Report Update

Ensuring Reliability: A Case Study of the PJM Power Grid

PREPARED FOR

AMERICA'S POWER
Reliable • Secure • Resilient • Affordable

DATE

February 2024

PREPARED BY

Henry Chao
HChao@Quanta-Technology.com
518.598.4796

Hisham Othman
HOthman@Quanta-Technology.com
919.334.3078

Report Contributors:

- Henry Chao
- Edison Cardona
- Khash Mahani
- Hisham Othman

Key Terms:

Reliability	Adequacy and security are two key aspects of reliability that broadly ensure the continued operation of the system over a broad spectrum of system conditions and following a wide range of probable contingencies.
Transmission Security	Planning and operating the system in a way that anticipates the possibility of failure of key system elements in order to minimize the loss of service to large groups of customers, to not cause any area of the Interconnected system to become unstable and lose its integrity, and to not cause generation or transmission equipment to operate outside their normal limits.
Resource Adequacy	Addresses the amount of capacity needed to serve a forecasted peak load while meeting the required loss of load expectation (LOLE) criterion. The LOLE criterion defines the adequacy of capacity that ensures that load cannot exceed available capacity, on average, more than one day in 10 years.
Resiliency	The capability of an energy system to tolerate disturbances and to continue to deliver energy services to consumers. Resilience, in the context of the bulk electric system, relates to preparing for, operating through, and recovering from a high-impact, low-frequency event.
Fuel-Secure	The capability of the resource to store fuel on-site in order to limit the exposure to a single common event and maintain its ability to deliver maximum energy output independent of the external fuel delivery infrastructure.
Thermal Overload	Power flows above transmission conductor thermal limits.
Grid Stability	The ability to balance power generation and power consumption dynamically in real time and to maintain system frequency within acceptable limits.
Energy-Only Resource	Refers to a generation resource that either did not offer or was not selected in the capacity auction, and thus it does not have the obligation to generate electricity when requested (i.e., Capacity Performance) but can bid into the energy market.
Single-Fuel Gas Unit	A generator whose sole fuel source is natural gas and which does not have an on-site fuel storage capability.
Common Mode Outage	Simultaneous outages of multiple components due to a common cause such as the failure in the natural gas delivery system causing multiple outages of the natural gas-fueled generation stations.
Non-coincident Peak Load	The sum of the individual maximum demands of each area of the system regardless of time of occurrence within a specified period.
Coincident Peak Load	The sum of each area's demand during the time when electricity demand system-wide is the highest.
ELCC	Effective Load Carrying Capability (ELCC), typically expressed as a percentage of a resource's installed MW rating, defines the capacity value of a resource as the extra load that can be added to the system once the resource is added without degrading a chosen reliability index (usually the loss of load probability).
OSW	Offshore Wind

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 Executive Summary

The electric power industry is required to comply with reliability standards established by the North American Electric Reliability Corporation (NERC) and its regional councils. NERC defines grid reliability in terms of 1) resource adequacy[1], which is the ability of the electric system to supply electricity to end-use customers at all times, and 2) transmission security, which is the ability of the system to withstand sudden disturbances while avoiding blackouts or damage to equipment. Assessing the challenges to compliance with reliability standards should consider not only normal circumstances but also contingencies such as fuel unavailability and greater-than-expected retirements of synchronous generation.

America's Power contracted Quanta Technology to update Quanta Technology's 2018 PJM grid reliability and resilience study[2] (hereafter, "2018 study") to show whether retirements of fossil-fueled synchronous generating units could lead to future reliability problems. The 2018 study used the PJM system as a case study to illustrate the potential reliability consequences of two major risks: increased coal retirements and fuel insecurity. The study showed that the premature retirement of coal-fired generation and the loss of natural gas-fired generation could adversely impact PJM's ability to meet reliability criteria.

This updated study projects a 2023 baseline scenario for PJM and analyzes seven future resource adequacy scenarios and four transmission operation scenarios based on updated information. The updated study determines whether any of these scenarios would violate NERC's reliability standards. The study year for the updated study is 2028. Three of the 11 scenarios assume hypothetical measures (hybrid solar and expanded electric transmission) in an attempt to mitigate reliability violations. Insights from the updated study include the following:

- The resource adequacy analysis shows a potential system loss of load of as much as 13,900 megawatts (MW) during extreme winter peak demand. This amount of lost load is based on PJM's accredited capacity values combined with assumed 40,000 MW of fossil retirements and the loss of 30,000 MW of gas-fired generation under extreme winter weather conditions.
- The transmission security analysis shows equipment overloads that trigger as much as 6,826 MW of load shedding during average winter peak demand under a high retirement scenario. This amount of load shedding is based on assumed fossil retirements. The analysis reveals the expected overload of 30 bulk transmission facilities (230 kV and higher) in the 2028 summer due primarily to high load growth associated mostly with new data centers. The planned retirements of coal and gas units increase the overloaded bulk transmission facilities from 30 to 32 and would require load shedding up to 3,547 MW to meet transmission security standards. The analysis shows a

[1] A system is resource adequate if it is able to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. The corresponding reliability standard, which is expressed as a loss of load expectation (LOLE), requires an involuntary load disconnection event not more than one day every 10 years, or 0.1 day per year. That is, any widespread loss of load of 300 MW or greater that lasts 3 to 24 hours is considered one event. One MW of generation, on average, will serve 1,000 to 1,500 homes.

[2] Quanta Technology, *Ensuring Reliability and Resilience: A Case Study of the PJM Power Grid*, reported for America's Power, April 2018.

worse situation in the 2028/2029 winter. The defined coal and gas retirements will increase the number of overloaded bulk transmission facilities from 36 to 52 and will require 4,708 MW of load shedding to meet transmission security standards. A sensitivity analysis of further retirements of 5 GW of coal plants increases the overloaded facilities to 57 and the required load shedding to 6,826 MW.

- Maintaining adequate resources will be a challenge for the PJM system in the future when the grid is likely to be operating under abnormal conditions (e.g., extreme weather events).
- Regional electric demand is peaking less in summer and more in winter, presenting a challenge in fueling electric generation during peak winter demand hours.
- Maintaining fuel diversity and understanding the seasonal operating attributes of new and existing resources are critical to maintaining grid reliability.
- Although a 50% increase in interzonal transmission capacity could avoid a resource adequacy problem, such a substantial increase would likely be impossible by 2028.
- When there is sufficient generation in the summer peak hours, the PJM transmission system would have enough dispatchable generation to help maintain secure transmission operation. However, the situation becomes very challenging during winter, particularly under severe weather conditions.

This updated study identified four key actions for meeting NERC reliability standards:

- First, policymakers and the electric industry must carefully consider if and when existing generation resources can be retired without negatively impacting resource adequacy and secure transmission operations.
- Second, regulators and utilities must coordinate to maintain a degree of existing dispatchable generation because new technologies (e.g., hydrogen blending for generation and long-duration energy storage) have yet to be proven on a larger scale to be practical and may not be able to perform to the same level as existing dispatchable generation.
- Third, the electric industry needs a better understanding of how extreme weather events and climate change affect power system needs.
- Finally, the electric power system must remain reliable and become more resilient because the nation is electrifying multiple economic sectors, which are increasingly dependent on electricity.

This is an independent report by the authors at Quanta Technology, supported by funding from America's Power. The report, however, reflects the analysis and judgment of the authors only.

2 Introduction

Quanta Technology was contracted by America's Power to update a 2018 PJM grid reliability and resilience study (2018 study) to show whether more retirements of fossil-fueled synchronous generating units would cause reliability problems for PJM. The 2018 study used the PJM system as a case study to illustrate the potential reliability consequences of two major risks: coal retirements and fuel insecurity. These were risks because PJM relies on coal and natural gas for about 70.5% of its electric generating capacity. The 2018 study analyzed nine scenarios to determine whether any of them would result in a violation of industry standards for transmission security and resource adequacy, which are measures of grid reliability. The report concluded that the PJM grid is reliable under capacity oversupply conditions. However, premature retirements of coal-fired generation and supply disruptions in natural gas-fired generation could limit PJM's ability to meet reliability criteria for transmission security, resource adequacy, or both under seven of the nine scenarios.

After the 2018 study, the PJM system has been concurrently experiencing fossil generation retirements and renewable generation additions. Similar to what NERC has identified about tightening resource adequacy due to the retirement of dispatchable resources throughout the country for both summer and winter periods[3], PJM has recognized the risks and studied them. In the *Resource Retirement, Replacement, and Risk*[4] report, PJM assumed 40 gigawatts (GW) of retirements during 2022–2030, and 60% (i.e., 24 GW) would be coal-fired generation. That is, 53%[5] of the coal fleet would be retired during that period. This situation is close to one of the scenarios in the 2018 study, namely, that half of PJM's coal capacity (about 30,000 MW out of 61,000 MW) was assumed to be retired. However, the anticipated future generation mix calls for an updated understanding of the two essential aspects of grid reliability: resource adequacy and transmission security. Specifically, the updated study (hereafter, "updated study") investigated the resource mix in PJM upon the retirement of 40 GW of coal together with other fossil generation. The updated study then illustrates whether the remaining dispatchable resources and other expected new generation resources could support reliable power grid operations.

Quanta Technology collected generation additions and retirements and then reviewed and updated the PJM resource and transmission models used in the 2018 study. The updated study consisted of three tasks:

- Task 1: Updating 2018 Study Models and Assumptions
- Task 2: Resource Adequacy Analysis
- Task 3: Transmission System Security Analysis

The following sections detail the approaches and findings of each task.

[3] NERC, *2023 Long-Term Reliability Assessment*, December 2023.
[4] PJM, *Energy Transition in PJM: Resource Retirements, Replacements & Risks*, February 24, 2023.
[5] Coal represents 24% of PJM's 187 GW total installed capacity currently. The total coal capacity is about 44 GW.

3 Task 1: Updating 2018 Study Models and Assumptions

The latest PJM load forecasts, generation additions, and retirements expected from 2021 to 2030 were used to update the resource adequacy models (PJM's 4R Report).[6] Since no significant retirements from 2028 to 2030 have been announced, 2028 was used as the study year. PJM's RTEP 2023 series of power flow cases were used as the topology with updated resource assumptions to update the transmission study; similarly, the transmission study was done for the year 2028. All the assumptions and study methodologies remain the same as in the 2018 study except for the load forecast and resources discussed in this section.

Like in the 2018 study, the PJM resource model was built based on Hitachi's latest PROMOD database, modified according to the information from PJM, and updated for retirement dates based on company announcements and state policies. The resource mixes for 2021 through 2030 are summarized in Table 1. Additional resource information can be found in the PJM 4R Report (see footnote 4).

Table 1. Resource Mix Summary (Nameplate in MW)

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BESS	209	2,101	2,629	2,629	2,729	2,729	2,729	2,729	2,729	2,729
Coal	43,295	42,103	35,830	34,951	33,022	33,022	29,775	21,963	21,963	20,425
DR	0	6,917	6,917	6,917	6,917	6,917	6,917	6,917	6,917	6,917
Gas	84,911	91,987	101,877	101,019	101,019	100,787	97,861	97,861	97,861	90,971
Hydro	3,091	3,129	3,207	3,252	3,261	3,261	3,261	3,261	3,261	3,261
Nuclear	32,749	32,749	32,749	32,749	32,749	32,749	32,749	32,749	32,749	32,749
Oil	5,810	5,739	4,952	3,943	3,546	3,546	3,538	3,538	3,538	3,438
OSW	162	410	428	1,417	2,690	4,810	9,715	10,315	10,815	10,815
Other	358	358	358	358	358	358	358	358	358	358
PS-Hydro	5,232	5,932	5,932	5,932	5,932	5,932	5,932	5,932	5,932	5,932
Renewable	1,506	1,481	1,481	1,481	1,481	1,481	1,481	1,481	1,481	1,481
Solar	7,300	33,092	42,180	43,679	44,279	44,279	44,279	44,279	44,279	44,279
Wind	11,058	22,887	24,074	24,074	24,074	24,194	24,194	24,194	24,194	24,194
Total*	195,680	248,884	262,614	262,401	262,057	264,065	262,789	255,577	256,077	247,549

*Note: Red highlighted numbers are the total generation capacity for PJM for 2023 and 2028. These include the generation resources that were not physically retired or existing but not offered to the PJM capacity auction in and before 2023. In the table, "Renewable" refers to clean energy resources other than solar, wind, hydro, offshore wind (OSW), or nuclear; solar and wind capacities stay constant after 2025 to reflect the activities of the PJM Queue.

[6] PJM, *Energy Transition in PJM: Resource Retirements, Replacements & Risks*, February 24, 2023.

Table 2 provides PJM's non-coincident load forecasts[7] for the system and its 12 zones for the years 2023 and 2028. Notably, a higher forecast load, such as 90/10, is about 7% higher than the average 50/50 forecast.

Table 2. Year 2023 Load Forecast (in MW)

Area Name	50/50 SP	90/10 SP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ratio*	max
APS	8,724	9,335	9,048	8,557	7,783	6,493	7,062	8,117	8,725	8,487	7,655	6,390	7,201	8,379	5.60%	9,048
AEP	22,548	24,126	22,497	21,312	19,508	16,343	18,378	20,794	22,328	22,019	20,147	16,190	18,184	20,774	14.46%	22,497
EMAAC	31,327	33,520	23,713	22,498	19,807	17,525	22,836	28,899	31,724	30,537	25,733	19,606	19,154	22,708	20.09%	31,724
SWMAAC	12,640	13,525	11,183	10,544	9,503	7,835	9,734	11,344	12,283	11,933	10,393	8,043	8,606	10,197	8.11%	12,283
COMED	20,417	21,846	15,046	14,312	12,528	11,400	14,710	18,857	20,638	20,025	17,049	12,343	12,318	14,553	13.10%	20,638
DAY	3,295	3,526	2,939	2,780	2,582	2,201	2,616	3,009	3,267	3,188	2,856	2,223	2,397	2,747	2.11%	3,267
DEOK	5,249	5,616	4,570	4,294	3,861	3,463	4,245	4,939	5,269	5,135	4,784	3,559	3,659	4,277	3.37%	5,269
DELCO	2,712	2,902	2,003	1,920	1,781	1,685	2,159	2,577	2,759	2,658	2,402	1,799	1,736	1,930	1.74%	2,759
SOUTH	23,947	25,623	24,150	22,591	20,340	17,513	19,670	21,798	23,130	23,015	20,732	17,885	19,718	22,245	15.36%	24,150
ATSI	11,962	12,799	10,097	9,727	9,168	8,090	9,670	11,557	12,349	11,900	10,548	8,167	8,664	9,764	7.67%	12,349
E. PA	10,215	10,930	10,113	9,558	8,853	7,485	8,296	9,701	10,352	9,995	8,782	7,377	8,228	9,295	6.55%	10,352
W. PA	2,871	3,072	2,775	2,682	2,443	2,184	2,242	2,656	2,807	2,669	2,446	2,192	2,365	2,641	1.84%	2,807
Total	**155,907**	**166,820**	**138,134**	**130,775**	**118,157**	**102,217**	**121,618**	**144,248**	**155,631**	**151,561**	**133,527**	**105,774**	**112,230**	**129,510**	**100%**	**157,143**

Table 3. Year 2028 Load Forecast (in MW)

Area Name	50/50 SP	90/10 SP	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ratio*	max
APS	9,568	10,238	9,245	8,745	7,899	6,539	7,087	8,076	8,769	8,519	7,726	6,474	7,340	8,459	5.88%	9,245
AEP	22,797	24,393	22,902	21,684	19,738	16,425	18,370	20,731	22,472	22,199	20,353	16,268	18,375	21,021	14.01%	22,902
EMAAC	30,863	33,023	24,298	23,081	19,962	17,453	22,836	28,776	31,835	30,662	25,941	19,716	19,330	23,232	18.96%	31,835
SWMAAC	12,520	13,396	11,485	10,844	9,656	7,831	9,715	11,266	12,237	11,940	10,412	8,130	8,814	10,415	7.69%	12,237
COMED	20,102	21,509	15,226	14,499	12,493	11,244	14,387	18,546	20,223	19,719	16,694	12,112	12,196	14,597	12.35%	20,223
DAY	3,280	3,510	2,962	2,804	2,627	2,197	2,625	2,979	3,275	3,171	2,858	2,214	2,398	2,733	2.02%	3,275
DEOK	5,204	5,568	4,684	4,403	3,953	3,523	4,299	4,996	5,382	5,219	4,883	3,619	3,734	4,331	3.20%	5,382
DELCO	2,702	2,891	2,030	1,943	1,816	1,713	2,191	2,605	2,812	2,705	2,464	1,845	1,778	1,942	1.66%	2,812
SOUTH	30,768	32,922	27,990	26,317	23,675	20,683	22,758	24,797	26,204	26,078	23,852	21,019	23,066	25,561	18.90%	27,990
ATSI	11,828	12,656	10,192	9,827	9,327	8,106	9,761	11,605	12,499	12,018	10,669	8,253	8,771	9,733	7.27%	12,499
E. PA	10,300	11,021	10,261	9,716	8,998	7,632	8,544	9,994	10,685	10,332	8,993	7,464	8,348	9,407	6.33%	10,685
W. PA	2,830	3,028	2,769	2,678	2,403	2,139	2,214	2,638	2,808	2,672	2,425	2,175	2,344	2,619	1.74%	2,808
Total*	**162,762**	**174,155**	**144,044**	**136,541**	**122,547**	**105,485**	**124,787**	**147,009**	**159,201**	**155,234**	**137,270**	**109,289**	**116,494**	**134,050**	**100%**	**161,893**

*Note: Ratio refers to the percentage of the peak load in the respective region to PJM's total peak load.

PJM revised its coincident load forecast upward for the year 2028 from 152,698 MW in its 2022 forecast to 155,703 MW in its 2023 forecast and again to 164,114 MW in its latest forecast issued in January 2024. The latest forecast shows the nominal (50/50) forecast for the summer peak of 164,114 MW and a winter peak of 147,918 MW. It also forecasts the

[7] PJM, *Load Forecast Report*, January 2022.

extreme weather (90/10) forecast for the summer peak of 177,046 MW and the winter peak of 155,447 MW.

Figure 1 provides the location of the PJM zones and member utility companies geographically within each of the 12 zones.

Zones	Utilities	Zone #
APS	AP	1
AEP	AEP, and OVEC	2
EMAAC	AE, DPL, JCPL, PECO, PSEG, and RECO	3
SWMAAC	BGE, and PEPCO	4
COMED	COMED	5
DAY	DAY	6
DEOK	DEOK	7
DELCO	DLCO	8
SOUTH	EKPC, and Dominion	9
ATSI	ATSI	10
E. PA	METED, and PPL	11
W. PA	PENELEC	12

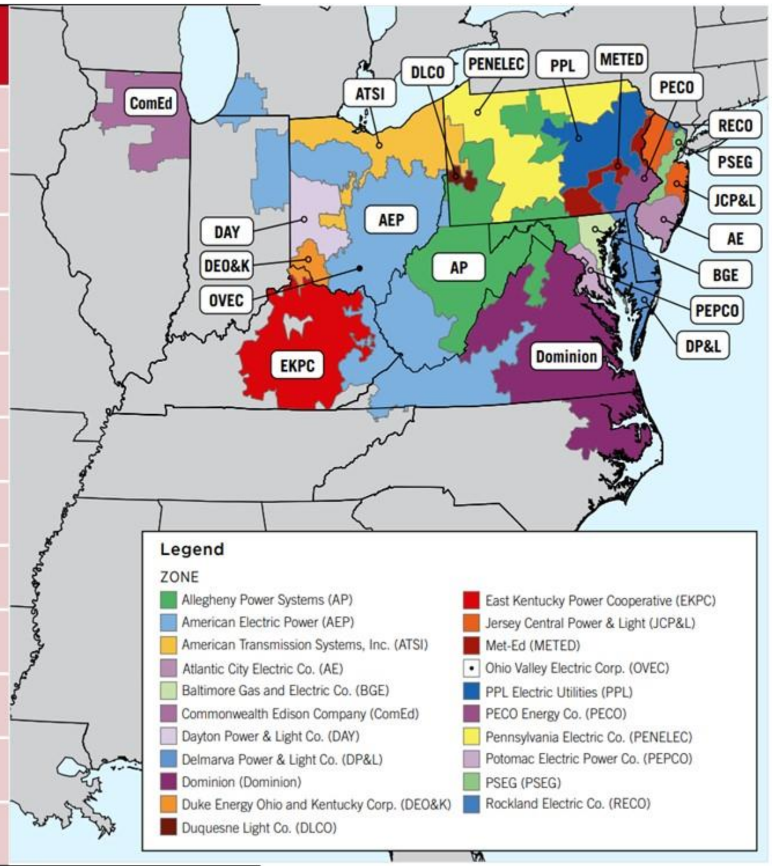

Figure 1. PJM Zonal Map and Member Utility Companies

With the capacity and resource mixes in Table 1 and the forecasted loads in

Table 2 and Table 3, the PJM system's resource adequacy measured by loss of load expectation (LOLE) is 0.000002 day per year and 0.000791 day per year for the years 2023 and 2028, respectively.[8] Normal performance means average performance annually, which does not reflect actual performance, for example, during severe winter weather.

PJM intends to improve its resource adequacy modeling and alignment with the eligibility of performance payments in the capacity market. In ER24-99 filed with FERC, PJM updated its risk modeling approach to use a marginal effective load carrying capability (ELCC) for all resources, which recognizes the reliability contributions of respective resources during the hours of greatest risk. While this filing included an annual approach, PJM ultimately intends to move to a seasonal approach, as was discussed in the PJM stakeholder process

[8] The PJM electric system is planned to meet an LOLE representative of an involuntary load disconnection event not more than once every 10 years, or 0.1 day per year.

that led to the FERC filing. During the stakeholder process, PJM studied resource seasonal performance-based capacity accreditation and published the seasonal capacity accreditation values, as shown in Figure 2.[9]

Note that the 22 percentage point derating (97% to 75%) for the gas-fired combined cycle generation and 36 percentage point derating (98% to 62%) for gas-fired combustion turbines from summer to winter reflects gas supply and delivery challenges in the winter season.

The capacity accreditations shown in Figure 2 were used in the updated study to reflect the ELCC values for renewable resources on the left of the figure. Note that solar without DC-coupled, on-site battery storage only has a 1% winter value for fixed solar panel PV and 2% for tracking solar panel PV.

	Summer	Winter	Annual Equivalent
Onshore Wind	9%	36%	25%
Offshore Wind	17%	68%	47%
Solar Fixed Panel	18%	1%	8%
Solar Tracking Panel	31%	2%	13%
4-hr Storage	90%	38%	59%
6-hr Storage	97%	48%	67%
8-hr Storage	99%	58%	75%
10-hr Storage	100%	69%	81%
Solar Hybrid Open Loop	53%	11%	28%
Solar Hybrid Closed Loop	53%	11%	28%
Hydro Intermittent	40%	44%	42%
Landfill Gas Intermittent	60%	51%	55%
Hydro with Non-Pumped Storage	97%	82%	88%

	Summer	Winter	Annual Equivalent
Thermals (Overall)	**94%**	**78%**	**84%**
Nuclear	97%	95%	96%
Coal	89%	83%	86%
Gas CC	97%	75%	83%
Gas CT	98%	62%	76%

** Additional thermal class accreditations forthcoming*

	Summer	Winter	Annual Equivalent
DR	109%	73%	87%

** DR values reflect status quo performance windows; assessment of 24-hour availability DR forthcoming*

Figure 2. PJM Estimated 2026/2027 Class Average Accreditation Value

The lower capacity accreditation values in the winter season (see Figure 2) require the updated study to focus on resource adequacy during the winter months. In fact, from observing the loss of load events over the annual LOLE Monte Carlo simulations, 99% of the risk occurred within a few weeks of the summer period when the load is high and during winter when the high load is combined with fewer resources. The seasonal share of the LOLE is much flatter in the annual study. The observed phenomena further helped shape the updated study to investigate 10 additional scenarios primarily for the winter seasons. These scenarios are listed in

Table 4.

[9] *Capacity Market Reform: PJM Proposal*, July 27, 2023, https://www.pjm.com/-/media/committees-groups/cifp-ra/2023/20230727/20230727-item-02a---cifp---pjm-proposal-update---july-27.ashx.

Table 4. Scenario Definition

	SCENARIO NAME	DESCRIPTION
	Resource Adequacy	
1.1	Baseline 2023	Resource mix and load for the year 2023 winter; ELCC impact is not considered for gas and coal units.
1.2	Baseline 2028	Resource mix and load for the year 2028/2029 winter; ELCC impact is not considered for gas and coal units.
2	Winter 2028/2029 with PJM Latest Capacity Accreditation	Resource mix and load for the year 2028/2029 winter; ELCC impact and capacity accreditation for all resources are considered.
3	Hybrid Solar for Scenario 2	All future solar units are assumed to be paired with battery storage to improve Scenario 2's LOLE in the winter season.
4	Higher Transmission Transfer Capability for Scenario 2	50% higher interzonal transmission capacity to improve Scenario 2's LOLE in the winter season.
5	Common Mode Outage on Top of Scenario 2	30 GW of gas units unavailable during extreme winter weather conditions based on Scenario 2. This level of gas unavailability is commensurate with levels observed during prior extreme winter events.
6	5 GW of Additional Coal Retirements based on Scenario 2	5 GW of additional coal retirements based on Scenario 2. This scenario does not include 30 GW of gas unavailability, and it applies the 5 GW of additional retirements as a uniform reduction of the rating of all existing coal plants. This scenario serves as a sensitivity to assess the impact of further coal retirements beyond those planned in Scenario 2.
7	More Transmission for More Coal Retirements based on Scenario 6	50% higher interzonal tie-line limits to improve Scenario 6's LOLE.
	Transmission Security	
8	Summer Peak Condition	For the 2028 summer based on Scenario 1.2.
9	Winter Peak Condition	For the 2028/2029 winter based on Scenario 2 before coal retirements.
10	Winter Peak with Resource Retirements	Winter peak condition with assumed resource retirements based on Scenario 2.
11	5 GW of Additional Coal Retirements based on Scenario 6	5 GW additional coal retirements based on Scenario 6.

4 Task 2: Resource Adequacy Analysis

For a control area in the power system such as PJM, its power sources should meet the forecasted demand with possible assistance from neighboring systems under all possible disturbances and contingency conditions. The default assumption in a resource adequacy assessment is that the primary fuel source is always available for generating energy, except when a resource is subject to equipment failure, represented by an equivalent forced outage rate (EFORd). While the reporting and calculation method for the EFORd is the industry standard for measuring annual average generator performance, the updated study also considered seasonal performance differences. This was done by adopting the resource capacity accreditation published by PJM together with the ELCCs for intermittent generation (solar and wind) to capture the true performance of the system resource.

Given the prevailing increased intermittent generation in the overall generation mix, resource adequacy was analyzed under abnormal weather events (i.e., severe winter weather events). Solar, wind, and load profiles, along with interzonal transmission transfer capability, natural gas interruption, and accelerated coal retirements, created several winter scenarios consisting of hourly data sets for the year 2028. Sufficient transmission transfer capacity is the conduit for firm resource sharing between the zones within PJM.

LOLEs for the PJM system and the average loss of load (LOL) in MW are provided in Table 5 for the seven study scenarios.

Table 5. Resource Adequacy Result Summary

#	SCENARIO NAME	CRITERIA MEASURES	
	Resource Adequacy	**LOLE**	**Average System LOL (MW)**
1.1	Baseline 2023	0.000002	0
1.2*	Baseline 2028	0.000791	5
2*	Winter 2028 with Capacity Accreditation	0.243	3,067
3	Hybrid Solar for Scenario 2	0.039	1,068
4	Higher Transmission Transfer Capability for Scenario 2	0.067	1,519
5	Common Mode Outage on Top of Scenario 2	2.024	13,909
6*	5 GW Additional Coal Retirements based on Scenario 2	0.633	4,864
7	More Transmission for More Coal Retirements based on Scenario 6	0.235	2,645

*Note: Transmission security violations that occurred under Scenarios 1.2, 2, and 6 were also studied for transmission security, as shown in Table 9-12.

The updated study calculated the LOLE for the PJM system and provided LOLEs for 12 zones within PJM as an indication of zonal resource strength (see Table 6 and Table 7). Each column in Table 6 and Table 7 refers to a scenario in Table 5. LOLE was calculated through a Monte Carlo probabilistic simulation of unit outages followed by an assessment of potential consequential loss of load. Solar and wind resources were modeled using their seasonal ELCCs. The simulation used a transportation model of the interregional grid and was performed at seven levels of the load, representing a range of scenarios between nominal and extreme weather. An outage event might interrupt load in one or multiple zones, and thus, the analysis quantified the expected LOLE at the system level (i.e., all of PJM) and at each zonal level.

Table 6. System and Zonal Level LOLEs

		LOLE							
Zone Name	Zone # / Scenarios -->	1.1	1.2	2	3	4	5	6	7
APS	1	0.000	0.000	0.000	0.000	0.000	0.083	0.003	0.001
AEP	2	0.000	0.000	0.000	0.000	0.000	0.022	0.004	0.000
EMAAC	3	0.000	0.000241	0.000	0.000	0.000	0.000	0.000	0.000
SWMAAC	4	0.000	0.000513	0.201	0.034	0.036	1.926	0.476	0.096
COMED	5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
DAY	6	0.000	0.000006	0.023	0.002	0.011	0.699	0.175	0.097
DEOK	7	0.000	0.000063	0.127	0.019	0.032	1.569	0.480	0.151
DELCO	8	0.000	0.000020	0.026	0.004	0.007	0.133	0.049	0.021
SOUTH	9	0.000	0.000016	0.105	0.007	0.031	1.213	0.287	0.115
ATSI	10	0.000	0.000334	0.026	0.004	0.002	0.643	0.061	0.004
E. PA	11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
W. PA	12	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
System Level		0.000	0.001	0.243	0.039	0.067	2.024	0.633	0.235

Note: The red LOLE numbers indicate resource adequacy criterion violations.

Table 7. System and Zonal Level Average LOL (MW)

		LOL (MW)							
Zone Name	Zone # / Scenarios -->	1.1	1.2	2	3	4	5	6	7
APS	1	-	-	0	0	0	79	2	0
AEP	2	-	-	0	0	0	18	3	0
EMAAC	3	-	1.53	-	-	-	0	-	-
SWMAAC	4	0	3.25	1,247	622	588	5,864	1,699	439
COMED	5	-	-	-	-	-	-	-	-
DAY	6	-	0.04	152	30	197	1,337	544	805
DEOK	7	-	0.40	1,055	341	425	3,221	1,756	842
DELCO	8	-	0.13	7	2	4	16	8	5
SOUTH	9	0	0.11	492	37	299	2,772	749	547
ATSI	10	-	2.11	113	36	6	601	103	7
E. PA	11	-	-	-	-	-	0	-	-
W. PA	12	-	-	-	-	-	0	-	0
System Level		0	5	3,066	1,068	1,519	13,909	4,864	2,645

When the ELCCs for renewables are not differentiated between summer and winter seasons, the LOLEs for Scenarios 1.1 and 1.2 are essentially zero, meaning adequate resource reserves for the system in 2023 and 2028. The 5 MW of expected load losses happen during winter months to the SWMAAC (BGE, PEPCO), ATSI, and EMAAC (AE, DPL, JCPL, PECo, PSEG, and RECo.) zones.

When the seasonal ELCCs and capacity accreditations are considered in Scenario 2, the LOLE at the system level is 0.243 with loss of load mainly occurring over three winter months (December, January, and February). The 0.243 LOLE is a violation to the resource adequacy criterion of 0.1 day per year. The expected load losses are 1,247 MW in SWMAAC and 1,055 MW in DEOK respectively, and a total of 3,066 MW for the PJM system.

The resource shortfall in the 2028/2029 winter is partially due to the near-zero ELCC for regular solar PVs. Pairing the solar PV with battery storage in Scenario 3 would increase the

ELCC from 1–2% to 11%, which is enough to bring the LOLE down to 0.039 and reduce the system-wide expected load loss to 1,068 MW.

Another mitigation means is to increase the interzonal transmission capacities from resource capacity surplus zones, such as APS, AEP, and ComEd. By increasing the transmission capacity by 50% to allow higher resource sharing between the zones, Scenario 4 shows a satisfactory LOLE at 0.067. However, expanding transmission capacity is notoriously difficult, so a significant expansion of transmission is not considered feasible.

Scenario 5 investigated gas unavailability. From a physical and operational standpoint, the electric utility network is highly dependent upon the uninterrupted performance of the gas production and delivery network. Without a reliable fuel source together with the fuel delivery network, the electric system cannot meet its reliability standards. Customers of both gas and electricity systems can suffer when this happens, as demonstrated by the natural gas sector's failure to provide gas for power generation during the two most impactful winters to PJM (2014 Polar Vortex and 2022 Winter Storm Elliott). Because both systems were not designed originally to function as an integrated whole, gas accounted for 72% of outages attributable to fuel during Elliott.[10] Between forced outages, derates, generators not starting on time, and the inability to replenish storage, PJM lost 47–90.5 GW of the generation fleet during Winter Storm Elliott. Indeed, when Scenario 5 assumed the loss of 30 GW of gas-fired generation, the LOLE increased 8.4 times, reaching 2.024, with an expected loss of load of 13.9 GW for the PJM system.

Scenario 6 tested a sensitivity to Scenario 2 with an additional 5 GW of coal retirements. The additional retirements push up the LOLE to 0.633. Transmission expansion alone would not improve the LOLE to meet the criterion as shown by Scenario 7.

With the resource adequacy analysis, it can be concluded that before the industry sets natural gas infrastructure reliability rules, overreliance on natural gas-fired generation for resource adequacy and grid operation can lead to reliability violations. Combined with the unavailability of solar generation during winter peak hours, the system must retain a sufficient level of diversified generation mix until the aspects of reliability and resilience are sufficiently understood and addressed in the era of energy transition.

[10] FERC, *Inquiry into Bulk-Power System Operations during December 2022 Winter Storm Elliott, FERC, NERC and Regional Entity Staff Report*, October 2023, https://www.ferc.gov/media/winter-storm-elliott-report-inquiry-bulk-power-system-operations-during-december-2022.

5 Task 3: Transmission System Security Analysis

Transmission reliability issues are identified via power flow studies for both summer and winter peak load conditions. In the updated study, the PJM transmission system with and without the assumed fossil generation retirements was analyzed. Tested conditions included a normal (N-0) condition with all transmission system elements in operation and 40,875 contingency conditions (N-1) with which at least one major facility—such as a transmission line or transformer—was taken out of service to simulate the planned or unplanned outage of transmission system elements. Comparisons of the transmission reliability criterion violations with and without the assumed retirements indicate the level of reliability the retiring fossil plants provide.

For fair comparisons, the updated study used security-constrained redispatch to adjust available generation and controllable transmission facilities (e.g., tap-changing transformers, phase angle regulators, switchable capacitors, and reactor banks) to control local thermal or voltage violations. If overloads still existed after exhausting all redispatch means, load shedding was applied to mitigate the remaining violations. Therefore, the number of violations and the amount of load shed were used as the comparison metrics. Bulk electric systems are planned to avoid thermal overloads and voltage violations under many types of contingencies. Load shedding is a protection measure to handle events beyond the planning contingencies, and thus, the amount of load shedding for N-1 contingencies indicates the severity of the reliability violation. Table 8 provides a summary of metrics for Scenarios 8–11.

Table 8. Transmission Security Result Summary

#	SCENARIO NAME	CRITERIA MEASURES	
	Transmission Security	**# Equipment Overloads**	**Mitigating Load Shedding**
8	Summer Peak Condition	30/32*	3,547/3,761*
9	Winter Peak Condition	36	3,567
10	Winter Peak with Resource Retirements	52	4,708
11	5 GW of Additional Coal Retirements based on Scenario 6	57	6,826

* Note: The numbers before "/" represent before retirement, and the numbers after "/" represent after retirement.

Table 9 provides details on maximum overloads, the number of overloads, and overloaded facilities for Scenario 8 for summer 2028. During the analysis of the single and multiple contingencies that fall within the bucket of the system's N-1 contingencies, certain transmission system overloads were detected. The amount of equipment involved in overloads after contingencies increases from 30 (Scenario 8) to 32 after retiring the fossil generation from Scenario 8. These overloads were primarily linked to significant increases in load, particularly due to new data center facilities. The most severe overloads were pinpointed in the Dominion zone, involving 23 facilities at voltage levels of 230 kV and above. These facilities could experience an overload of up to 55.2% following a contingency in the transmission system.

Notwithstanding the fact that PJM is addressing most of these issues with its Transmission Expansion Advisory Committee, the updated study applied transmission security-constrained dispatch using available generation to minimize the number of overloads. If the overload still existed after the generation redispatch, a minimum amount of load curtailment that was necessary to mitigate the overload was applied and used as the measure for the severity of the transmission security violation. Table 10 lists the amount of generation dispatched for Scenario 8 and Scenario 8 with assumed retirement up to 2028. Specifically, 2,050 MW of generation was redispatched before the 2028 resource retirements, and 2,601 MW was redispatched after the 2028 resource retirements. Since most of the retirements were assumed to be coal-fired generation, the redispatched resources were primarily gas-fired generation units. The severeness of the transmission security violation measured by the amount of load curtailments is 3,547 MW (Scenario 8 before the assumed retirements) and 3,761 MW (Scenario 8 after the assumed retirements).

With the relatively small incremental increase in the number of overloads, the amount of generation that needs to be redispatched, and eventually the amount of load shed to secure the system, Scenario 8 with resource retirements (coal and gas) would have a sufficient amount of resources in the summer season to keep the transmission security violation to a minimum.

Table 9. Number of Transmission Facilities Overloaded in Summer 2028

Zone # / Tie Line		Maximum loading [%]		Recurrence of Overloads		Overloaded Equipment	
		Scenario 8	Scenario 8 + Retirements	Scenario 8	Scenario 8 + Retirements	Scenario 8	Scenario 8 + Retirements
215	DLCO	116.3	105.0	1	1	1	1
228	JCPL	103.5	103.5	1	1	1	1
229	PL	116.4	131.3	5	6	1	1
230	PECO	102.0	115.4	4	16	1	4
233	PEPCO	111.4	107.6	4	2	2	2
345	DVP	153.9	153.5	82	70	23	20
229/232	TIE LINE	140.2	155.2	7	6	1	1
230/232	TIE LINE	< 100	104.7	0	4	0	1
232/230	TIE LINE	< 100	107.8	0	3	0	1
TOTALS				104	109	30	32

Note: "Maximum loading [%]" is the excess thermal loading of any transmission facility expressed in percentage of the facility's rating; "Recurrence of Overloads" is the number of combinations of facility contingency that lead to overloads and thus the higher the occurrence the higher the number of ways the facility can overload; and "Overloaded Equipment" is the number of transmission facilities (e.g., transmission lines) that are expected to overload under a contingency.

Table 10. Mitigating Load Shedding (MW) in Summer 2028

Zones	Load Shedding (MW)	
	Scenario 8	Scenario 8 + Retirements
201 AP	152	0
205 AEP	0	0
212 DEO&K	100	97
227 ME	0	0
229 PL	7	7
230 PECO	61	50
232 BGE	390	1081
235 DP&L	0	0
345 DVP	2788	2473
231 PSEG	0	0
222 CE	49	55
TOTAL	**3,547**	**3,761**

In winter 2028, the system faces a significant challenge due to the early retirements of coal and gas resources as shown in Scenarios 10 and 11. The resulting resource balance is highly limited, making it extremely difficult to meet the load requirements while ensuring transmission security and reliability. The situation becomes more dire in Scenario 11, which incorporates the planned 2028 retirements and an additional 5 GW of coal retirements. This scenario necessitates using 100% of coal generation resources and 97.5% of gas-fired generation plants, leaving little room for dispatchable generation to secure system operation.

Upon analyzing both single and multiple contingencies falling under the N-1 category, the results revealed that the transmission system could face severe thermal overload issues under Scenario 11. Such issues occur when the resulting power flows exceed the thermal limits of transmission facilities, with the maximum load reaching 270.2% of the thermal limit for certain equipment. Again, based on the security-constrained dispatch analysis, some adjustments were made to the generation among the remaining power plants to address these overloads, which mitigated some issues. In cases where the generation redispatch was insufficient, specific loads were shed to mitigate the overloads and to measure the severity of the issues. The results are shown in Table 11 and Table 12.

In Scenario 9, 36 equipment overloads were identified within the 230 kV and above voltage level transmission systems. In Scenario 10, after the assumed retirements, equipment overloads increased to 52. In the more complex simulated Scenario 11 that considered the 2028 retirements and an additional 5 GW of coal retirements, the equipment overloads rose to 57. The load curtailment required was 3,567 MW in Scenario 9, 4,708 MW in Scenario 10, and 6,826 MW in Scenario 11. Among the affected zones, Dominion Virginia Power, Baltimore Gas & Electric Company, and Allegheny Power experienced the most significant impact in terms of load curtailment.

Table 11. Number of Transmission Facilities Overloaded under Winter Scenarios

AREA / CASE		Maximum Loading [%]			Recurrence of Overloads			Overloaded Equipment		
		Scenario 9	Scenario 10	Scenario 11	Scenario 9	Scenario 10	Scenario 11	Scenario 9	Scenario 10	Scenario 11
201	AP	< 100	102.7	< 100	0	1	0	0	1	0
227	ME	114.0	134.8	152.2	5	19	26	1	2	2
228	JCPL	102.8	102.8	102.8	1	1	1	1	1	1
229	PL	113.7	134.4	147.4	14	42	63	4	9	13
230	PECO	196.1	239.3	270.2	34	212	227	3	3	3
232	BGE	112.5	127.3	135.3	24	64	106	8	12	15
233	PEPCO	114.0	123.9	122.2	11	13	13	2	2	2
345	DVP	119.3	126.7	123.7	19	33	27	7	10	9
227/229	TIE LINE	117.0	140.1	157.6	10	10	11	2	2	3
229/232	TIE LINE	135.1	158.4	173.0	12	22	37	2	2	2
230/232	TIE LINE	183.8	225.8	256.0	5	27	76	1	1	1
233/345	TIE LINE	118.6	127.5	128.7	5	5	5	1	1	1
225/232	TIE LINE	102.1	114.3	118.4	6	11	14	2	2	2
225/229	TIE LINE	108.4	112.9	112.3	5	6	6	2	2	2
225/233	TIE LINE	< 100	100.6	105.5	0	1	1	0	1	1
340/345	TIE LINE	< 100	102.0	< 100	0	1	0	0	1	0
TOTAL					151	467	613	36	52	57

Table 12. Mitigating Load Shedding (MW) under Winter Scenarios

Zones	Load Shedding (MW)		
	Scenario 9	Scenario 10	Scenario 11
201 AP	654	867	933
205 AEP	0	0	0
212 DEO&K	8	8	8
225 PJM	0	0	0
226 PENELEC	0	0	0
227 ME	28	31	33
229 PL	125	125	15
230 PECO	41	41	41
232 BGE	1103	1492	2697
233 PEPCO	0	0	679
235 DP&L	0	0	0
320 EKPC	379	367	288
345 DVP	1228	1778	2132
222 CE	0	0	0
228 JCPL	0	0	0
209 DAY	0	0	0
TOTAL	3,567	4,708	6,826

6 Observations and Discussion

- Under normal operating conditions and with generation resources secured with sufficient fuel for uninterrupted generation, the PJM system's resources meet the demand and maintain the electric grid's reliability (Scenario 1). Even so, adequate resources will challenge the PJM system in the future when the grid is under abnormal grid operating conditions, which will happen more often than previously.
- Transportation and building sector electrification and load increases due to emerging industry developments (e.g., hydrogen production and data centers) create fast load growth and electricity use never seen historically. Further, the regional electric demand is peaking less in summer and more in the winter, presenting a challenge in fueling the electric generation during peak demand hours. As shown by Scenarios 2, 5, 6, and 7, maintaining resources of sustained generation capability is imperative as the electric system adjusts to these new load demands during extreme weather events.
- Maintaining fuel diversity and understanding new energy resources' different seasonal operating attributes are important in maintaining grid reliability and resilience. PJM has recognized the differences via its installed capacity markets and accredited the different resources with seasonal accreditation values. Using these values, Scenario 2 has demonstrated a potential inadequate resource situation for winter 2028/29. One possible mitigation involves pairing long-duration storage with all newly planned solar PV in 2028. This strategy can help the system satisfy the LOLE standard (Scenario 3). However, this strategy needs to be supported by PJM's competitive market if it is to be economically attractive for all future solar projects to pair with long-duration storage. Additionally, it can be operationally challenging to manage the charging and discharging of an extremely large number of long-duration battery storage units without negatively impacting transmission security.
- The electric grid is highly dependent upon the uninterrupted performance of the generation resources. Because the natural gas transportation system and the electric power grid were not originally designed to function as an integrated whole nor to the same reliability standards, failure in the natural gas delivery system presents a common mode of multiple outages of the natural gas-fueled generation stations. Such common mode outages could make the reliability 8.4 times worse, from an LOLE of 0.24 (Scenario 2) to 2.02 (Scenario 5) for winter 2028.
- The regional transmission upgrades can improve the integration of more renewable resources, reduce renewable curtailment, and provide the needed capacity and energy among various PJM zones. Scenario 4 illustrated that an increase of 50% in interzonal transmission capacity adjacent to these zones can decrease the LOLE from 0.24 (Scenario 2) to 0.04. This mitigation will satisfy the 0.1 day per year criterion. However, expanding transmission capacity is very difficult, so a significant expansion of transmission is not considered feasible.
- The resource shortfall shown in Scenario 2 can worsen if an additional 5 GW of coal-fired generation is retired (Scenario 6). This situation cannot be mitigated by adding intermittent resources alone, as the grid is losing dispatchable generation resources of relatively high availability and predictability. The intermittent resources have much lower production per installed MW of capacity and cannot produce energy without sun or wind.

- The resource adequacy criterion violation with an additional 5 GW of coal-fired generation retired could not be mitigated by transmission expansion (Scenario 7). Maintaining a sufficiently diversified resource mix is essential and allows ample time for the changing dynamics to be understood as the future system evolves and new information becomes available. However, expanding transmission capacity is very difficult, so a significant expansion of transmission is not considered feasible.
- Dispatchable generation is essential for secure transmission system operations. When there is sufficient generation during the summer peak hours, the transmission system would have enough dispatchable generation to help maintain secure transmission operation. The situation becomes very challenging during winter, particularly under severe winter weather conditions.
- The transmission system security analysis showed that in simulating the single and multiple contingencies for the summer 2028 under scenario 8, certain transmission system overloads were detected in facilities at voltage levels of 230 kV and above. The amount of equipment involved in overloads after contingencies increases from 30 (Scenario 8) to 32 after retiring the fossil generation from Scenario 8. These facilities could experience an overload of up to 55.2% following a contingency in the transmission system.
- In winter 2028, the system encountered a notable hurdle with the assumed retirements of coal and gas resources. The resultant resource balance is severely constrained, posing significant challenges in delivering energy to consumers while upholding security and reliability standards for the transmission systems. The predicament intensifies in Scenario 11, which assumes, in addition to the retirements in 2028, an additional 5 GW of coal retirements. In this scenario, 100% of coal generation resources and 97.5% of gas-fired generation plants must be used, leaving minimal leeway for dispatchable generation to participate in securing transmission operations.

Appendix A: Resource Capacity for Y2028

The PJM resources are summarized in Table 13 for year 2028 based on existing resources, planned and anticipated retirements, and PJM's interconnection queue. The namelplate ratings are scaled by the ELCC of each resource and by their EFORd to yield a uninterrupted capacity value (UCAP) in the summer and the winter seasons. The installed nameplace capacity ratings (ICAP) and UCAP are compared to PJM's peak load forecast issued in January 2024 to determine the level of reserve margins under nominal and extreme weather conditions.

PJM determined the required level of installed reserve requirement (IRM)[11] to be 17.6% and its forecasted pool requirement (PFR), which accounts for EFORd, to be 11.65%.

Table 13 shows the reserve margin based on ICAP (17.8%) to be inline with PJM's recommendation in the summer while being deficient in the winter (only 14.7%). Similarly, the PFR is adequate in the summer (13.6%) and deficient in the winter (10.7%).

Table 13: Expected Resources and Capacity Values in Y2028

Resource Types (Y2028)	NAMEPLATE MW	ELCC Summer	ICAP+ELCC (Summer)	(1-EFORd)	UCAP (Summer)	ELCC Winter	ICAP+ELCC (Winter)	(1-EFORd)	UCAP (Winter)
BESS	2,729	77%	2,101	100%	2,101	33%	887	100%	887
Coal	21,963	100%	21,963	91%	19,986	93%	20,482	91%	18,639
Gas	97,861	100%	97,861	96%	93,946	77%	75,665	96%	72,639
Hydro	3,242	93%	3,015	100%	3,015	79%	2,548	100%	2,548
Nuclear	32,749	100%	32,749	99%	32,421	98%	32,073	99%	31,753
Oil	3,569	100%	3,569	90%	3,212	100%	3,569	90%	3,212
OSW	10,315	31%	3,198	100%	3,198	100%	10,315	100%	10,315
Other	358	100%	358	95%	340	100%	358	95%	340
PS-Hydro	5,932	100%	5,932	98%	5,813	100%	5,932	98%	5,813
Renewable	1,481	100%	1,481	90%	1,333	100%	1,481	90%	1,333
Solar	44,279	26%	11,513	100%	11,513	1%	640	100%	640
Wind	24,194	12%	2,903	100%	2,903	48%	11,613	100%	11,613
DR	6,917	100%	6,917	100%	6,917	67%	4,632	100%	4,632
Grand Total	**255,588**		**193,558**		**186,698**		**170,197**		**164,365**
PJM Load Foreacst (50/50)			164,114		164,114		147,918		147,918
Reserve Margin %			**17.9%**		**13.8%**		**15.1%**		**11.1%**
PJM Load Foreacst (90/10)			177,046		177,046		155,447		155,447
Reserve Margin %			**9.3%**		**5.5%**		**9.5%**		**5.7%**

[11] 2023 PJM Reserve Requirement Study - PJM Resource Adequacy Planning, October 3, 2023.

Appendix B: Assumptions

In addition to the scenario description in

Table 4, several key assumptions were made about the PJM system, including:

Where did the power flow base cases come from? Base cases for the power flow analysis are publically available from FERC (the FERC 715 power flow cases filed by PJM).

Where was the resource adequacy model prepared? The PJM model data were extracted from the commercially available ABB Ventyx 2022 PROMOD model for 2027. The retirement dates of thermal units were scrutinized and updated to reflect corporate public announcements, integrated resource plan (IRP) filings, economics, state policies (e.g., CEJA in Illinois and Carbon CO2 rule in Jew Jersey), and various EPA guidelines and rulings.

What years and seasons were studied? Peak summer 2028 and winter 2028/2029.

How and where was the coal capacity assumed to be retired in the study? The study modeled resource retirements between 2022 and 2030 in line with the assumptions in PJM's 4R report[12] and summarized in Table 14. Out of the 40 GW of anticipated retirements, 24 GW (60%) are coal plants.

Table 14: Resource Retirements between 2022 and 2030

Y2022-2030	COAL	GAS	OIL	TOTAL
APS	1,458	0	0	**1,458**
AEP	4,408	461	0	**4,869**
EMAAC	412	3,625	1,038	**5,075**
SWMAAC	1,588	128	447	**2,163**
COMED	3,842	8,260	100	**12,203**
DAY	0	0	0	**0**
DEOK	1,020	0	0	**1,020**
DELCO	0	0	0	**0**
SOUTH	2,247	155	787	**3,189**
ATSI	1,491	330	0	**1,822**
E. PA	2,585	0	0	**2,585**
W. PA	5,289	598	0	**5,887**
Total	**24,341**	**13,558**	**2,372**	**40,270**

What assumptions were made about replacement capacity? Future development of resources was scrutinized against the maturity of the respective interconnection queue pipeline. Future resource additions were consistent with PJM assumptions in their 4R report and were in between the base scenario and the high new entry scenario.

[12] PJM, Energy Transition in PJM: Resource Retirements, Replacements & Risks, February 24, 2023

Appendix C: Report Contributor Bios

- **Henry Chao, PhD,** *EXECUTIVE ADVISOR, Vice President, RTO/ISO Markets,* has over 30 years of leadership and technical management experience in delivering technology solutions and professional services to the electric utility industry with a focus on public policy development, renewable interconnection, grid reliability and resiliency, system planning, operations, engineering, project development, power market efficiency, and regulations. While as VP of System and Resource Planning at NYISO, he led and initiated several critical policy-driven studies for New York in recent years, including a STARS study to explore and promote an incremental value of replacing aging infrastructure in New York in 2009 that led to the public policy transmission development by the PSC and the NYISO; the Growing Wind study in 2010 to message the need for transmission expansion and market structure change to facilitate continuing renewable penetration; the New York State Scenario Resource Planning study in 2015 to assess what mix of resources (generation, transmission, EE, DR, and DER) needed to be deployed by 2030 to meet public policies and regulations cost-effectively while maintaining reliability; and Clean Power Plan Assessment in 2016 to provide the New York State Department of Environmental Conservation, policymakers, and NYISO market participants important information about the ability of New York to achieve compliance with federal environmental regulations. Dr. Chao has a strong academic background, including a PhD in Electrical Engineering from the Georgia Institute of Technology and Executive MBA training in programs at Duke and Harvard.

- **Edison Cardona,** *SENIOR ADVISOR,* is an engineer in electrical power systems with 29 years of technical and managerial experience in the planning and operation of markets and transmission systems. He worked for most countries in Central and South America, with a strong emphasis on power system reliability and grid integration of renewables and energy storage.

- **Khash Mahani, PhD**, *Principal Engineer,* received his PhD degree in Industrial and Systems Engineering from Rutgers University and a BS degree in Electrical Engineering from the University of Tehran. His focus is on the development, analysis, and financial evaluation of sustainable electricity markets, distributed energy resources (DERs), electric vehicles, and smart energy solutions. His analytical skills and experience range from engineering economics to control theory and stochastic optimization.

- **Hisham Othman, PhD**, *EXECUTIVE ADVISOR, Senior Vice President*, has over 35 years of technical and managerial experience in the electricity sector with a strong emphasis on power system dynamics and controls, flexible AC transmission, operational IT, grid integration of renewables and energy storage, financial modeling, and investment analysis. Hisham leads the transmission and regulatory compliance consulting services team, providing advanced power system technical and economic studies to help customers address their evolving and challenging business needs.