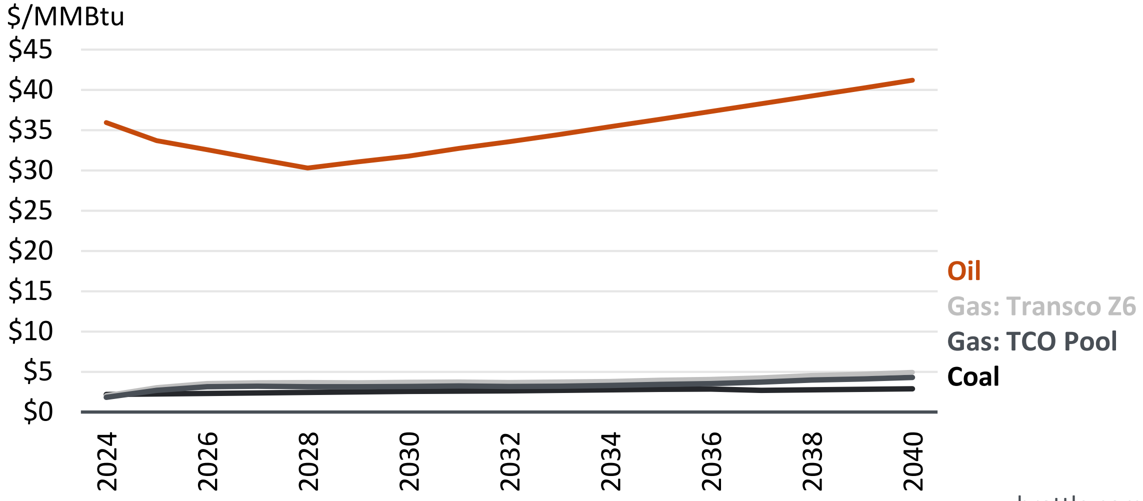
Gas prices are sourced from recent forwards through 2036 from S&P Global Market Intelligence and grown at EIA AEO 2023 growth rates through the modeling horizon. Gas prices vary across the PJM zones and capture monthly volatility.

Coal and oil prices are based on EIA AEO 2023 forecasts for the PJM region.

Modeled Monthly Gas Price by Region



Modeled Annual Fuel Prices



PJM Capacity Expansion Benchmarking

Our modeled capacity expansion results fall between the Policy and Accelerated cases. The differences in results are driven by varying input assumptions. The PJM model relies on:

- PJM 2022 load forecast (vs. our PJM 2025 load forecast)
- Lower resources costs that do not reflect recent cost estimates
- Outdated state clean energy and capacity procurement targets

PJM 2035 Capacity Expansion Results (ICAP GW)

Table 1. Installed Capacity by Resource Type

	Base	Policy	Accelerated
Offshore Wind	1,469	14,908	14,908
Onshore Wind	3,890	16,775	101,391
Onshore Wind Hybrid	-	45	400
Solar	18,081	42,247	77,366
Solar/Storage Hybrid	1,680	3,470	53,378
Battery Energy Storage	386	6,451	27,473
Coal	39,940	25,711	15,765
Natural Gas	99,772	82,256	62,762
Nuclear	34,003	34,003	34,003
Oil	5,949	4,266	727
Hydro	9,526	9,521	9,555
Other Renewable	1,330	1,370	1,262
Other	292	373	302
Demand Response	7,286	7,286	7,129
Total	223,604	248,681	406,422

Source: https://www.pjm.com/-/media/DotCom/library/reports-notices/special-reports/2024/20240808-energy-transition-in-pjm-flexibility-for-the-future-addendum.ashx

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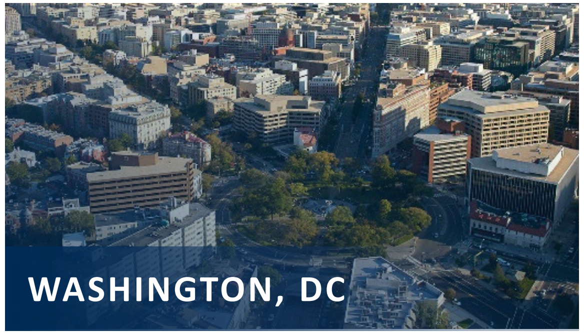

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