November 9, 2023

Review of Expected Resource Adequacy in PJM under Stress Conditions during Summer and Winter Peak Periods

Prepared for:

Center for Applied Environmental Law and Policy (CAELP); Natural Resources Defense Council (NRDC); and Environmental Defense Fund (EDF)

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1 Introduction

This memo provides a description of work performed by ICF on behalf of the Center for Applied Environmental Law and Policy (CAELP), the Natural Resources Defense Council (NRDC), and the Environmental Defense Fund (EDF) (collectively the "Client") to consider the implications of weather stressors on resource adequacy in the PJM system assuming a given capacity expansion plan.

Based on this high level analysis, the capacity expansion plan within PJM, and accounting for limited imports during a small number of hours, included sufficient capacity to serve the expected hourly load in PJM. In the 2030 Weather Stressed case summer peak week, nine hours required capacity in excess of that assumed to be available within PJM. Across those nine hours, 0.8 GW to 2.7 GW, or roughly 0.5% to 1.7% of the hourly demand in those hours, of incremental resource was assumed to be imported from neighboring regions.[1]

2 Methodology

Assuming the pre-existing capacity expansion plan in the Client's "EPA Policy Case 1" (PC1) for 2030, 2035, and 2040, ICF generated an alternate scenario for the summer and winter based on potential weather stressors. These organizations, as part of their assessment of EPA's proposed Greenhouse Gas Standards and Guidelines for Fossil Fuel-Fired Power Plants (released May 2023), utilized IPM® to develop a capacity expansion plan based on their own assumptions to assess how the country's electric generation fleet may respond to the Proposed Rule. IPM® is an economic capacity expansion and production-costing model of the power sector that produces, among other outputs, plant retirement and build decisions based on multiple operational, economic, and energy demand assumptions and constraints.[2]

The scenario examined the expected changes to load and supply in PJM given the weather stress conditions assumed. After determining the impact on load and supply, the expected capacity position for PJM in PC1 was examined to determine if adequate generation resources would be available in the stress conditions. The analysis performed was illustrative in nature and considered simplified hourly dispatch for a one-week period in both the summer and winter for the years considered to assess the resource adequacy.

[1] The need for capacity in the nine hours was always below PJM's Capacity Benefit Margin of 3,500 MW - Website: https://pjm.com/-/media/committees-groups/committees/pc/2023/20231003/20231003-item-05a---pjm-2023-rrs-report.ashx (Last accessed: October 29, 2023)

[2] For more information on the CAELP, NRDC, and EDF Policy Case 1, see https://www.nrdc.org/sites/default/files/2023-08/comments-epa-power-plant-rule-nrdc-catf-20230808.pdf, in which this case is referred to as the "EPA Policy Case".

2.1 CAELP/NRDC/EDF PC1 Case Analyzed

The Client's PC1[3] capacity expansion plan was developed under the following key assumptions.

- Electric load was based on EIA's 2023 Annual Energy Outlook (AEO) Reference Case
- PJM (Annual) Reserve Margin was modeled after EPA v6 Post-IRA 2022 Reference Case assumptions, at 15.7%
- Generation profiles for new wind and solar units were modeled after EPA v6 Post-IRA 2022 Reference Case assumptions.
- EPA's May 2023 Proposed Rule for the Clean Air Act section 111(d) standards on existing coal and gas units, and section 111(b) standards on new gas units were assumed.[4]
    - Compliance options considered for units affected by the proposed rules included carbon capture and storage coal and gas plants, reducing generation at coal and gas plants, hydrogen-cofiring at gas plants, and natural gas-cofiring at coal plants.

[3] Policy Case 1 was based off the 2023 Reference Case developed for NRDC. The modeling of the Reference Case and Policy Case 1 represents assumptions developed by NRDC, EDF, and CAELP based on consultation with energy experts, partners, and industry. The modeling of these assumptions was performed by ICF using its Integrated Planning Model (IPM®).

[4] "New Source Performance Standards for Greenhouse Gas Emissions From New, Modified, and Reconstructed Fossil Fuel-Fired Electric Generating Units; Emission Guidelines for Greenhouse Gas Emissions From Existing Fossil Fuel-Fired Electric Generating Units; and Repeal of the Affordable Clean Energy Rule", A Proposed Rule by the Environmental Protection Agency on 05/23/2023

2.2 Scope of Analysis

To consider the reference case for the hourly conditions in the summer and winter peak weeks, the Client's PC1 capacity expansion plan was examined on an hourly basis using an illustrative dispatch of resources to determine if sufficient resources were available in each hour in each week for 2030, 2035, and 2040 (aka the "Reference" scenario). The "Weather Stressed" scenario was then designed to reflect the impact of approximately a one-in-ten-year weather extreme on load and resource availability for both the summer and winter peak weeks. The approach used in developing the Weather Stressed scenario assumptions is found in subsections 2.3 and 2.4 below. Assumptions for loads and resource supply availability are summarized in Table 1. Once the Weather Stressed Scenario was designed, the implied hourly resource adequacy was examined using the same illustrative dispatch logic.

Key Variable Considered

- **Study Region** – PJM
- **Periods of Study** – Winter and Summer Peak Weeks (two 7-day x 24-hour periods)
- **Years of Study** – 2030, 2035, and 2040
- **Capacity Expansion Plan** – PC1
- **PJM transmission constraints** – Not captured
- **Load forecast** – Reference case based on EIA AEO 2023, and weather stressed sensitivity
- **Supply parameters** – Solar, wind, and thermal unit performance under Reference case and weather stressed sensitivity
- **Capacity Benefit Margin**[5] – 3,500 MW

[5] PJM's Capacity Benefit Margin of 3,500 MW - Website: https://pjm.com/-/media/committees-groups/committees/pc/2023/20231003/20231003-item-05a---pjm-2023-rrs-report.ashx (Last accessed: October 29, 2023)

Table 1: Load and resource supply availability

			Reference Scenario Conditions		Weather Stressed Scenario Conditions	
Parameter	Description	Year	Summer	Winter	Summer	Winter
Load	Peak hour and weekly average load condition	2030	160 GW peak / 125 GW avg.	124 GW peak / 104 GW avg.	167 GW peak / 131 GW avg.	134 GW peak / 114 GW avg.
		2035	167 GW peak / 130 GW avg.	128 GW peak / 107 GW avg.	175 GW peak / 136 GW avg.	139 GW peak / 117 GW avg.
		2040	175 GW peak / 135 GW avg.	133 GW peak / 111 GW avg.	184 GW peak / 142 GW avg.	145 GW peak / 121 GW avg.
Supply	Average Solar availability over peak week	2030	27%	16%	26%	16%
		2035	26%	17%	26%	16%
		2040	27%	16%	27%	16%
	Average Onshore Wind availability over peak week	2030	33%	49%	16%	33%
		2035	28%	51%	17%	34%
		2040	27%	50%	17%	34%
	Average Offshore Wind availability over peak week	2030	42%	70%	18%	30%
		2035	48%	65%	18%	31%
		2040	51%	65%	19%	31%
	Storage availability	All years	Hourly generation and charging modeled according to load net of renewable energy to minimize net system peaks and maximize charging during lowest net load hours within the operating limits of storage resources. Storage availability in each hour was the lesser of the installed capacity or charge level at the beginning of the hour. Storage resources had an assumed 85% round-trip efficiency, and duration of either 4 or 8 hours.			
	Nuclear availability[6]	All years	99% of Installed Capacity (1 – WEFORd) for all winter and summer hours			
	Coal and other fossil steam availability	All years	85% of Installed Capacity (1 – WEFORd) for all winter and summer hours			
	Combined Cycle availability	All years	96% of Installed Capacity (1 –WEFORd) for all winter and summer hours			
	Combustion Turbine availability	All years	94% of Installed Capacity (1 – WEFORd) for all winter and summer hours			
	Hydro availability	All years	29% of Installed Capacity (Historical average generation held constant in all hours)			

[6] Nuclear, coal, fossil steam, combine cycle, and combustion turbine availability were calculated using the 2023 PJM annual weighted average EFORd report, located at: https://pjm.com/-/media/planning/res-adeq/res-reports/2018-2022-pjm-generating-unit-class-average-values.ashx (website last accessed October 31, 2023)

2.3 Variability in Renewable Energy Profiles

A review of historical wind and solar data at sample locations across the PJM territory was conducted to establish a range of representative seasonal output availability by resource type and to identify levels towards the low ends of these ranges to represent seasonally low availability levels for the Weather Stressed scenario. This review was not based on a comprehensive probabilistic analysis, but rather compiled as a representative exercise using 20 years of historical data for four onshore wind locations, one offshore wind location, and typical solar year data for 10 solar locations. Output levels for solar and wind availability were based on a review of rolling seven-day average capacity factors ("7-day average CF") during winter and summer seasons for representative solar and wind sites within the PJM territory. The seven-day average capacity factors were compared to average seasonal capacity factors for each season to identify the range of 7-day average CFs at these locations occurring above or below the seasonal averages. A "% Discount" was calculated for the 7-day average CF associated with the bottom 10th percentile by season, compared to the average seasonal capacity factor for the representative data. This % Discount was then applied to the seasonal average capacity factor, according to the same hourly production profiles for the peak weeks for the wind or solar profiles assumed in the Reference scenario for the PJM buildout to arrive at the target level of production availability for each resource type for the summer and winter peak weeks in 2030, 2035, and 2040. Provided in Table 2 are the % Discount factors associated with these reduced levels of availability by season and renewable energy resource type.

Table 2: Renewable energy discount factors, average seasonal availability and Weather Stressed peak week average availability

	Year	Solar		Onshore Wind		Offshore Wind	
		Winter	Summer	Winter	Summer	Winter	Summer
P10 % Discount	All	16.8%	9.7%	32.5%	44.9%	41.9%	53.0%
Average Seasonal Availability	2030	19.6%	28.2%	48.5%	29.6%	50.9%	37.7%
	2035	19.7%	29.1%	50.3%	30.5%	52.4%	38.5%
	2040	19.1%	29.6%	50.2%	30.5%	53.2%	39.3%
Weather Stressed Peak Week Availability (Average Seasonal Availability * (1 – P10 % Discount))	2030	16.3%	25.5%	32.7%	16.3%	29.6%	17.7%
	2035	16.4%	26.3%	34.0%	16.8%	30.4%	18.1%
	2040	15.9%	26.7%	33.9%	16.8%	30.9%	18.5%

Due to the variability between weekly availability rates in the base renewable energy profiles modeled in IPM for PC1, the peak week profiles are often higher or lower than the seasonal averages. So, in some instances, such as the winter 2030 and 2040 peak weeks for solar, the availability of the specific peak week may already be below the target level availability, i.e. below the bottom 10th percentile of the seasonal availability range. Table 3 provides the % Discount levels calculated for the Reference peak weeks compared to the average seasonal availability in the Reference profiles. No adjustments were made to the base profiles for these weeks in the Reference scenario; this comparison is provided to illustrate how the peak week availability levels in the Reference scenario compare to seasonal averages in similar terms to the Weather Stressed availability provided in Table 2.

Table 3: Renewable energy average seasonal availability compared to Reference peak week discount (or premium) below (or above) seasonal average availability

	Year	Solar		Onshore Wind		Offshore Wind	
		Winter	Summer	Winter	Summer	Winter	Summer
Average Seasonal Availability	2030	19.6%	28.2%	48.5%	29.6%	50.9%	37.7%
	2035	19.7%	29.1%	50.3%	30.5%	52.4%	38.5%
	2040	19.1%	29.6%	50.2%	30.5%	53.2%	39.3%
Reference Peak Week % Discount from Average Seasonal Availability ((Average Seasonal Availability – Peak Week Availability) / Average Seasonal Availability)	2030	18.4%	4.3%	-0.2%	-11.5%	-37.1%	-11.4%
	2035	14.7%	9.6%	-1.2%	8.9%	-23.9%	-25.7%
	2040	18.3%	9.8%	-0.4%	12.1%	-22.2%	-29.0%

The reason for using the % Discount, rather than directly applying the pure target level capacity factor from the representative sites is to control for differences in technology or specific site location between the representative sites and the specific technology buildout assumed in the PC1 IPM output. This method effectively assumes that the percent deviation from the seasonal average capacity factors remains consistent across different technologies and specific locational characteristics.

Variability in renewable energy availability for the Weather Stressed scenario was calculated utilizing the same methodology for solar, onshore wind, and offshore wind. ICF obtained historical daily meteorological data from several[7] representative onshore wind, offshore wind, and solar locations across PJM states with generic technology assumptions applied to estimate associated daily output levels. The daily output was divided by 24 hours and by the unit's capacity to

[7] Onshore and Offshore wind capacity factors were calculated using two decades of historical daily output data within the PJM region. Solar capacity factors were calculated using a typical year profile based on solar output at 10 locations across PJM..

calculate the daily capacity factor for each source. The 7-day rolling average capacity factors were calculated for the summer months (June through August) and for the winter months (December through February). The distribution of 7-day rolling averages provided a range of % Discount factors with associated probability levels, of which the % Discount associated with the lowest 10th percentile level of availability was applied to the average seasonal capacity factor of the Reference scenario profiles and peak week availability profiles for the Weather Stressed scenario renewable energy availability profiles.

Presented in Table 4 are the summer and winter peak week renewable energy availability levels for each study year assumed in the Weather Stressed scenario, as well as the seasonal average availability rates from the underlying renewable energy profiles modeled in IPM for comparison.

Table 4: Seasonal average renewable energy availability compared to peak week availability for the Weather Stressed scenario

Year	Season	Solar		Onshore Wind		Offshore Wind	
		Seasonal Average	Weather Stressed Peak Week	Seasonal Average	Weather Stressed Peak Week	Seasonal Average	Weather Stressed Peak Week
2030	Summer	28%	26%	30%	16%	38%	18%
	Winter	20%	16%	49%	33%	51%	30%
2035	Summer	29%	26%	31%	17%	39%	18%
	Winter	20%	16%	50%	34%	52%	31%
2040	Summer	30%	27%	31%	17%	39%	19%
	Winter	19%	16%	50%	34%	53%	31%

2.4 Variability in Summer & Winter Peak Load

The Summer and Winter peak load variability assumptions were calculated using PJM's 2023 Annual Load Reports (ALR).[8] Reported peak load, defined as the unrestricted peak in the ALR, represents coincident peak load in PJM prior to reductions for load management or voltage reductions. PJM provides both reported and weather-normalized peak load data. Annual reported and weather normalized peak load data were collected for both summer and winter peaks from 2013 through 2022. The difference between the reported and weather normalized load was divided

[8] "Load Forecast Development Process." PJM©, www.pjm.com/planning/resource-adequacy-planning/load-forecast-dev-process. (Last accessed on October 29, 2023.)

by the normalized load to derive percent variability in summer and winter peaks between reported and weather normalized loads, from which maximum and minimum values could be obtained. The maximum overages of reported loads that were above weather normalized loads, 9% for winter peaks and 5% for summer peaks, were identified and applied to the respective winter and summer peak loads for all hours, including the peak hour, from the Reference scenario to create the Weather Stressed hourly load profile. These data and comparisons are provided in Table 5 for PJM summer peaks and Table 6 for PJM winter peaks. The winter event associated with the winter 2014/2015 was the 2014 Polar Vortex, and while Winter Storm Elliot occurred after the winter of 2021/2022, a similar comparison identified a lesser, 8% exceedance from normal weather conditions.

Table 5: PJM Summer reported versus weather-normalized peak load

PJM Summer Peaks										
Year	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**
Reported (GW)	159	142	144	152	145	151	151	144	148	147
Normalized (GW)	152	152	151	150	151	150	150	147	150	149
Delta (%)	5%	-7%	-5%	1%	-3%	0%	1%	-2%	-1%	-1%

Table 6: PJM Winter reported versus weather-normalized peak load

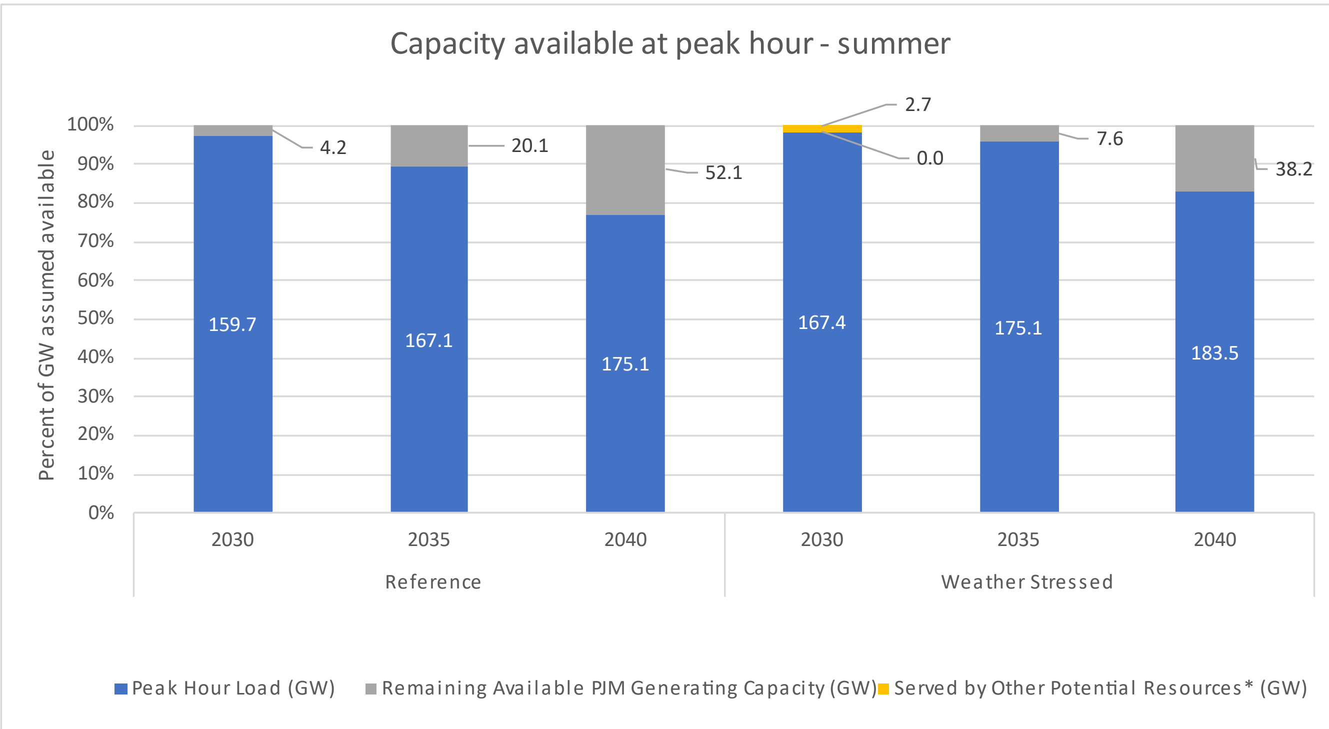
PJM Winter Peaks									
Year	**2013/14**	**2014/15**	**2015/16**	**2016/17**	**2017/18**	**2018/19**	**2019/20**	**2020/21**	**2021/22**
Reported (GW)	142	143	130	131	137	138	120	117	129
Normalized (GW)	130	131	131	130	131	131	131	130	131
Delta (%)	9%	9%	-1%	0%	5%	5%	-9%	-10%	-2%

2.5 Limitations

Both the Reference and Weather Stressed scenarios were modeled based on simplified assumptions for the supply and demand of energy within the PJM region and forecast periods of study. Supply and demand balances were based on capacity availability by generating resource types each consecutive hour, but were not modeled according to security constrained economic dispatch logic, nor did modeling consider unit level operating constraints, such as ramp rates, must-run requirements, or other cycling constraints. The model assumed that across or between resource types, all capacity that is assumed available in each hour is able to serve load. The analysis also assumed no transmission constraints across PJM that may prevent deliverability between available generating units and load across the regional footprint.

3 Results

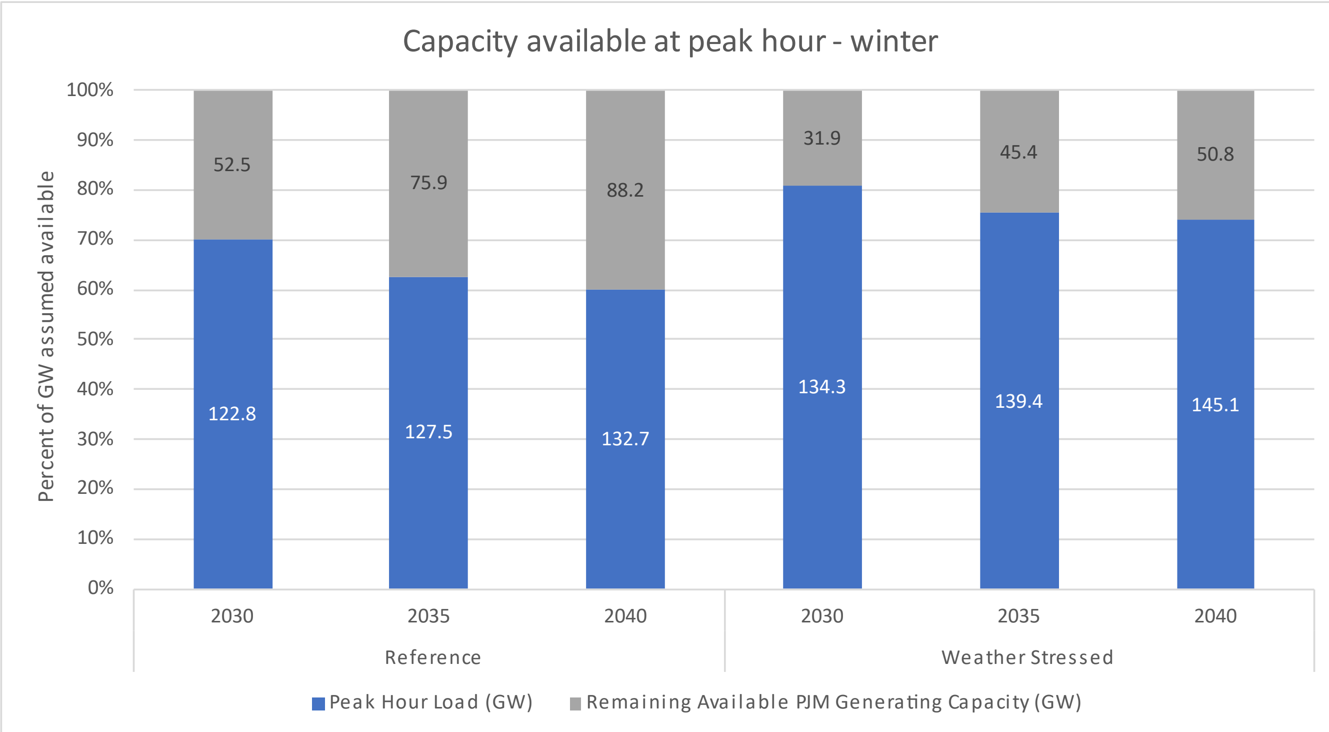
The results of the analysis are presented below for the Reference and Stressed Weather Scenarios, with additional hourly dispatch results, compared to the hourly available resources, provided for each scenario, year, and week combination provided in Appendix A. The results shown in the graphics below and in Appendix A for capacity available during peak hours, shortest hours, and average across peak weeks for summer and winter peak weeks are based on the capacity availability assumptions described in the sections above.

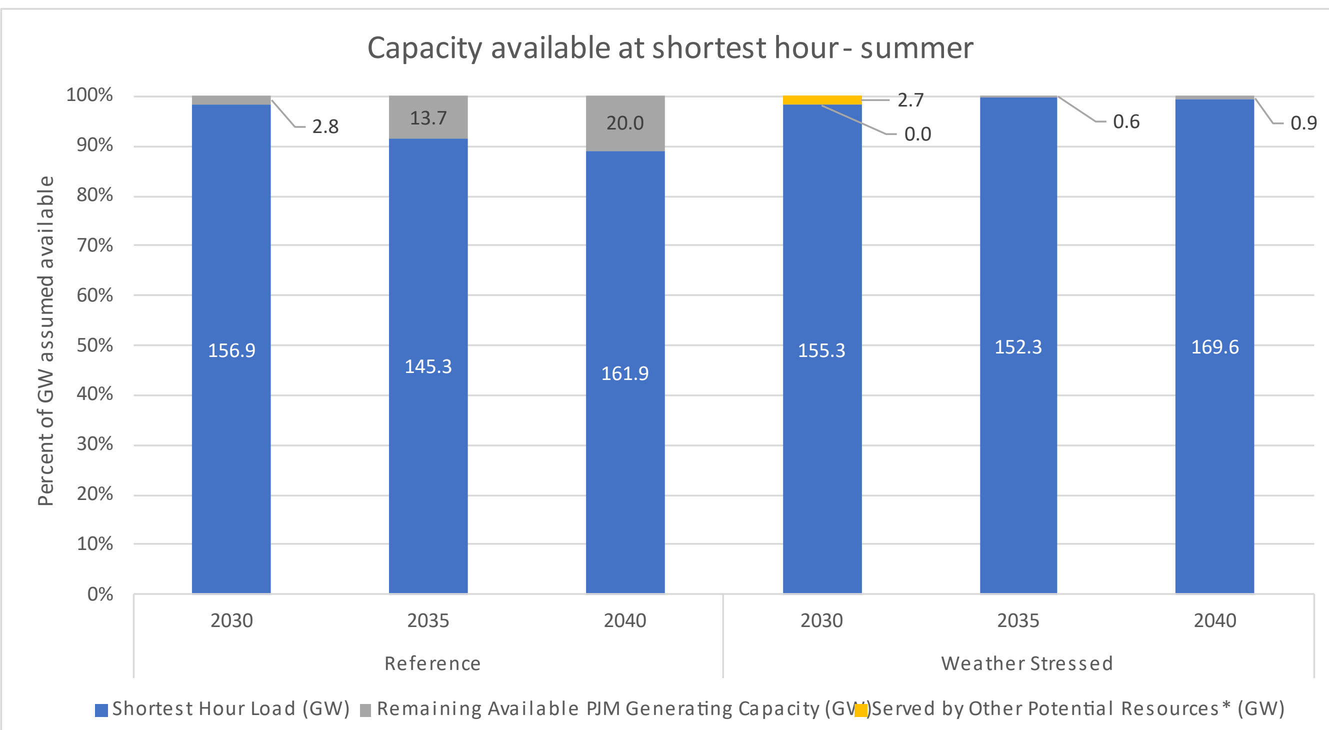


*The summer peak hour in the Weather Stressed scenario for 2030 required all available capacity within PJM as well as nearly an additional 2.7 GW, presumed available from non-PJM generating resources, such as imports from other regions, demand response, or other resources. This additional need is below both PJM's Capacity Benefit Margin of 3.5 GW, as well as PJM's reported 5.1 GWof contracted load management.[9] [10]

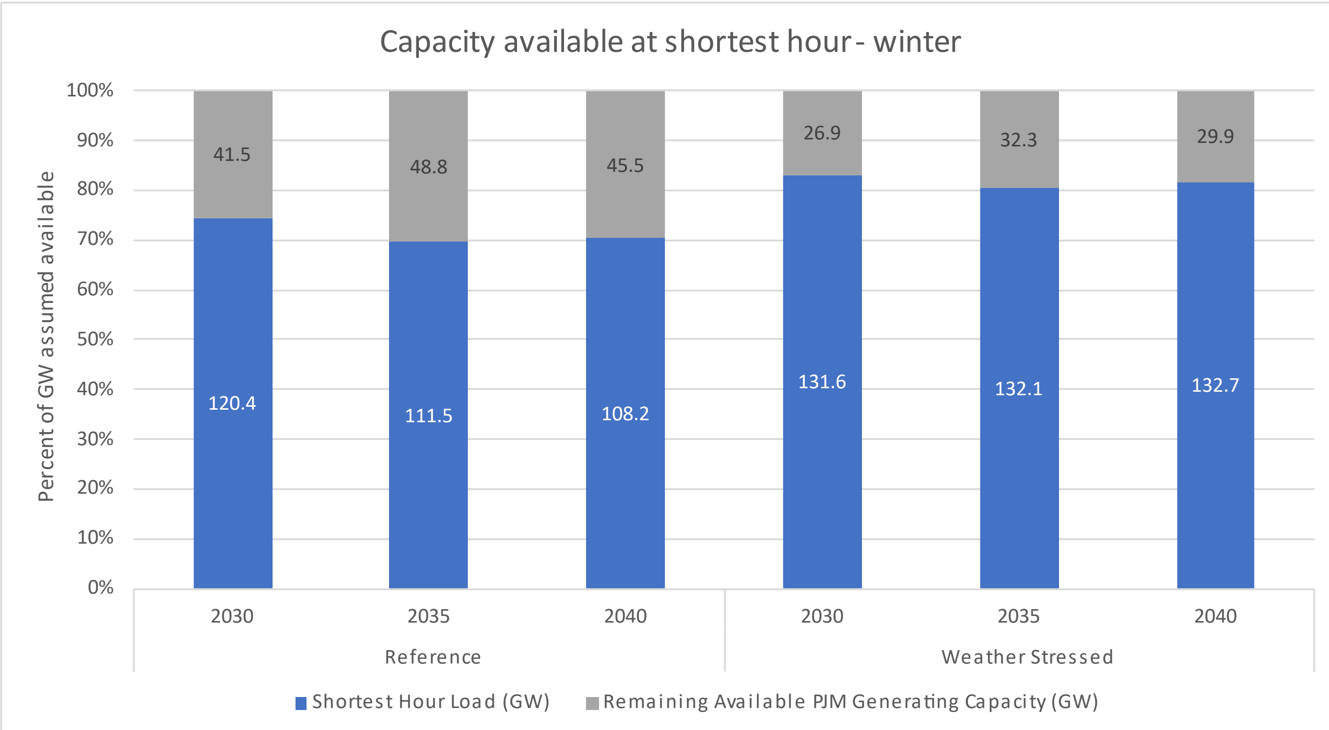
[9] Website: https://pjm.com/-/media/committees-groups/committees/pc/2023/20231003/20231003-item-05a---pjm-2023-rrs-report.ashx (Last accessed: October 29, 2023)

[10] Website: https://www.pjm.com/-/media/library/reports-notices/load-forecast/2023-load-report.ashx (Last accessed: November 7, 2023)

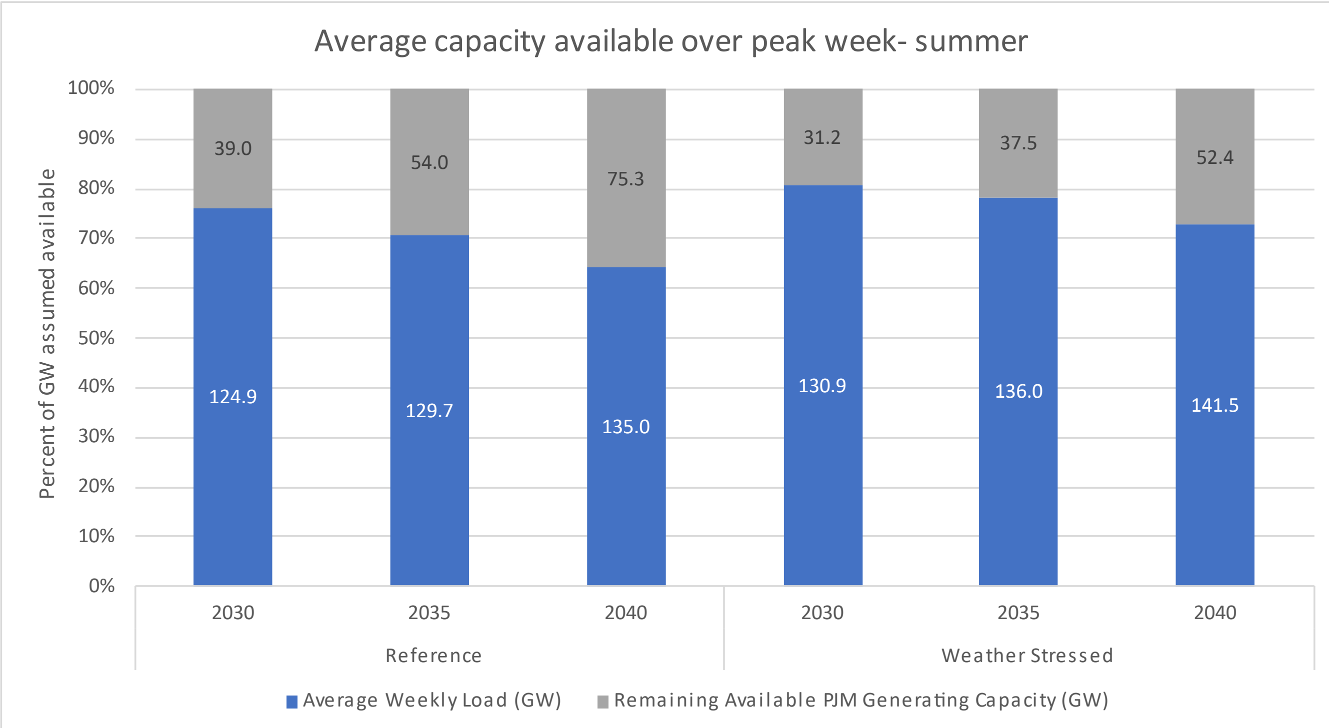


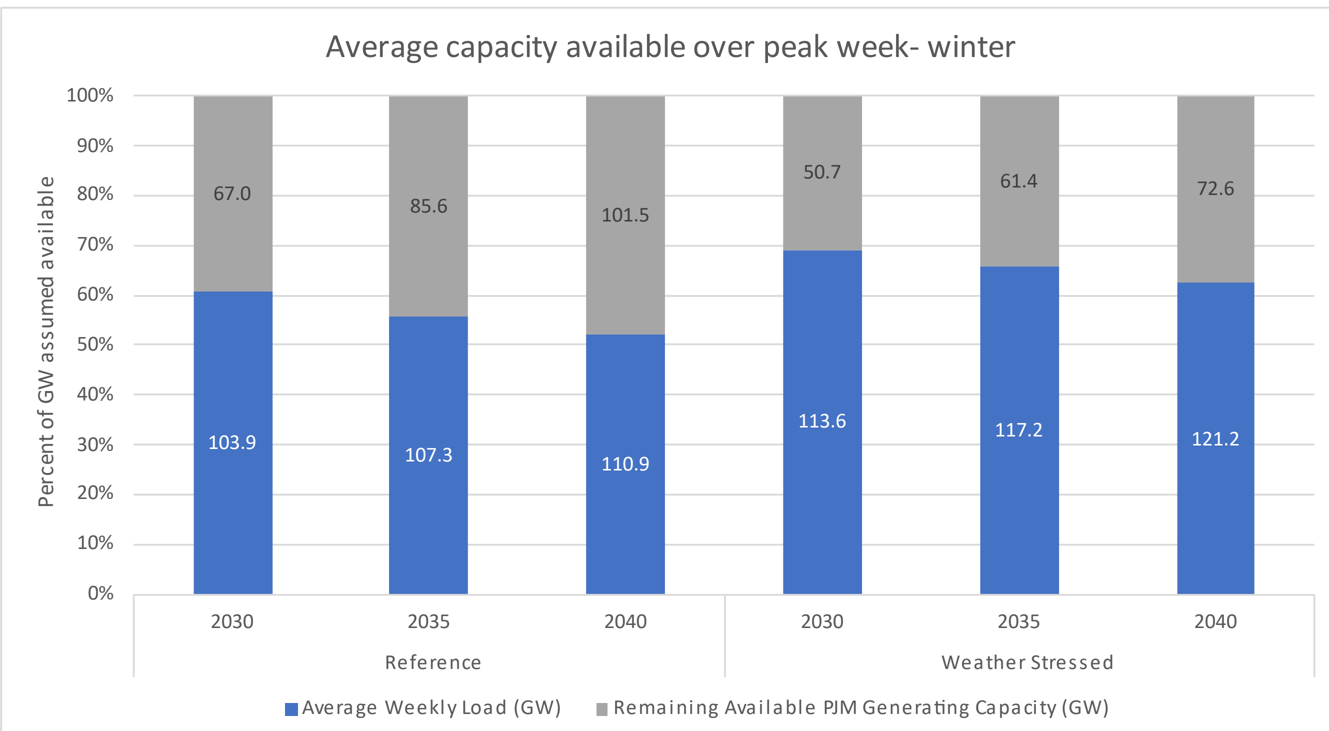


*The summer shortest hour in the Weather Stressed scenario for 2030 required all available capacity within the PJM territory as well as an additional 2.7 GW, presumed available from non-PJM generating resources, such as imports from other regions, demand response, or other resources. This additional need is below both PJM's Capacity Benefit Margin of 3.5 GW, and PJM's reported 5.1 GW of contracted load management.[11] [12]

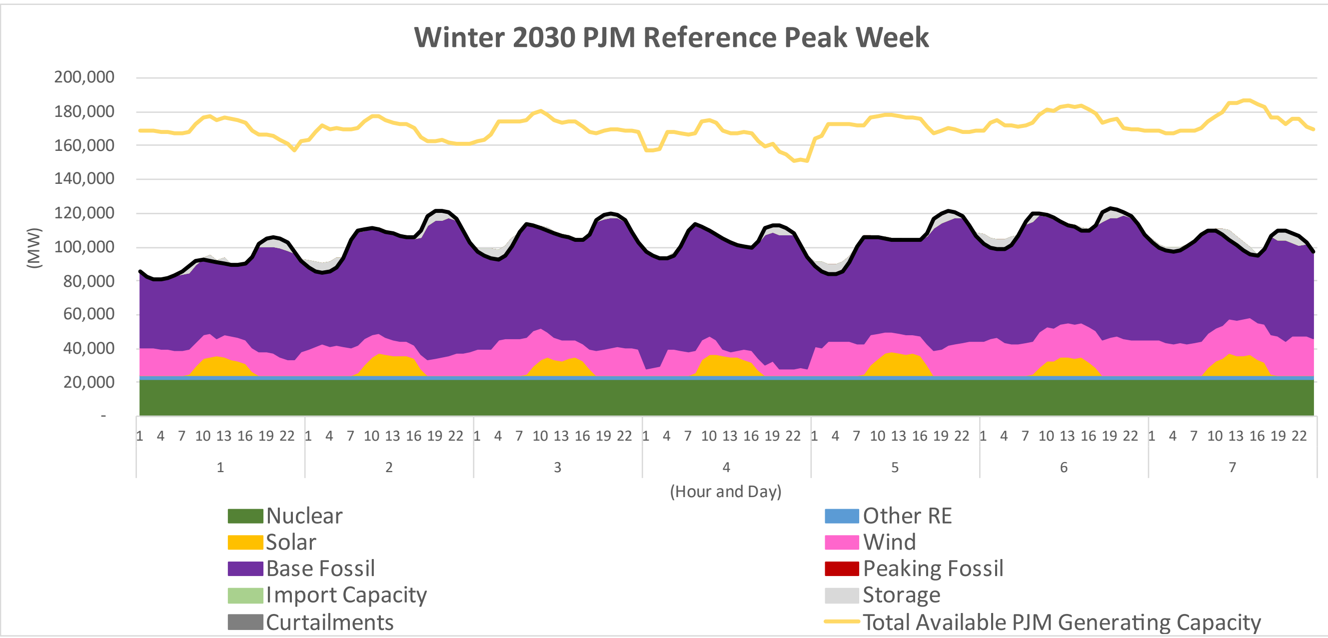


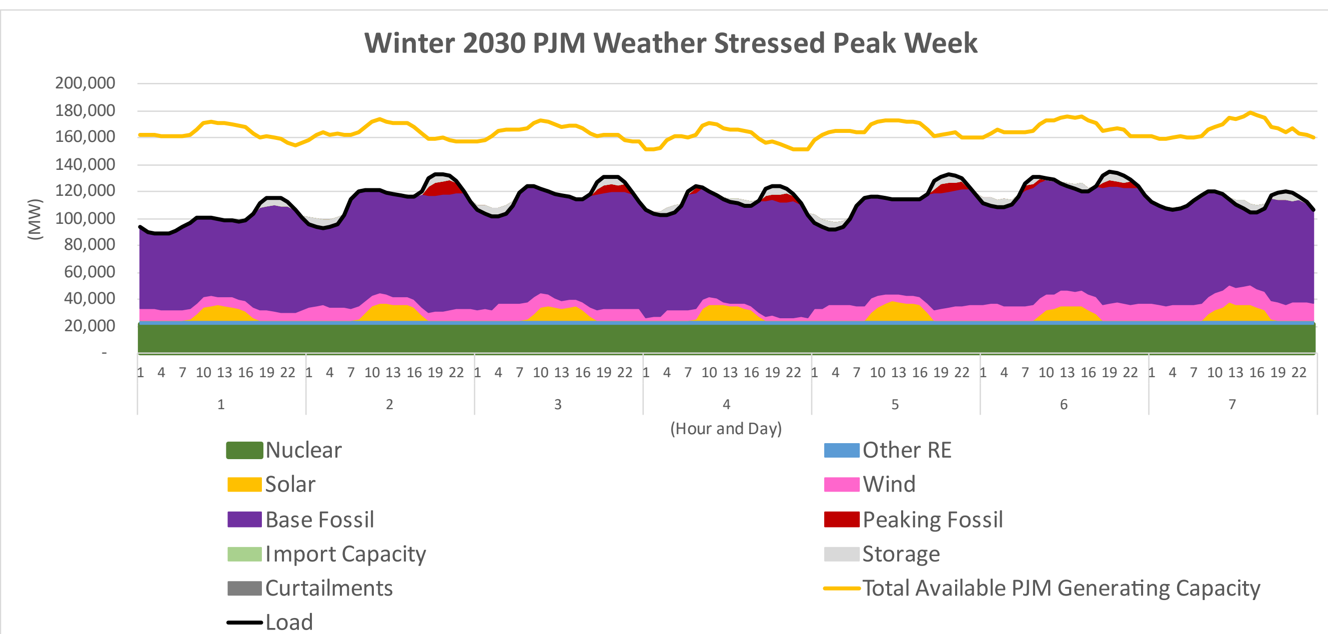
[11] Website: https://pjm.com/-/media/committees-groups/committees/pc/2023/20231003/20231003-item-05a---pjm-2023-rrs-report.ashx (Last accessed: October 29, 2023)
[12] Website: https://www.pjm.com/-/media/library/reports-notices/load-forecast/2023-load-report.ashx (Last accessed: November 7, 2023)

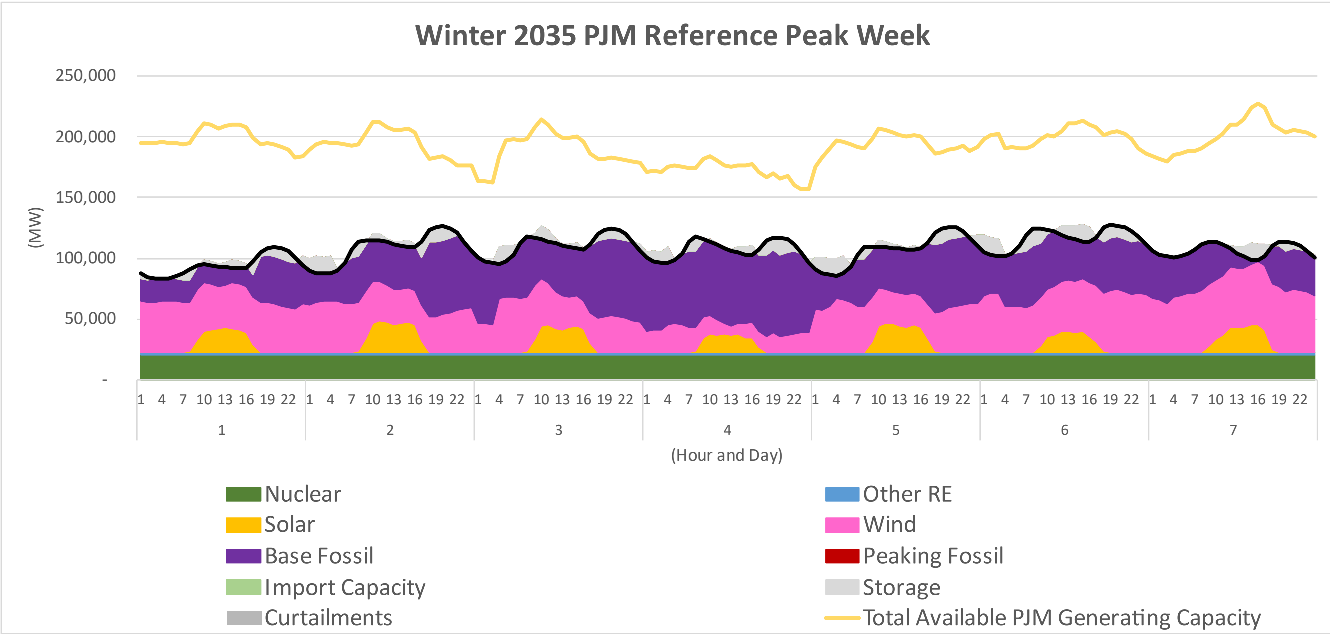

Average capacity available over peak week- summer
Percent of GW assumed available
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
39.0
54.0
75.3
31.2
37.5
52.4
124.9
129.7
135.0
130.9
136.0
141.5
2030
2035
2040
2030
2035
2040
Reference
Weather Stressed
Average Weekly Load (GW)
Remaining Available PJM Generating Capacity (GW)

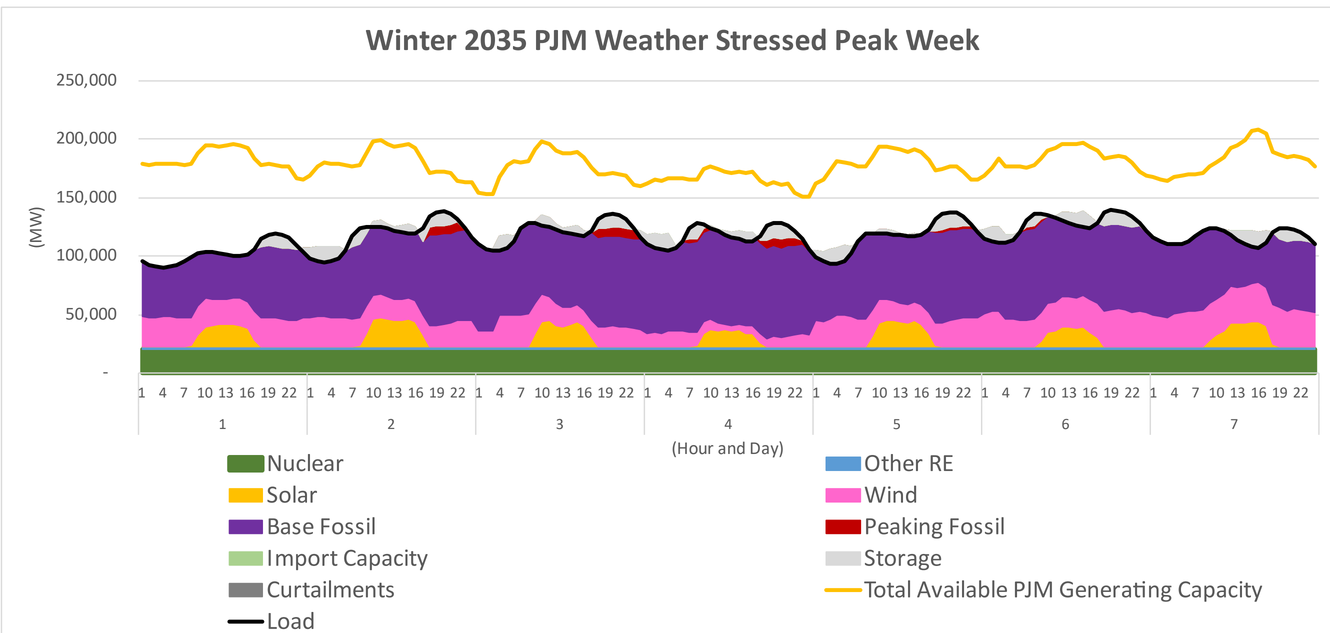

Average capacity available over peak week- winter
Percent of GW assumed available
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
67.0
85.6
101.5
50.7
61.4
72.6
103.9
107.3
110.9
113.6
117.2
121.2
2030
2035
2040
2030
2035
2040
Reference
Weather Stressed
Average Weekly Load (GW)
Remaining Available PJM Generating Capacity (GW)

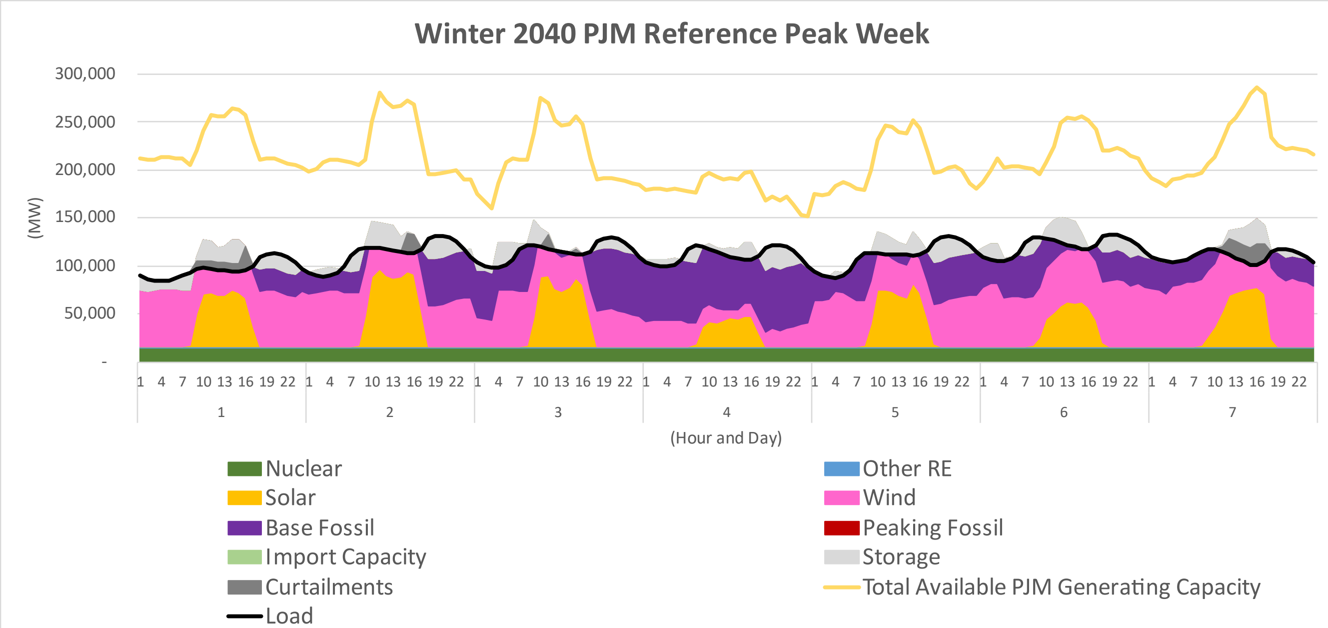
4 Appendix A – Hourly Dispatch and Resource Availability

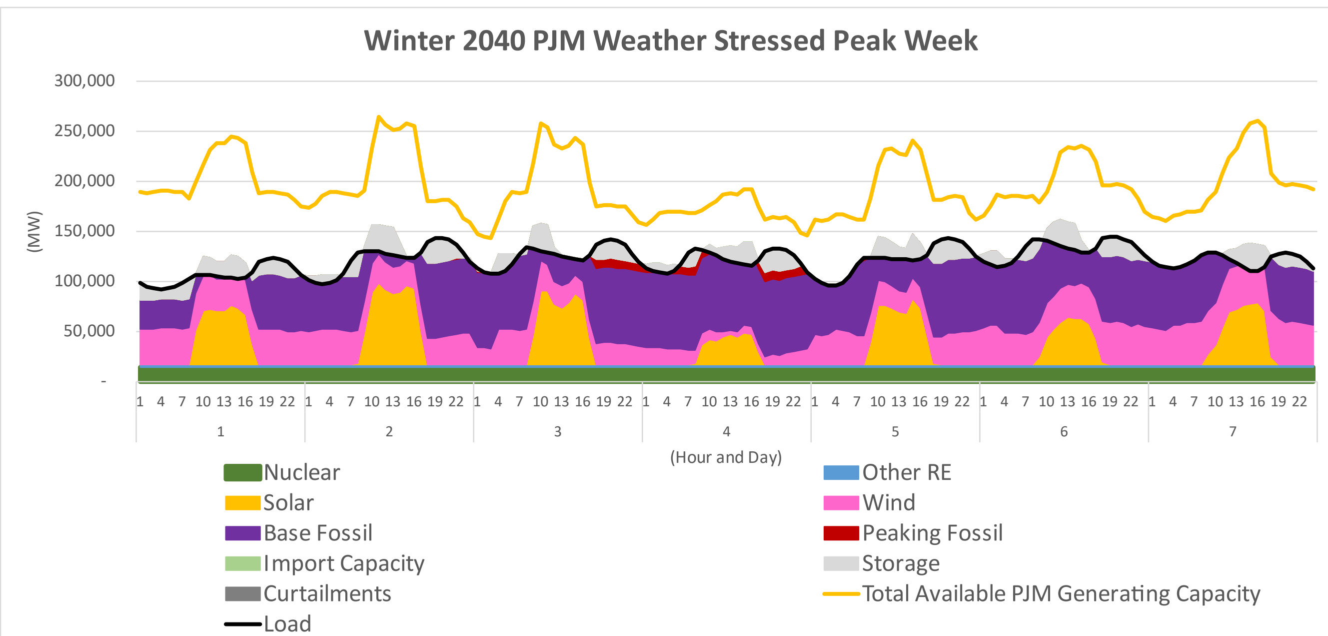


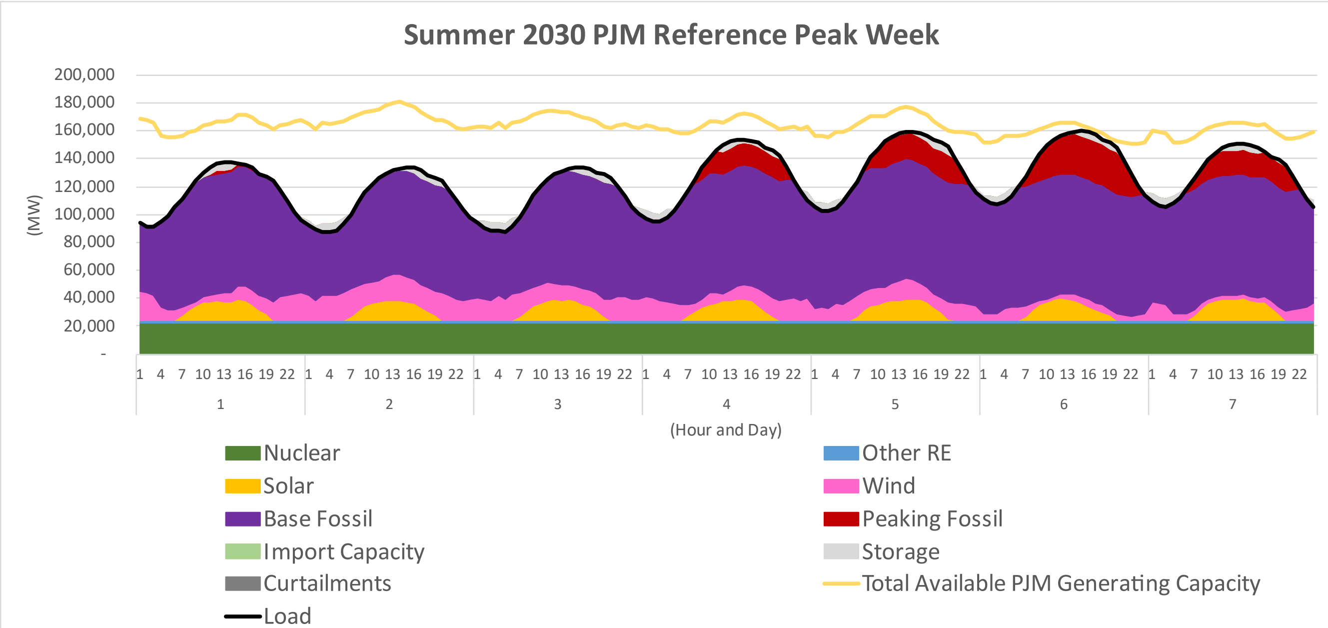


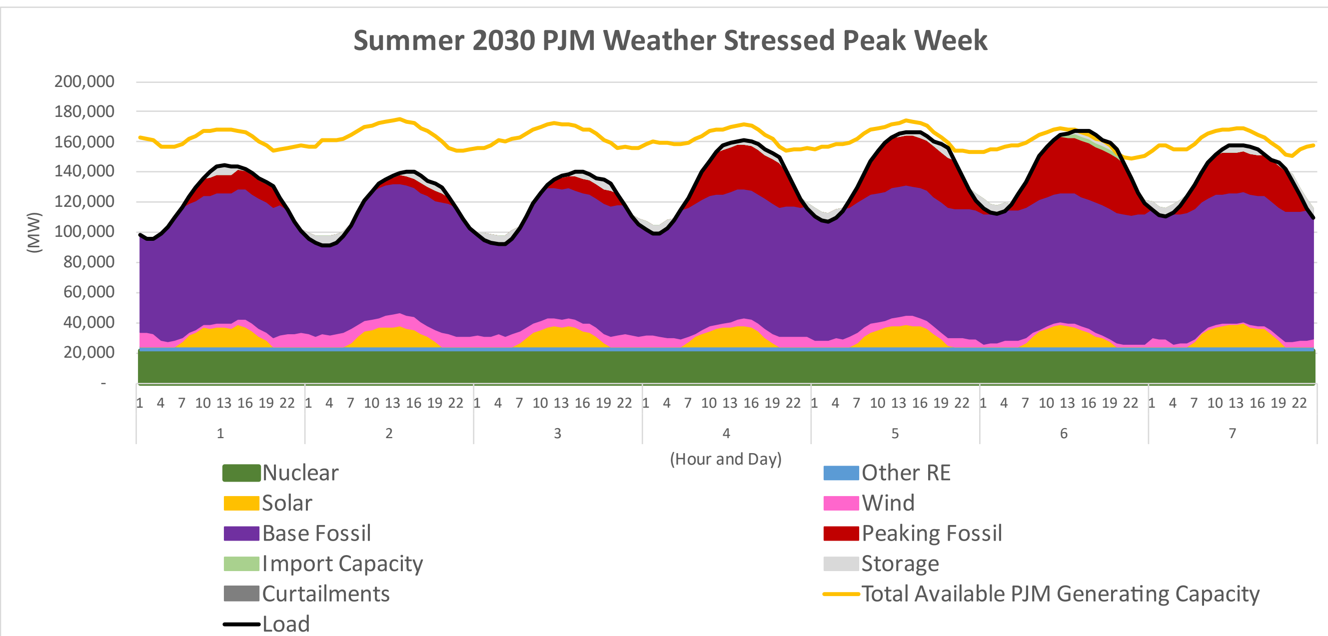

Winter 2035 PJM Reference Peak Week
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1 2 3 4 5 6 7
(Hour and Day)
Nuclear
Solar
Base Fossil
Import Capacity
Curtailments
Other RE
Wind
Peaking Fossil
Storage
Total Available PJM Generating Capacity

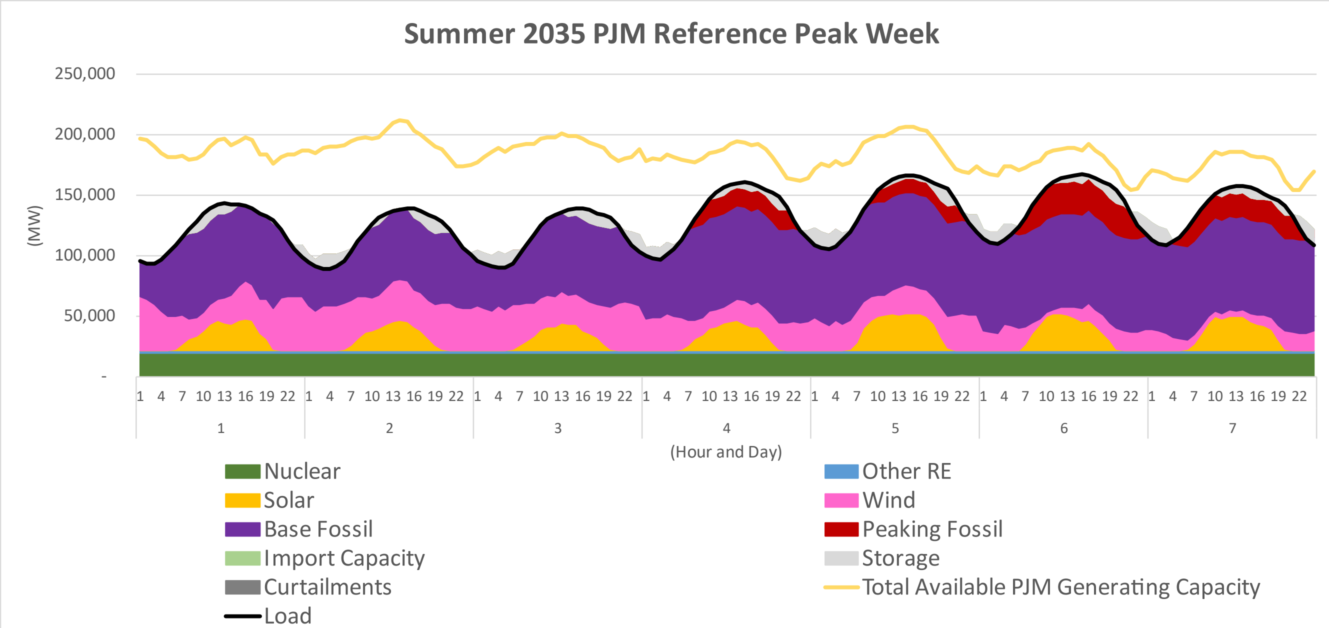

Winter 2035 PJM Weather Stressed Peak Week
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1 2 3 4 5 6 7
(Hour and Day)
Nuclear
Solar
Base Fossil
Import Capacity
Curtailments
Load
Other RE
Wind
Peaking Fossil
Storage
Total Available PJM Generating Capacity

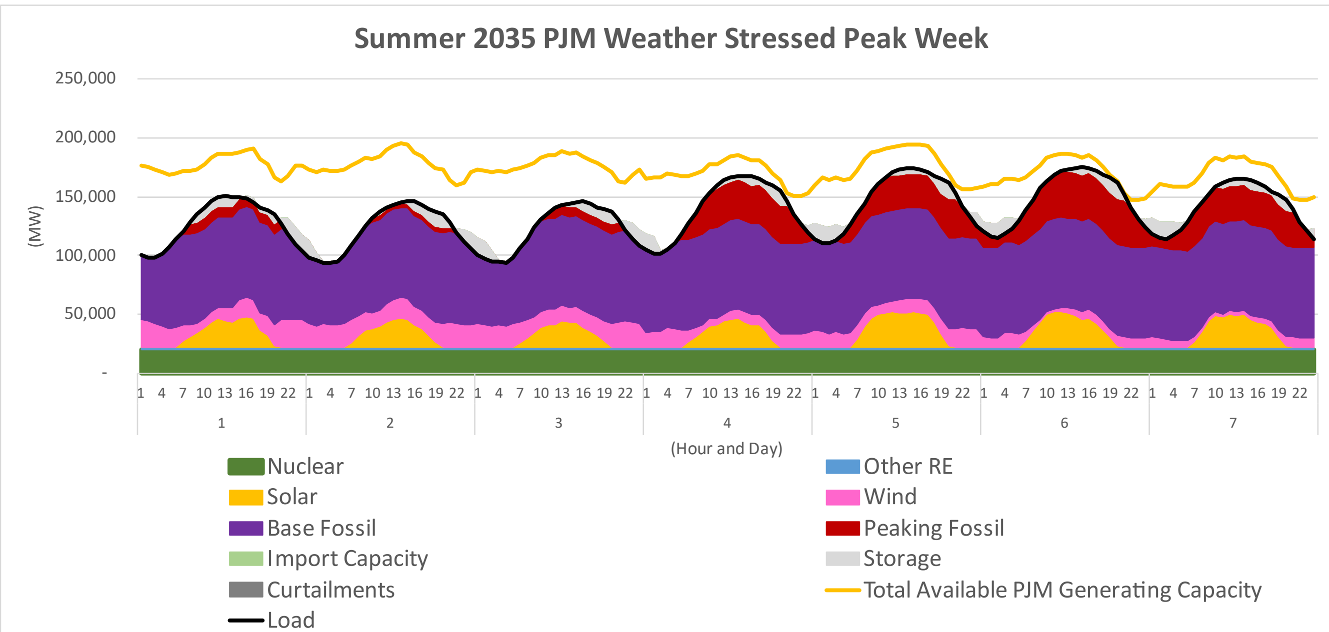

Winter 2040 PJM Reference Peak Week
300,000
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Solar
Base Fossil
Import Capacity
Curtailments
Load
Other RE
Wind
Peaking Fossil
Storage
Total Available PJM Generating Capacity

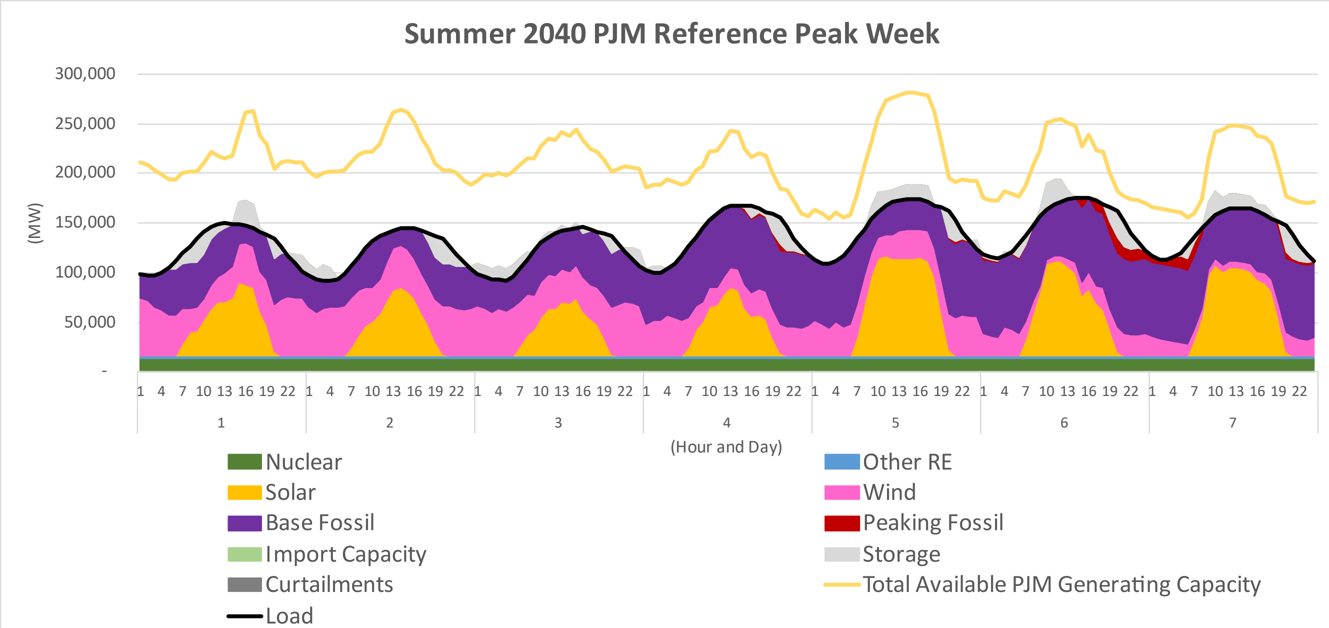

Winter 2040 PJM Weather Stressed Peak Week
300,000
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Solar
Base Fossil
Import Capacity
Curtailments
Load
Other RE
Wind
Peaking Fossil
Storage
Total Available PJM Generating Capacity

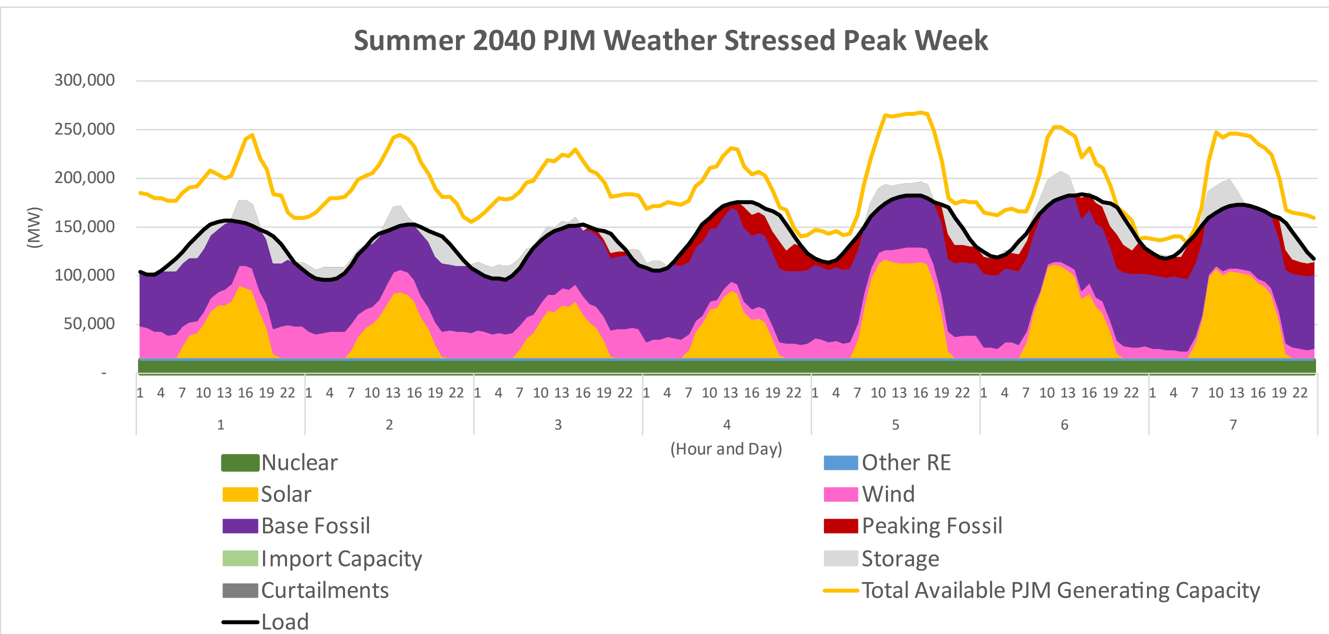

Summer 2030 PJM Reference Peak Week
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Other RE
Solar
Wind
Base Fossil
Peaking Fossil
Import Capacity
Storage
Curtailments
Total Available PJM Generating Capacity
Load


Summer 2030 PJM Weather Stressed Peak Week
200,000
180,000
160,000
140,000
120,000
100,000
80,000
60,000
40,000
20,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Other RE
Solar
Wind
Base Fossil
Peaking Fossil
Import Capacity
Storage
Curtailments
Total Available PJM Generating Capacity
Load


Summer 2035 PJM Reference Peak Week
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Other RE
Solar
Wind
Base Fossil
Peaking Fossil
Import Capacity
Storage
Curtailments
Total Available PJM Generating Capacity
Load


Summer 2035 PJM Weather Stressed Peak Week
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Other RE
Solar
Wind
Base Fossil
Peaking Fossil
Import Capacity
Storage
Curtailments
Total Available PJM Generating Capacity
Load


Summer 2040 PJM Reference Peak Week
300,000
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Solar
Base Fossil
Import Capacity
Curtailments
Load
Other RE
Wind
Peaking Fossil
Storage
Total Available PJM Generating Capacity


Summer 2040 PJM Weather Stressed Peak Week
300,000
250,000
200,000
150,000
100,000
50,000
-
(MW)
1 4 7 10 13 16 19 22
1
2
3
4
5
6
7
(Hour and Day)
Nuclear
Solar
Base Fossil
Import Capacity
Curtailments
Load
Other RE
Wind
Peaking Fossil
Storage
Total Available PJM Generating Capacity

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