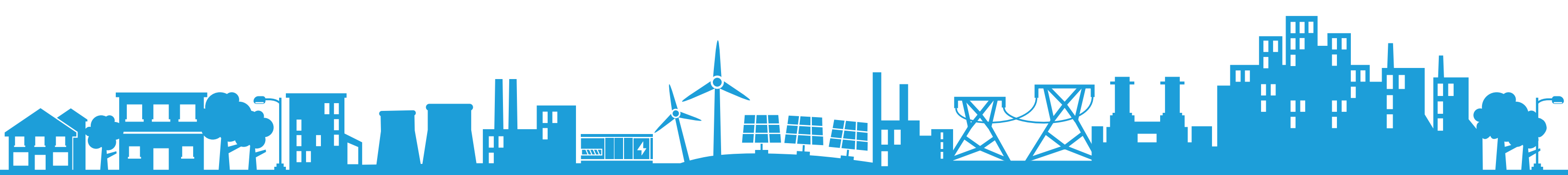
Working to Perfect the
Flow of Energy

FUEL SECURITY ANALYSIS:

A PJM RESILIENCE INITIATIVE

PJM Interconnection

December 17, 2018



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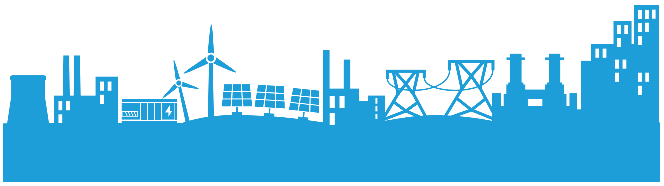
Errata

Dec. 17, 2018: A header on Fig. 15 was updated and the titles of Fig. 16 and Fig. 17 were swapped.

Jan. 16, 2019: A typo in the yellow "Assumptions" box on page 22 was corrected.

Jan. 16, 2019: Links to the technical appendix and scenario summaries documents were added to page 42.

Table of Contents



Highlights

- PJM's fuel security analysis is the next step in ensuring the resilience of the grid, focusing on one of its most important elements, fuel security.[1]
- This analysis demonstrates that the PJM system is reliable today and will remain reliable into the future. It also demonstrates the fuel security of the system under many stressed conditions.
- In the analysis, PJM stress-tested fuel delivery systems serving generation in the PJM region under plausible but extreme scenarios to identify when the system begins to be impacted and to identify the key study assumptions that trigger impacts to the grid.[2]
- Key elements such as on-site fuel inventory, oil deliverability, availability of non-firm natural gas service, location of a pipeline disruption and pipeline configuration become increasingly important as the system comes under more stress.
- This analysis modeled the impacts of a 14-day weather event. While the availability of all resource types was studied, the focus was on analyzing the risks to natural gas and fuel oil, which represent the largest amount of generation in PJM with less than 14 days of on-site fuel.
- While there is no imminent threat, fuel security is an important component of reliability and resilience – especially if multiple risks come to fruition. The findings underscore the importance of PJM exploring proactive measures to value fuel security attributes, and PJM believes this is best done through competitive wholesale markets.
- PJM will continue to engage the Federal Energy Regulatory Commission (FERC), the U.S. Department of Energy, the states in the PJM region and stakeholders on these issues. In addition, PJM has outlined specific proposals to FERC in its resilience docket and is committed to continuing to work with policymakers on issues that require national consideration and action by policymakers.

1 For the purposes of this paper, the use of the term "fuel security" refers to the availability of fuel, both on-site and the associated delivery systems, required for a unit to generate consistent with dispatch signals or Operating Instructions. "Fuel supply" is defined as the production, delivery and storage of fuel resources for generation. In instances where the term "fuel supply" is used, PJM is not focused on fuel production, since production issues have not been experienced and are not the focus of this analysis.

2 The analysis is neither meant to be predictive of future conditions nor meant to imply that analyzed scenarios are unavoidable.

Executive Summary

Focus on Fuel Security

Electricity is a public necessity and is critical to the health and welfare of the nation. Keeping power available whenever and wherever it is needed is the number one priority of PJM Interconnection and other grid operators. In the last several years, changes in the energy industry and increased cyber and physical threats to the grid and the fuel supply serving that grid have introduced a heightened focus on ensuring a resilient system to deliver electricity to consumers. Grid operators around the world find themselves contending with new challenges, including a rapidly changing fuel mix, stressed fuel delivery systems, extreme weather, cyberattacks and physical security threats. As a result, fuel security – one component of the resilience of the power grid – has become an increased area of focus.

Analysis: Assumptions and Scenarios

PJM designed its analysis to stress-test the grid under a series of extreme but plausible events. As in any stress test, the analysis was intended to discover the point at which the PJM system begins to be impacted.[3] PJM did not assign probabilities to single events or the convergence of events. It falls to policymakers and stakeholders to determine the relative costs and benefits of reinforcing the system to withstand particular events and the impacts of their potential convergence.

PJM studied 324 different scenarios that could occur during an extended period of cold weather, varying elements such as customer demand (also called "load"), fuel availability, oil refueling frequency, generator forced outage rates, retirements, level of reserves and natural gas pipeline disruptions.[4] Each of the assumptions that make up the scenarios is based on events that the PJM region has experienced (though not necessarily at the same time). Their recurrence is therefore very likely, and this reality should trigger discussions of potential means to address those events and the relative costs and benefits of doing so.

In order to develop a robust and plausible set of assumptions, sensitivities and scenarios, PJM analyzed historical weather data spanning more than 45 years, researched previously completed studies, issued surveys to PJM generation owners, and met extensively with industry groups, generation owners, various companies in the fuel supply chain in the PJM region, government agencies, neighboring independent system operators and regional transmission operators, and regulators (NERC, FERC and ReliabilityFirst).

3 The time at which system operators issue emergency actions such as voltage reduction or load shed, consistent with established procedures.

4 The impact of available demand response, renewables and energy storage was incorporated in the analysis for all scenarios.

The key variables included in the analysis were:

- Availability of non-firm gas transportation service
- Ability of the fuel-oil delivery system to replenish oil supplies during an extended period of extreme cold weather
- Physical breaks at key locations on the pipeline system
- Customer demand (load)
- Generator retirements, replacements and resulting installed reserve margin
- Use of operating procedures to conserve fuel during peak winter conditions

Results: Reliable Under All but the Most Extreme Scenarios

The analysis showed no reliability issues on the system over a prolonged period of cold weather with typical winter load, accounting for announced retirements[5] and new generation slated to be in operation by 2023 (using 2023/2024 as the study year). Even in a scenario such as extreme winter load combined with a pipeline disruption at a critical location on the pipeline system from which a significant number of generators are served, PJM's system would remain reliable and fuel secure. While there could be reserve shortages in the extreme winter load scenarios, the grid continues to deliver electricity reliably under these extreme conditions.

For the more extreme scenarios, PJM analyzed two separate generation retirement scenarios that reduced reserves to the 15.8 percent installed reserve margin (IRM) requirement, termed escalated 1 and escalated 2.[6] When combined with extreme winter load, PJM's analysis shows that the two escalated retirement scenarios indicate the system may be at risk for emergency procedures and operator-directed load shed.[7]

In looking at 324 scenarios, it is clear that key elements such as availability of non-firm gas transportation service, oil deliverability for purposes of replenishing on-site oil tanks, pipeline design, reserve level and method of dispatch become increasingly important as the system comes under more stress.

In particular, the combination of the following factors contributes to potential load shed events:

- The level of retirements and replacements
- The availability of non-firm gas transportation service
- The ability to replenish oil supplies
- The location, magnitude and duration of pipeline disruption
- Pipeline configuration

While there is no imminent threat, fuel security is an important component of ensuring reliability and resilience – especially if multiple risks come to fruition. The findings underscore the importance of PJM exploring proactive measures to value fuel security attributes, and PJM believes this is best done through the competitive wholesale markets.

5 Retirements announced by Oct. 1, 2018.

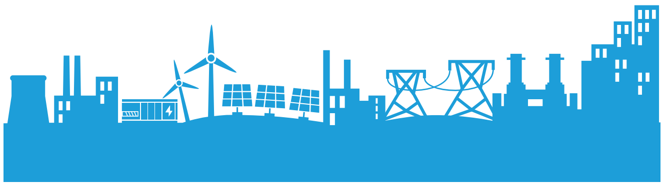
6 Escalated 1: Generation retirements of 32,216 MW by 2023, with 16,788 MW of capacity added to meet the installed reserve margin requirement (15.8 percent). Escalated 2: Generation retirements of 15,618 MW by 2023 with no capacity replacement.

7 All emergency procedures referred to in this analysis, including voltage reduction and load shed, are directed by system operators in a controlled fashion, consistent with established procedures.

Next Steps

Results from the analysis were first reported in PJM's Nov. 1, 2018, Special Markets & Reliability Committee meeting. This report is intended to be a more detailed explanation of the approach, assumptions, and results of the analysis, which can be used to further inform more in-depth stakeholder discussions scheduled for 2019. In parallel, PJM has engaged U.S. federal agencies to define further scenarios for PJM to analyze using the model developed for this analysis. PJM will also continue to engage FERC in the national consideration of fuel security issues addressed in FERC's resilience docket.[8]

8 https://www.pjm.com/-/media/documents/ferc/filings/2018/20180309-ad18-7-000.ashx.



Background

The energy industry is in the midst of dramatic change. Over the last decade, as shale gas hydraulic fracturing has become widespread, new gas-fired generation has increased in PJM. Other new technologies such as renewable generation, demand response and distributed energy resources have also increased dramatically. At the same time, coal has been retiring at a quicker pace, and the prospect for retirement of nuclear generation has increased.

Given these industry trends, PJM analyzed reliability attributes associated with a variety of potential future resource mixes, and released the results in a paper entitled PJM's Evolving Resource Mix and System Reliability in March 2017.[9] PJM's analysis concluded that the bulk electric system could be operated reliably under an array of future supply portfolios. However, the scope of the analysis did not include the resilience of the system under various potential portfolios nor the risks associated with significant disruptive events. As the paper noted, "Heavy reliance on one resource type, such as a resource portfolio composed of 86 percent natural gas-fired resources, however, raises questions about electric system resilience, which are beyond the reliability questions this paper sought to address." These unanswered questions prompted PJM to undertake an analysis of fuel security in April 2018.[10]

Fuel Security as a Resilience Effort

Resilience is how grid operators manage the risk of high-impact disruptions, which can happen simultaneously or persist for a period of time. Grid operators must prepare for, be capable of operating through and be able to recover as quickly as possible from these events, no matter the cause. There are many dimensions of resilience, which span the markets, operations, planning and supporting infrastructures of the grid. Fuel security is one aspect of resilience.

9 https://www.pjm.com/~/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx

10 https://pjm.com/-/media/library/reports-notices/fuel-security/20180430-valuing-fuel-security.ashx?la=en

Understanding the Study

The fuel security analysis described on the following pages was designed to stress-test the PJM grid and the fuel delivery systems serving generation in the PJM under a series of extreme but plausible future events (using 2023/2024 as the study year). As in any stress test, the analysis was intended to discover the point at which the PJM system begins to be impacted (i.e., when system operators initiate emergency actions) and to identify key drivers of risk.

This analysis represents Phase 1 of PJM's fuel security efforts. In Phase 2, the analysis results are being used to inform the stakeholder process, which will help to define fuel security attributes for PJM, location and magnitude of how many fuel secure resources or megawatts are needed, as well as determine how to value fuel secure resources. PJM may also use the results of the study to determine how best to incorporate fuel security into other aspects of its operations, markets and planning.

Phase 3, occurring concurrently with Phase 2, is a cooperative effort between PJM and U.S. federal agencies to define and analyze further scenarios based on classified information about credible risks to fuel security that could have impacts on the grid.[11]

The risks to the grid and the fuel supply that serves it are varied, multi-dimensional and range from fairly frequent events such as a typical winter cold snap to highly improbable events. PJM chose to focus on what it considers plausible risks (described further in the "Scope of Analysis" section). Some more extreme risks will be analyzed in Phase 3.

Outreach and Research

Research, including coordination with organizations outside of PJM, was important to the fuel security analysis. In order to develop a robust and plausible set of assumptions, sensitivities and scenarios, PJM researched previously completed studies, issued surveys to PJM generation owners and met extensively with industry groups, generation owners, various companies in the fuel supply chain in the PJM region, government agencies and other system operators. A full description of external coordination, outreach approach and research is contained in the Technical Appendix[12] of this paper.

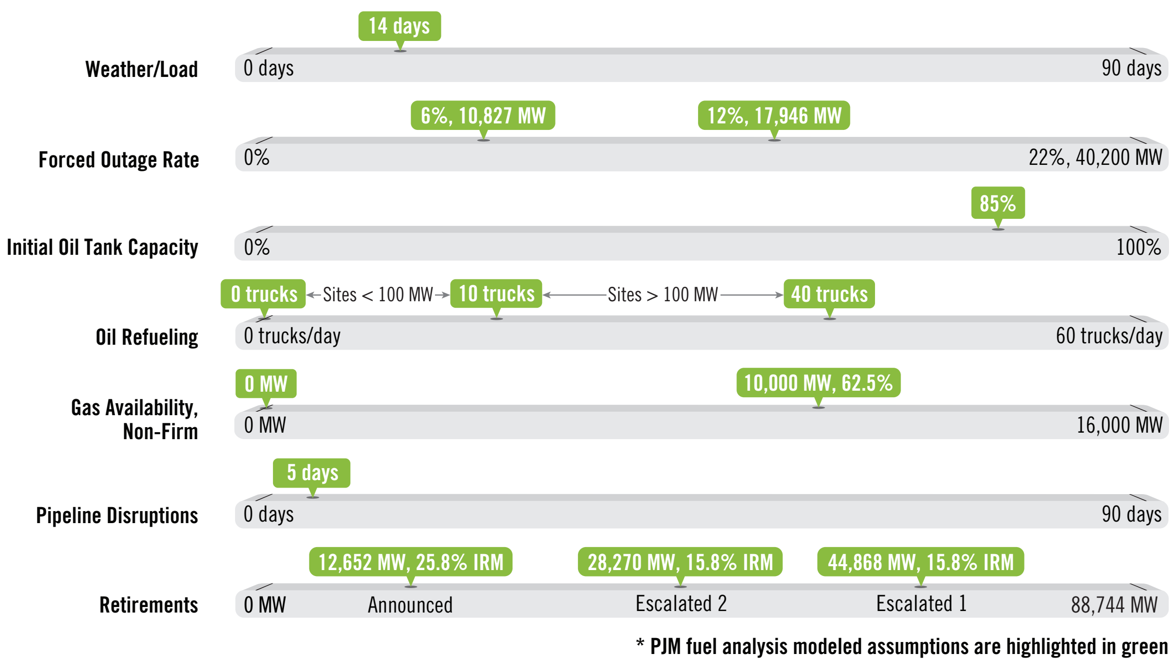
11 https://www.pjm.com/-/media/library/reports-notices/fuel-security/fuel-security-summary-of-discussions-with-federal-agencies-and-requested-analyses.ashx?la=en

12 A separate technical appendix of the fuel security analysis can be found on the PJM website: https://www.pjm.com/-/media/library/reports-notices/fuel-security/fuel-security-technical-appendix.ashx?la=en. The technical appendix contains additional detail and in-depth information on the assumptions, approach, analysis and results of the fuel security study. Further detail can also be requested via the stakeholder process educational sessions.

Key Assumptions Comparison

In the course of conducting research, it became clear that certain assumptions and sensitivities were of high importance and that there were divergent views of what was a plausible assumption, and not considered too conservative or too extreme. Through research, targeted outreach and historical analysis, PJM was able to develop a robust set of informed assumptions that, when combined, result in extreme but plausible sensitivities and scenarios. **Figure 1** provides a visual illustration of where PJM's assumptions fall within the extremes. The far left and far right of the scale represent boundaries for each assumption, and the text in green bubbles is the assumption that PJM chose. The assumptions are discussed in detail in the "Assumptions" section of the paper.

Figure 1: Ranges of Assumption Recommendations



Scope of Analysis

As described further in the "Weather and Load" section, the analysis modeled a 14-day cold weather duration based on historical weather analysis. This study focuses on cold weather events because risks to PJM generation's ability to procure adequate fuel to serve load is most prominent during the winter. This is primarily because during the winter, the needs of commercial and residential heating are competing with natural gas-fired and dual-fuel generators (which generate more than 30 percent of the megawatt-hours of energy produced in PJM) for natural gas, oil, pipeline transportation and oil deliveries. Historical events, such as the deep freeze of 1994, the 2014 Polar Vortex and the most recent 2017/2018 cold snap, highlight strains on fuel delivery methods like pipelines, trucking and barges.[13, 14]

13 https://www.pjm.com/-/media/library/reports-notices/weather-related/20180226-january-2018-cold-weather-event-report.ashx.

14 https://pjm.com/-/media/library/reports-notices/weather-related/20140509-analysis-of-operational-events-and-market-impacts-during-the-jan-2014-cold-weather-events.ashx?la=en.

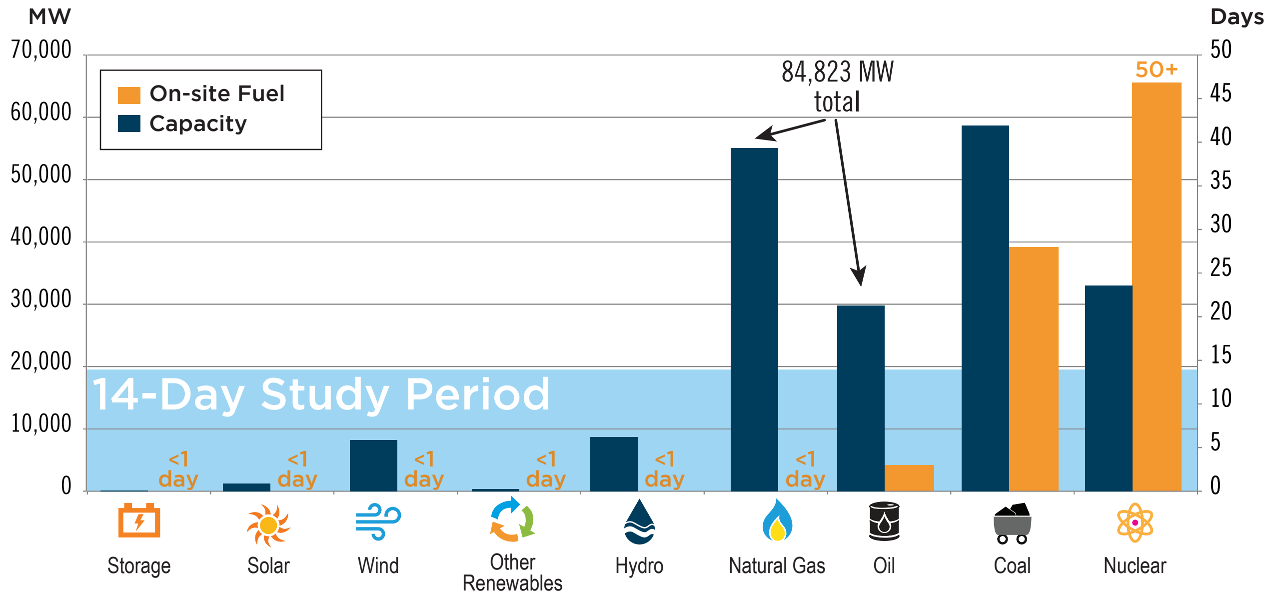
One method to mitigate fuel security risk is having fuel on site and readily available. **Figure 2** illustrates PJM's resource portfolio, comparing consecutive days of on-site fuel and the capacity of various resources.[15] Natural gas and fuel oil represent a large amount of PJM's capacity, while also having less than 14 days of fuel on site. While the availability of all resource types was studied, the focus of detailed sensitivities was on analyzing the risks to the 84.8 GW of generation in PJM with less than 14 days of on-site fuel represented by natural gas and fuel oil.

Approach and Methodology

In order to conduct the study, various assumptions were made, such as level of generation retirements, weather, load and fuel supply disruptions. These assumptions drove 324 study scenarios. The scenarios were simulated using hourly security constrained unit commitment and economic dispatch simulations over a 14-day time horizon consistent with current PJM market practices and dispatch mechanisms.

PJM used highly customizable commercial software[16] that provided the flexibility needed to accurately model and simulate the complexities of PJM's system, time-varying decision-making, and fuel delivery and inventory constraints.

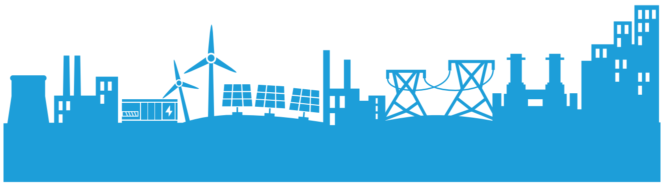
Figure 2: Fuel Security Analysis Scope



Data shown here is for existing PJM generation only, not queued generation. The natural gas columns consist of gas-only generation. The oil columns consist of both oil only and dual-fuel (natural gas + oil) generation. On-site fuel data was obtained through generation owner surveys.

15 Additional detail on analysis of on-site fuel inventories by resource type is included in the Technical Appendix.

16 PLEXOS Simulation Software, produced by Energy Exemplar, https://energyexemplar.com/products/plexos-simulation-software/.



Assumptions

As mentioned in the “Outreach and Research” section, PJM worked extensively with members and industry experts and used independent research to determine and vet assumptions used in this study. These assumptions lead PJM to study 324 scenarios. This section includes a detailed description of each assumption used in the analysis. More detail can be found in the Technical Appendix.

Weather and Load

For the purposes of this analysis, the typical winter load shape and extreme winter load shape have three primary characteristics: cold weather event duration, peak load and hourly shape. PJM examined weather data for the current PJM footprint from 1973 through the 2017/2018 winter and used this as the basis for establishing the cold weather event duration and for developing the peak forecast distribution.

ASSUMPTIONS

Weather Scenario

Typical and Extreme: 14 days

Load Scenario

Typical: 50/50 - 1 in 2 years; (134,976 MW peak)

Extreme: 95/5 - 1 in 20 years; (147,721 MW peak)

Load Profile

Typical: 2011/2012 winter
Extreme: 2017/2018 winter

Duration and Peak Load

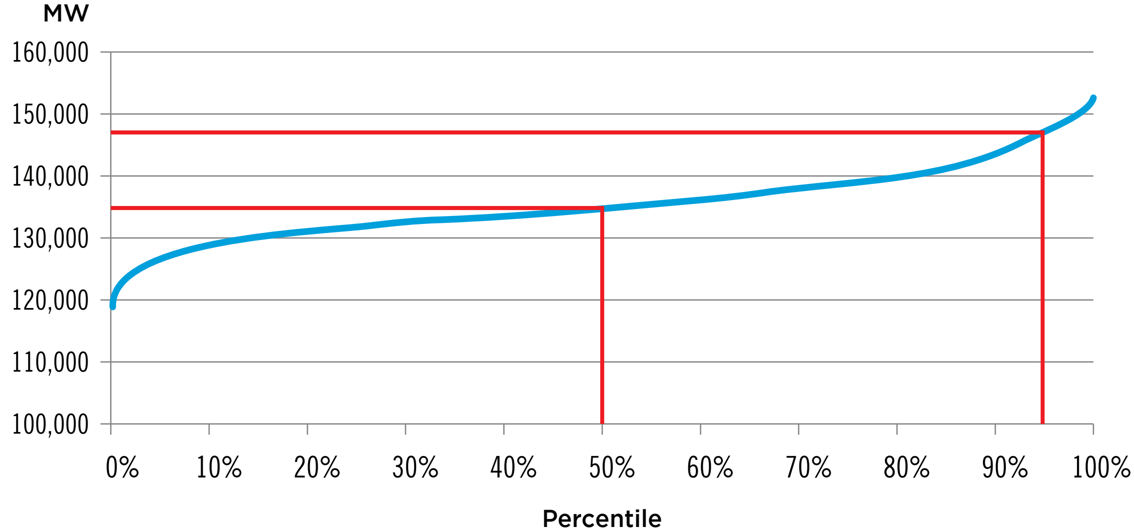
The 1989/1990 winter was particularly notable, with both an extended cold period and weather eliciting an extreme peak. For 14 days, the average wind-adjusted temperature across the PJM footprint was less than 20 degrees (90th percentile daily winter weather) and the single coldest day produced a 95/5 (once in 20 years) peak load. Therefore, the 1989/1990 winter is the basis for establishing 14 days as the cold weather event duration and for the peak load weather conditions in the extreme winter load scenario (See the "Hourly Load Shape" section for more detail).

The typical load for winter 2023/2024 is defined as the 50/50 load (134,976 MW), which is the load that corresponds to the 50th percentile of the forecast distribution. Similarly, extreme winter load is defined as the 95/5 load (147,721 MW), the load that corresponds to the 95th percentile of the forecast distribution. See **Figure 3**.

Hourly Load Shape

The 50/50 and 95/5 peak loads are each applied to an hourly load shape expressed as a fraction of the seasonal peak to yield the hourly megawatt values. To select the hourly load shape for the typical load case, PJM computed an RTO-wide shape that had typical characteristics in terms of energy use by week. This was then used as the basis for selecting a historical year that would reflect

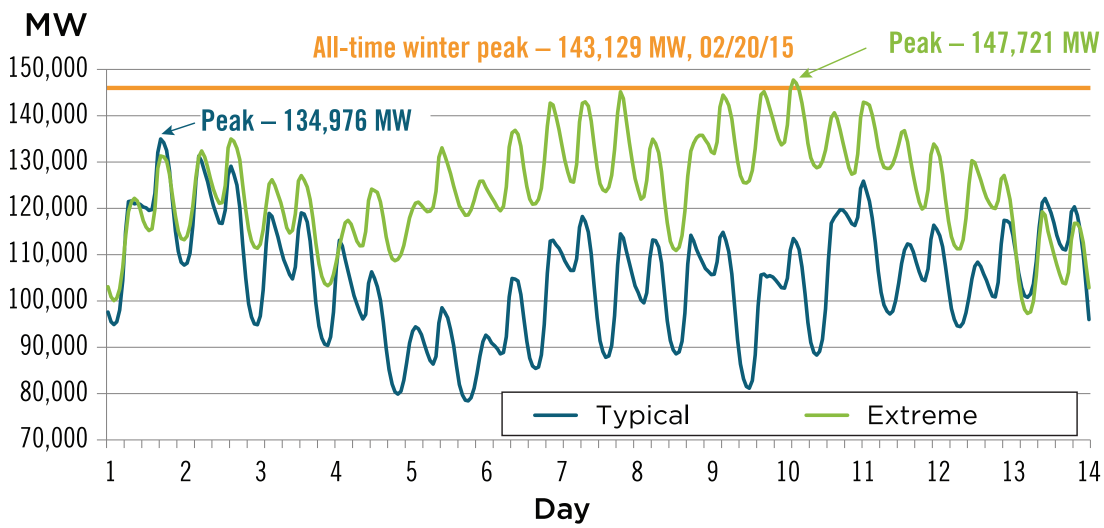
Figure 3: 2023/2024 Winter Peak Forecast Distribution



typical winter load diversity between zones. The 2011/2012 winter season best matched the manufactured shape and was used for the typical winter load. For the extreme winter load, the 2017/2018 winter season was selected, as it is much more recent than the 1989/1990 winter and contains a 12-day duration cold weather event (the second-longest cold snap in the last 45 years).[17] See **Figure 4**.

PJM therefore concludes that the extreme weather scenario is plausible based on the 1989/1990 winter in which a 14-day cold snap coincided with a 95/5 winter peak load.

Figure 4: Hourly Load Shapes



17 The only 14-day cold snap experienced in the last 45 years in PJM occurred in the 1989/1990 winter season. The winter hourly load profile from 1989/1990, however, is not a candidate for use in this study because loads are unavailable for many PJM zones prior to 1998. (It would also not be prudent to use hourly load profiles that are nearly 30 years old.)

Dispatch

Economic dispatch refers to PJM's typical process of using security constrained unit commitment and security constrained economic dispatch with the objective of minimizing production costs while satisfying electricity demand, meeting reserve requirements, and respecting system constraints such as transmission limits and generator operational parameters and availability. To simulate economic dispatch for winter 2023/2024, PJM calculated future fuel prices that were incorporated into generator offers. More information on this fuel price methodology is discussed in the "Fuel Prices" section.

> ASSUMPTIONS
>
> **Dispatch**
>
> **Typical:** Economic
>
> **Extreme:** Economic or optional maximum emergency operational procedures if extreme cases present operational issues

Maximum emergency dispatch is an emergency procedure described in PJM Manual 13, Emergency Operations.[18] This operating procedure allows PJM dispatchers to preserve fuel that would otherwise be consumed through normal economic dispatch by manually dispatching fuel-limited resources to optimize the amount of load served. When a potential capacity shortage is identified, maximum emergency dispatch helps ensure that adequate generation capacity is available during critical periods. In the simulation, PJM modeled maximum emergency dispatch by adjusting oil prices to be higher than gas prices in order to programmatically measure the benefits of a manual dispatch procedure.

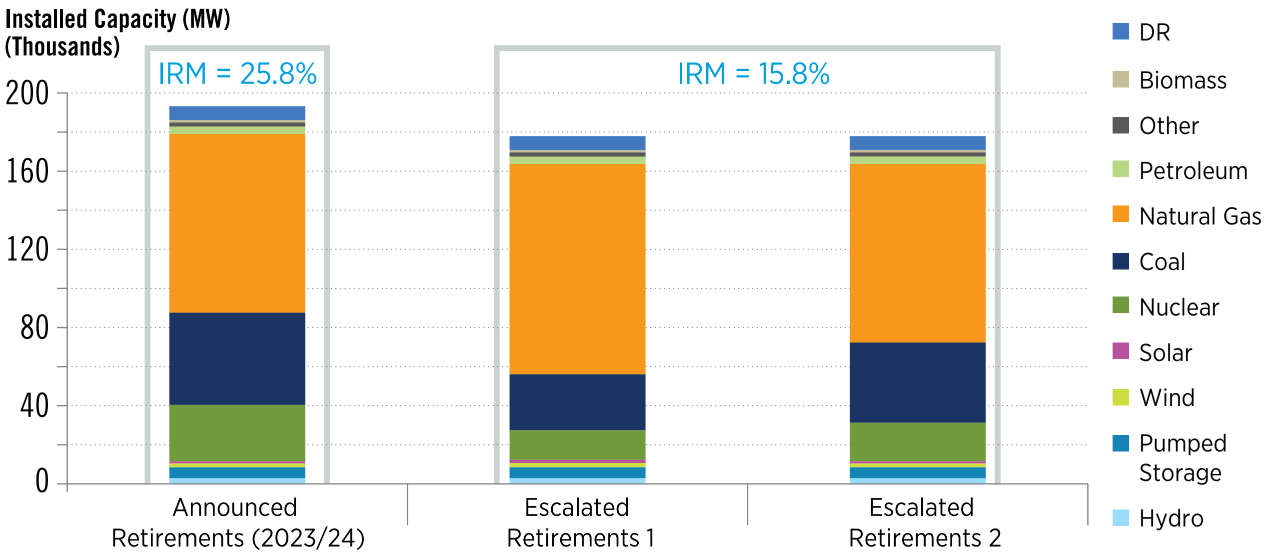
Retirement Portfolios

> ASSUMPTIONS
>
> **Retirements**
>
> **Announced:** Generation retirements announced by Oct. 1, 2018, and new generation in the PJM interconnection queue and slated to be in operation by 2023
>
> **Escalated 1:** Generation retirements of 32,216 MW by 2023, with 16,788 MW of capacity added to meet the installed reserve margin requirement (15.8%)
>
> **Escalated 2:** Generation retirements of 15,618 MW by 2023 with no capacity replacement
>
> **Escalated 1 Replacement Capacity Approach**
>
> - Replacement resources reflective of PJM interconnection queue and commercial probability calculation
> - Replacement combined cycle natural gas resources modeled as firm supply and transport
> - Replacement combustion turbine natural gas resources modeled as dual-fuel with interruptible gas

Three resource portfolios with different levels of generation retirement and replacement were considered in the study: announced, escalated 1 and escalated 2. The announced retirement portfolio accounted for announced retirements as of October 1, 2018. The escalated 1 and escalated 2 retirement portfolios are stressed portfolios that account for coal and nuclear retirements beyond what was announced as of Oct. 1, 2018, using differing assumptions for the replacement of those retiring resources to maintain the installed reserve margin requirement. See **Figure 5.**

18 https://www.pjm.com/-/media/documents/manuals/m13.ashx

Figure 5: Summary of Portfolios Analyzed



Announced Retirements Portfolio

Table 1: Announced Retirement Portfolio: Installed Capacity by Resource Type

Resource Type	ICAP MW
Biomass	2,208
Coal	47,241
Hydro	2,941
Natural Gas and Other Gases	91,896
Nuclear	28,800
Petroleum	4,389
Pumped Storage	5,574
Solar	1,153
Wind	1,945
Demand Response	7,092
Total	**193,239**
2023/2024 Forecasted Summer Peak Load	153,632
Reserve Margin	**25.8%**

The announced retirements portfolio accounted for announced retirements as of Oct. 1, 2018, and projects in the interconnection queue for the 2023/2024 Regional Transmission Expansion Plan. The announced retirements included all in-service capacity resources (regardless of their prior capacity market auction clearing status), all interconnection queue resources with a signed Interconnection Service Agreement, and energy-only units located within the PJM footprint. Demand response (DR) resources are included in the portfolio based on the DR forecast provided in the 2018 PJM Load Forecast Report,[19] adjusted as described in the "Demand Response" section of this report.

The reserve margin for the announced retirements portfolio is 25.8 percent. This was calculated based on the 2023/2024 forecasted summer peak load as reported in the 2018 PJM Load Forecast.[20] To calculate the reserve margin, wind and solar resources were valued at their current capacity credit averaged across the PJM footprint. Current average capacity credit values are 13 percent and 38 percent of nameplate capacity for wind and solar, respectively. **Table 1** includes the installed capacity by resource type used for the announced retirements portfolio.

19 https://www.pjm.com/-/media/library/reports-notices/load-forecast/2018-load-forecast-report.ashx.

20 Ibid.

Escalated Retirements Portfolios

In order to introduce stressed conditions to the study, additional retirements beyond the announced retirements portfolio were considered. Given recent coal retirement trends and potential nuclear retirements and considering the efforts of Monitoring Analytics, PJM's independent market monitor (IMM) to analyze "at risk" generator retirements for nuclear and coal,[21] only additional coal and nuclear retirements were considered as part of the escalated retirements portfolios.

PJM used a resource-specific retirement approach to determine specific coal and nuclear resource retirements. This approach considered forward-looking economic profit and loss analysis, which is similar to the IMM's "at risk" coal and nuclear retirement study approach.

Methodology of Profit and Loss Analysis

The following information and methodologies were used to compare projected resource-specific energy and capacity market revenues to estimated cost. Fixed resource requirement resources were not included as part of this retirement analysis.

- **Future Energy Market Revenue.** Data acquired from the production cost model used in the most recent 2016/2017 market efficiency planning analysis cycle
- **Future Variable Operations and Maintenance Cost.** Data acquired from the production cost model used in the most recent market efficiency analysis cycle
- **Future Capacity Market Revenues.** Calculated using commitments and clearing prices from the 2021/2022 Base Residual Auction (i.e., capacity market auction)
- **Resource Capital Costs Based on Resource Type**
  - **Coal Units:** Costs defined by the PJM default avoidable cost rate[22]
  - **Nuclear Units:** Fixed costs from the U.S. Environmental Protection Agency's Integrated Planning Model, escalated for 2020/2021[23]
- **Fixed resource requirement (FRR) resources** were not included as part of this retirement analysis

To stress the analysis under extreme but plausible scenarios, PJM developed these portfolios so that they meet the 15.8 percent installed reserve margin (IRM)[24] but do not exceed it. Although most PJM capacity market Base Residual Auctions (Auctions) have historically procured reserves considerably above the IRM (as high as 23.3 percent in the 2020/2021 Auction), there have been Auctions such as the 2010/2011 Auction in which the procurement (16.4 percent) was close to the IRM for that year (15.5 percent).

If the rate at which existing resources exited the market were to exceed the rate at which new resources enter the market, it is reasonable that a future Auction's procurement will meet, but may not exceed, the 15.8 percent IRM. The escalated retirements portfolios are potential realizations of such a scenario.

21 http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2017/2017-som-pjm-volume2.pdf.

22 PJM Open Access Transmission Tariff (OATT), Attachment DD, Section 6, https://agreements.pjm.com/oatt/5159.

23 https://www.epa.gov/airmarkets/documentation-epas-power-sector-modeling-platform-v6.

24 The IRM is the level of reserves above the RTO forecasted peak necessary to meet the 1 day in 10 years loss of load expectation criterion.

Escalated 1 Retirements Portfolio

The escalated 1 portfolio accounts for the retirement of 55 coal and nuclear units that, based on the methodologies above and for the purposes of this study, were deemed to be at risk of retirement. Escalated 1 modeled the retirement of 32,216 MW with replacements of 16,788 MW to meet the 15.8 percent IRM reliability requirement. The replacement of generation was determined based on commercial probabilities of projects in the facilities study stage of the PJM interconnection queue. PJM analyzed recent and future generator interconnection trends to determine the level of firm, non-firm and dual-fuel replacement capacity.

Natural gas-fired resources made up approximately 16,000 MW (96 percent) of the replacement capacity and renewables made up approximately 700 MW (4 percent). Of the 16,000 MW of natural gas generators, 15,500 MW were modeled as combined-cycle generators with firm transport. Approximately 500 MW of combustion turbine generators were modeled as dual-fuel generators with non-firm transport.

Figure 6 shows a map of PJM areas (East, West and South), designated for the purposes of this study, and the transmission zones within those areas. **Figure 7** shows the retirements and replacements for escalated 1 by area. **Table 2** shows the megawatt amounts of installed capacity (ICAP) included in escalated 1 by resource type.

Figure 6: PJM Areas and Transmission Zones

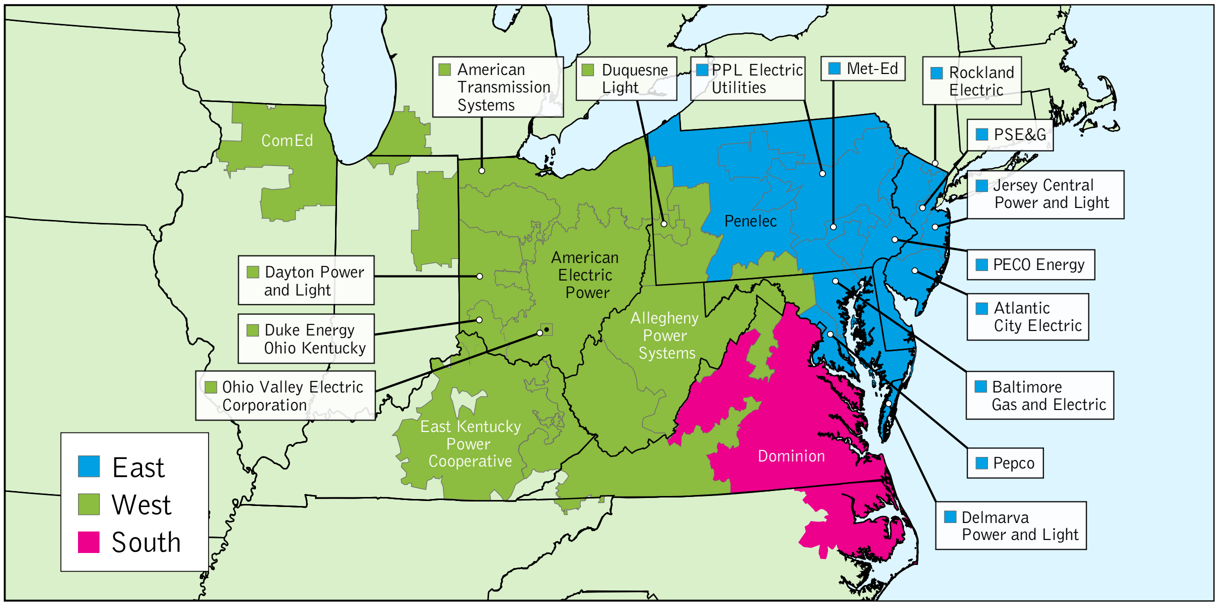


Figure 7: Escalated 1: Retirements and Replacements by Location

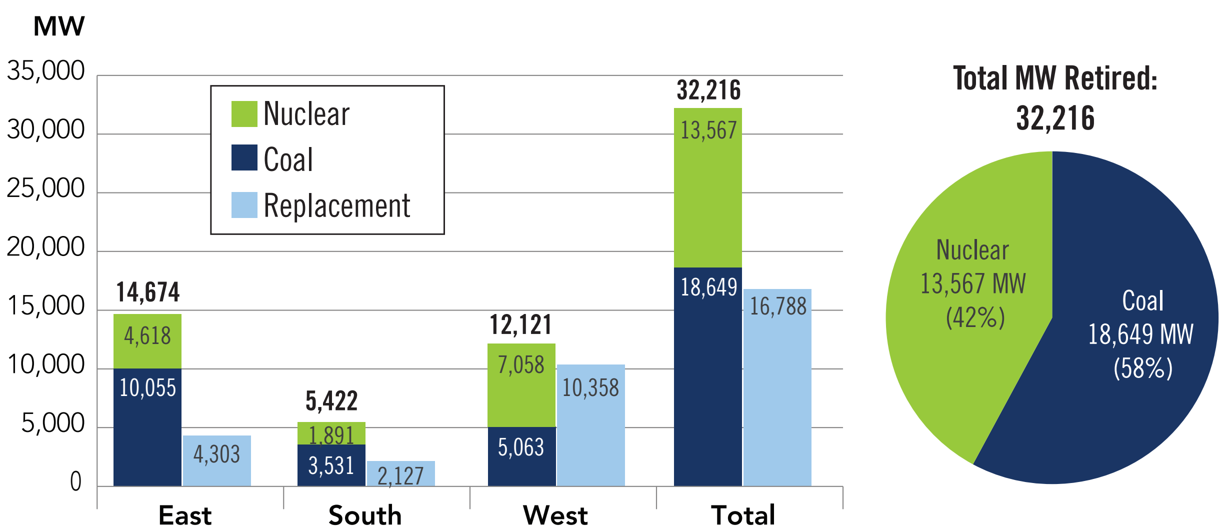


Table 2: Escalated 1 Retirements Portfolio: Installed Capacity by Resource Type

Resource Type	ICAP MW
Biomass	2,208
Coal	28,643
Hydro	2,941
Natural Gas and Other Gases	108,013
Nuclear	15,233
Petroleum	4,426
Pumped Storage	5,574
Solar	1,613
Wind	2,163
Demand Response	7,092
Total	**177,906**
2023/2024 Forecasted Summer Peak Load	153,632
Reserve Margin	**15.8%**

Escalated 2 Retirements Portfolio

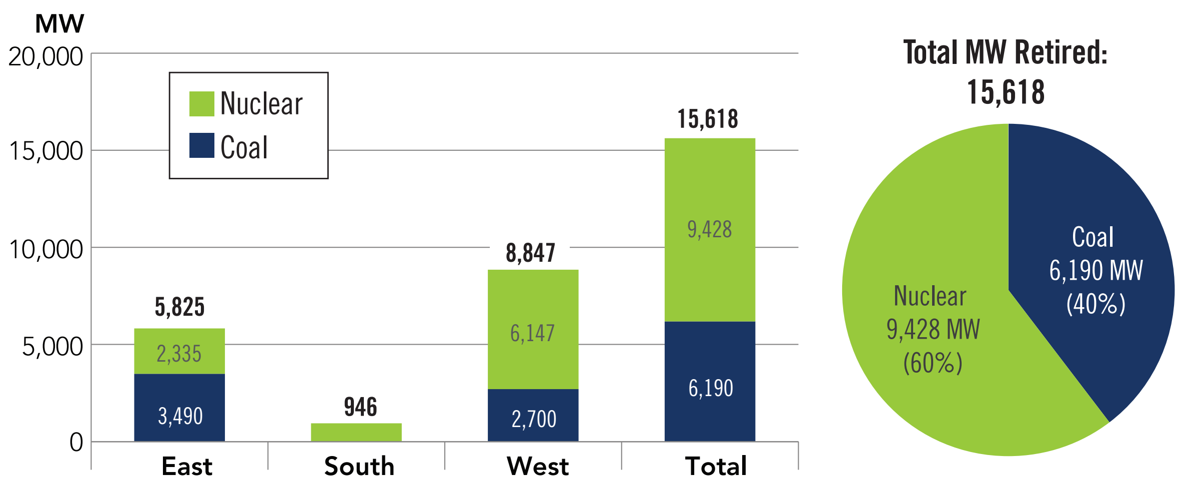
The escalated 2 retirements portfolio maintains the 15.8 percent IRM reliability requirement but only accounts for the retirement of the least profitable units down to the 15.8 percent IRM and does not include any replacements. As resources retire, energy and capacity prices can increase, which can influence the retirement decisions of other units. Escalated 2 was developed to account for this potential outcome by only retiring a megawatt value to the 15.8 percent IRM. Escalated 2 includes the retirement of 18 coal and nuclear resources, resulting in a total of 15,618 MW of retirements.

Figure 8 shows the retirements for escalated 2 by area. **Table 3** shows the megawatts of ICAP by resource type included in escalated 2.

Table 3: Escalated 2 Retirements Portfolio: Installed Capacity by Resource Type

Resource Type	ICAP MW
Biomass	2,208
Coal	41,051
Hydro	2,941
Natural Gas and Other Gases	91,896
Nuclear	19,672
Petroleum	4,389
Pumped Storage	5,574
Solar	1,153
Wind	1,945
Demand Response	7,092
Total	**177,921**
2023/2024 Forecasted Summer Peak Load	153,632
Reserve Margin	**15.8%**

Figure 8: Escalated 2: Retirements and Replacements by Location



Outreach and Collaboration on Retirement Assumptions

PJM collaborated with the IMM and the Nuclear Energy Institute (NEI) to conduct this portion of the study. PJM also reviewed the American Coalition for Clean Coal Electricity (ACCCE) retirement analysis. **Table 4** provides a comparison.

Table 4: Summary of PJM, IMM, NEI and ACCCE Retirement Analysis Results

Retirements Portfolio	Nuclear		Coal		Other		Total	
	MW	Units	MW	Units	MW	Units	MW	Units
Announced Retirements*	4,757	5	7,484	27	411	6	12,652	38
Announced + Escalated 1 Retirements*	18,324	18	26,134	69	411	6	44,868	93
Announced + Escalated 2 Retirements*	14185	14	13,674	36	411	6	28,270	56
IMM Retirements*†	7,058	5	21,039	46	2,688	93	30,785	118
NEI Retirements (accounts for nuclear units only)	11,283	11	N/A	N/A	N/A	N/A	N/A	N/A
ACCCE Retirements (accounts for coal units only)	N/A	N/A	0 to 30,000	N/A	N/A	N/A	N/A	N/A

*PJM and IMM results differ due to differences in tools and techniques used for the analysis; underlying economic profit and loss premise aligns between these analyses.

†2017 State of the Market Report for PJM, Section 7, Table 7-36 http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2017/2017-som-pjm-sec7.pdf

Non-Firm Natural Gas Availability

Natural gas is shipped on pipelines based on contracts for transportation. Firm transportation contracts guarantee delivery under all circumstances, except *force majeure*. Non-firm transportation contracts (also called interruptible) are lower priority, depend on the availability of pipeline capacity, and may be interrupted should conditions warrant. For more information, see the Technical Appendix.

ASSUMPTIONS

Non-Firm Gas Availability

Typical & Extreme:
62.5% and 0%

Firm Service

Generators obtain firm service by reserving and paying for firm deliveries to fixed delivery points or obtain firm transportation closer to real time and often bundled with the commodity through the secondary market. The primary firm market is transparent and observable while firm transportation purchases through the secondary market are not.

Nevertheless, PJM has seen extensive use of the secondary market for acquiring both commodity and firm transportation even during highly stressed conditions. Accordingly, PJM ran scenarios both assuming historic results of obtaining firm transportation service through the secondary market and other scenarios assuming zero availability of firm on the secondary market.

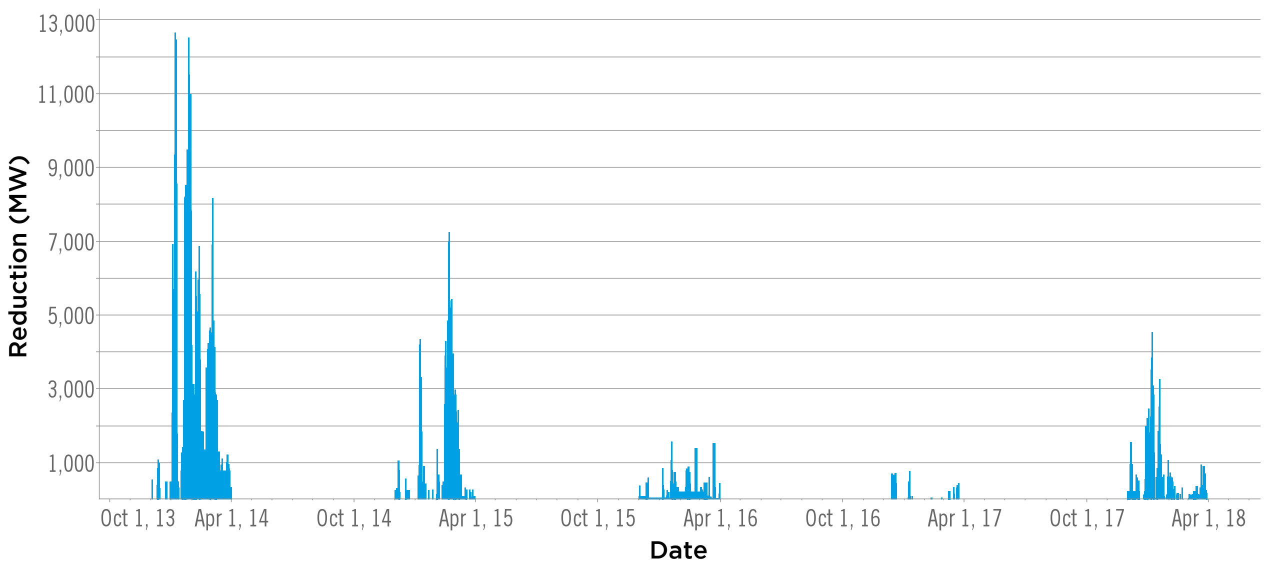
Non-Firm Gas Generation in PJM

Through annual fuel surveys and outreach to generation owners, PJM identified a segment of natural gas generation assets that are solely reliant on natural gas for operation and indicated that they do not have a firm natural gas transportation contract. Based on PJM's most recent generation owner survey and outreach information, non-firm gas-only generation accounts for approximately 16,000 MW of PJM resources. Most of the year, many of these generators are able to secure gas supply from the secondary market[25] by working with various suppliers, even during times of high system demand. PJM has also seen availability of firm gas transportation services through the secondary market even during conditions of extreme cold and has recognized that in some, but not all, of its scenarios.

As part of the fuel security study, PJM performed an analysis of NERC Generating Availability Data System (GADS) Lack of Fuel Cause Code data[26] over the last five years to analyze historic outage rates resulting from an interruption or curtailment of non-firm gas. The highest total outage rates that could be attributed to the Lack of Fuel Cause Code[27] ranged from less than 1,000 MW (2016/2017 winter) to more than 12,000 MW (2013/2014 winter).

PJM performed a sensitivity analysis of the secondary market's ability to "firm up" non-firm gas in order to better understand the impact of the potential unavailability of natural gas supply. PJM analyzed 0 MW (0 percent) and 10,000 MW (62.5 percent) of available non-firm natural gas-only generators during the 14-day cold weather event. PJM used both NERC GADS and PJM eDART lack of fuel outage data to determine the sensitivity thresholds.

Figure 9: NERC GADS Non-Firm Gas Outage Data



25 The secondary market essentially consists of a large pool of natural gas marketers and suppliers that have a portfolio of various natural gas transportation and supply assets that they can offer to the market. Generators will often rely on these marketers to deliver gas to them, most often on a firm basis.

26 https://www.nerc.com/pa/RAPA/gads/Pages/default.aspx.

27 https://www.nerc.com/pa/RAPA/gads/Pages/Data%20Reporting%20Instructions.aspx.

Gas Pipeline Disruptions

A key objective of this study was to understand the impact of physical gas pipeline disruptions. Disruptions were modeled for each of the scenarios. PJM simulated partial and full disruption of supply in a segment of four different natural-gas pipelines. This resulted in reduced capacity on the constrained portion of the interstate pipeline in the PJM region, thereby impacting the ability to deliver natural gas to generating units downstream of the disruption.

The disruption scenarios were developed based on the limited history of events on the pipeline system and through consultation with the Natural Gas Council[28] and major interstate pipelines. Natural gas fuel delivery characteristics such as limited availability of interruptible capacity during the cold weather period were also taken into consideration.

> **ASSUMPTIONS**
>
> **Disruptions**
>
> **Medium impact:**
> Days 1-5: 50-100% disruption; days 6-14: 100% output (0% derate)
>
> **High impact:**
> Days 1-5: 100% disruption; days 6-14: 20% derate

About Physical Pipeline Disruptions

While the physical severing of an interstate pipeline is a very uncommon event, it can occur. Typically, it would be the result of pipeline corrosion or, even more commonly, third-party damage to a particular pipeline segment, called a "line hit." Third-party line hits occur when another party, such as a construction crew, is excavating near an existing underground pipeline and accidentally hits or digs up the pipe, causing a rupture and potentially an explosion. Both types of disruptions have occurred in the PJM footprint over the last two years.

As in both of the incidents that occurred in PJM, the way a pipeline disruption is handled and resolved is dictated by how the disruption happens and the time of year. When the cause is identified immediately, such as in a third-party line hit, the repair and return to full capacity typically occurs within five days. If the cause of the disruption is not easily identifiable (as in a corrosion-induced failure), the problem may be more systemic and require a longer outage and potential derating of the pipeline capacity in order to perform necessary inspections.

Pipeline Network in PJM

Pipelines are constructed to meet the volume and pressure of the natural gas to be transported, which determines the size (diameter and thickness) of the pipeline as well as the compression requirements. The natural gas pipeline network across PJM consists of thousands of miles of large-diameter pipelines, with the physical commodity being moved through the pipes via pressure from hundreds of compressor stations located at various points along the lengths of each of the pipelines. The majority of interstate pipeline companies interconnect with neighboring pipelines, which provides additional delivery flexibility in many portions of the network.

28 The Natural Gas Council includes five organizations: American Gas Association, American Petroleum Institute, Independent Petroleum Association of America, Interstate Natural Gas Association of America, and The Natural Gas Supply Association.

Pipeline Disruption Impacts on Generation

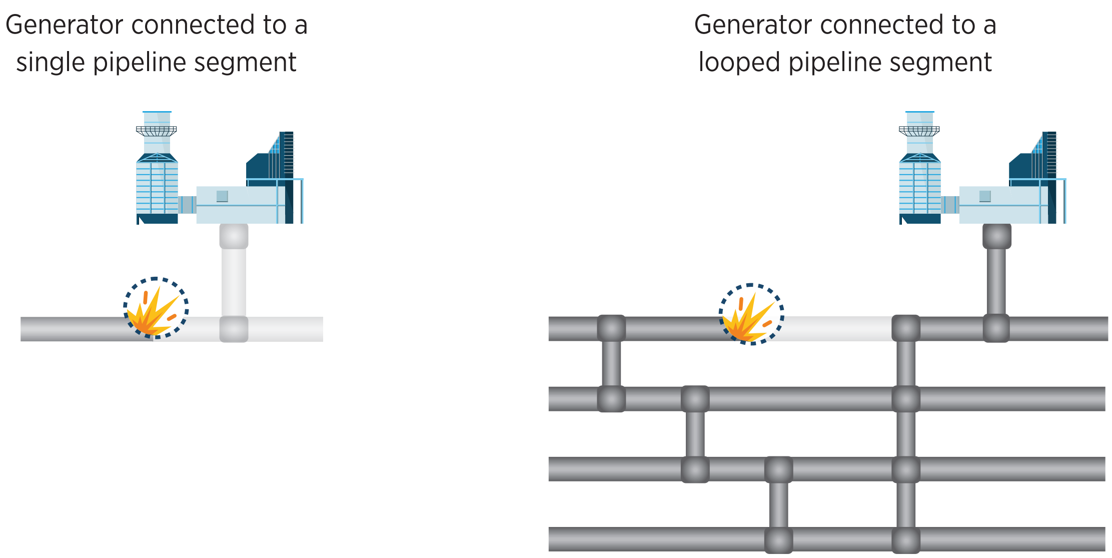
From PJM's perspective, the most important information when a pipeline disruption occurs is the impact on gas-fired generators downstream of the incident. This crucial information includes how long the downstream units can run before losing supply pressure, what the area of impact is, how quickly the pipeline can be replaced and how much fuel can be re-routed to supply the impacted generators from alternate sources.

Looped and Single-Feed Pipelines

Many of the interstate pipeline companies have continued to add additional capacity to the network by adding looping facilities. Looped pipeline is, in essence, a second (and in some cases a third and fourth) pipeline alongside the originally built pipe. This method of adding additional paths for gas to flow along the pipeline right-of-way creates greater reliability and operational flexibility. If one pipe should fail, gas can still flow along the other looped segments of pipeline.

Although pipeline looping is increasingly common, there are a number of generators in the interstate network that are reliant on a single segment of pipeline. Because of a lack of looping, the reliance on a single feed provides potentially greater vulnerability if a disruption event were to occur within this single pipeline segment. See **Figure 10.**

Figure 10: Single Pipeline vs. Looped Pipeline



Disruption Assumptions

When forming the disruption scenarios for the fuel security study, each of these factors was weighed and incorporated into the analysis and assumptions. PJM modeled disruptions on both looped and single-feed pipelines. The methodology for layering in the disruption scenarios was based on observed conditions during recent events as well as consultation with several interstate pipeline companies serving the PJM region.

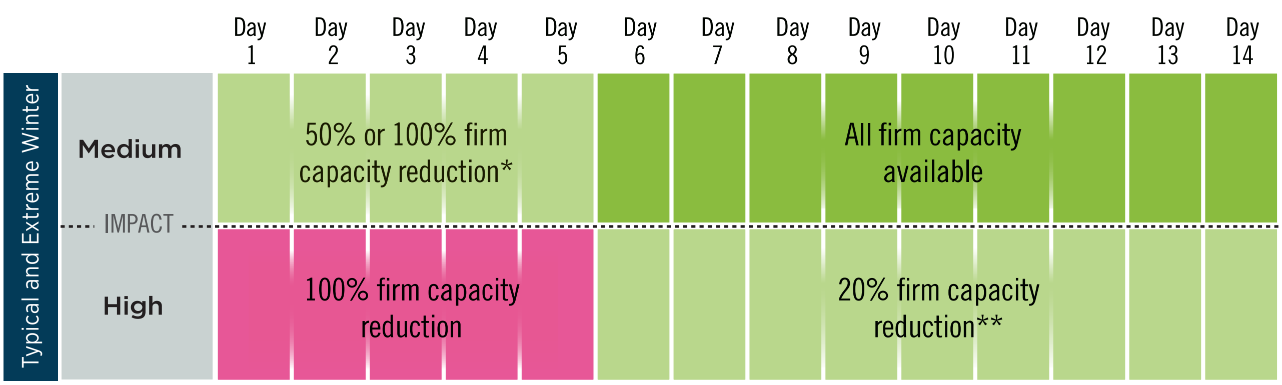
For purposes of the disruption analysis, all generating units with firm capacity were assumed to be available under all temperature conditions and only impacted within a pipeline disruption scenario. All dual-fuel units were assumed to be operating on backup fuel during a pipeline disruption.

As shown in **Figure 11**, two variations of impacts were studied — a medium-impact and a high-impact event. The duration assumption is that under both high- and medium-impact events, the pipeline can be physically replaced within five days.

Medium-Impact Event

A medium-impact event was considered either a partial or full disruption of supply in a segment of pipeline, depending on the design of that pipeline (looped or single). An example of a partial-impact event would be the loss of a single pipeline in a right-of-way where more than one line is present, thus firm gas can still flow, but at reduced levels (50 percent). If there is only a single pipeline in the impact zone, no gas (firm or non-firm) would be able to flow, thus capacity would be reduced by 100 percent. In the medium-impact scenario, the pipeline returns to full capacity on day 6 of the 14-day study period.

Figure 11: Duration of Pipeline Disruption



* Firm capacity reduction level depends on pipeline design redundancy.

** 20% of capacity remains unavailable due to assumed PHMSA (Pipeline Hazardous Materials Safety Administration) requirements.

High-Impact Event

A high-impact event is defined as a full disruption of supply in a segment of pipeline. An example would be the loss of either a single segment of pipe or multiple pipelines (looped) in a right-of-way. In that case, no gas (firm or non-firm) would be able to flow, thus any generation downstream of the event would lose all supply from that pipeline.

In the high-impact scenario, the pipeline is out completely for the first five days of the 14-day cold weather period, and returns to service on day 6, but the capacity is limited to 80 percent of pre-incident levels. This 20 percent reduction in firm capacity for days 6 through 14 is intended to model a potential mandatory reduction from the Pipeline and Hazardous Materials Safety Administration.[29]

The Technical Appendix contains additional details summarizing PJM natural gas generator statistics as well as details on interstate gas pipeline contingency determination.

29 49 CFR 195.452(i), https://www.gpo.gov/fdsys/pkg/CFR-2010-title49-vol3/pdf/CFR-2010-title49-vol3-sec195-452.pdf.

Fuel-Oil Replenishment

Three generalizing assumptions were made for fuel-oil replenishment in the study: initial oil inventory level, oil refueling constraints and oil refueling rates. These assumptions are based on data provided by generation owners through surveys and targeted discussions with generation owners about specific details of oil replenishment. Based on PJM outreach, the primary constraint around oil replenishment is not the actual supply of oil but transportation of oil from the supply terminals to generators. As such, the study simulations restrict oil solely due to transportation, not considering the availability of oil supply.

Initial Oil Inventory Levels

Initial oil inventory levels were based on a combination of factors. Since PJM did not have specific information about oil tank capacity for all sites, nor how those tanks are associated with various units, information was collected through surveys and direct communication with the unit owners. The information was then analyzed to determine tank size and which units are associated with which tanks. Each tank was then set at an initial inventory volume of 85 percent. This initial inventory is the median value provided by the power plants with oil storage capabilities.

ASSUMPTIONS

Initial Oil Inventory Level

Moderate and Limited: 85%

Oil Refueling (>100 MW site)

Moderate: 40 trucks daily refueling rate, capped at maximum tank capacity

Limited: 10 trucks daily refueling rate, capped at maximum tank capacity

Oil Refueling (<100 MW site)

Moderate: 10 trucks daily refueling rate, capped at maximum tank capacity

Limited: 0 trucks daily refueling rate, capped at maximum tank capacity

Oil Replenishment Rates

Oil replenishment rates are unique to each site and dependent on a large number of individual factors. PJM does not have access to all relevant information for each site, so a sensitivity range was used based on the size of the units supplied by each oil tank.

Generators and oil suppliers most frequently speak of oil volumes in terms of the trucks that are used for oil deliveries. The most common volume of truck, used widely across the industry and confirmed by PJM's outreach to multiple generation owners, is a 7,500 gallon truck. This is what PJM used in its study to model inventory deliveries for oil. While it depends on the specific heat content of the oil delivered and the heat rate of the unit consuming that oil, one truck delivery of 7,500 gallons of oil translates roughly to a range of 115 MWh to 150 MWh of electric generation.

Per generator outreach, smaller sites (less than 100 MW) tend to have restricted truck receiving and offloading capabilities. Larger sites (more than 100 MW) are much more likely to have invested in additional oil delivery infrastructure that allows them to offload trucks at a faster rate or even offload multiple trucks simultaneously.

Two replenishment rates were applied, moderate and limited. Under moderate replenishment, larger sites were refueled at a rate of 40 trucks per day while smaller sites were refueled at a rate of 10 trucks per day. Under limited replenishment, larger sites were refueled at a rate of 10 trucks per day while smaller sites did not receive any oil deliveries at all. Refueling was applied every 12 hours in the model, with assumed daily mmBtu divided up accordingly.

The market for delivery of oil is neither regulated nor transparent. As a result, PJM used the assumptions outlined above in performing this part of its analysis. This a difficult area to analyze based on verifiable data because of the lack of transparency of the specific arrangements generators have with oil delivery companies and the "just in time" nature of some of the procurements during extreme cold weather conditions when the oil delivery system is stressed with competing demands from customers for heating oil.

Forced Outages

Some generators are not available for PJM dispatch during peak periods, mainly due to generator forced outages.[30] To account for generator forced outages, PJM used two separate models as part of this study: a historical five-year average model and an extreme winter weather regression model. These models are only applied to thermal generators, not renewable resources.

To model renewable resources, PJM used hourly unit-specific output profiles from the 2017/2018 winter. PJM also disregarded fuel supply-related forced outages for gas and oil-fired resources,[31] since gas and oil fuel-unavailability outage sensitivities are explicitly modeled as part of the analysis.

Given the typical weather conditions in its 50/50 winter scenarios, PJM applied a historical five-year average forced outage rate. In order to recognize the impact of extreme weather on generator performance in the 95/5 winter scenarios, PJM calculated forced outage rates using a random effects panel regression model (see Technical Appendix for details).

ASSUMPTIONS

Expected Forced Outages

Five-Year Average: Historic five-year average, discounting gas and oil fuel supply outages

Modeled: Regression model of expected outage rates, discounting gas and oil fuel supply outages

Transmission Modeling

The approach to modeling transmission constraints varied depending on the retirement portfolio.

Constraints for Announced Retirements Portfolios

As noted in the "Retirement Scenarios" section, announced retirements as of Oct. 1, 2018, and the associated transmission upgrades, are included in the announced retirements portfolio. As a result, a comprehensive set of transmission constraints (230 kV and above) were modeled for the study scenarios in the announced retirements portfolio.

Constraints for Escalated Retirements Portfolios

Both escalated retirements portfolios included a significant amount of additional coal and nuclear retirements. To accommodate such a large number of retirements, a significant amount of transmission changes would likely be necessary. However, determining the exact number and location of the reinforcements and the potential make-up of the transmission system is a significant and time-consuming task and therefore deemed out-of-scope for this study.

The PJM Regional Transmission Expansion Plan (RTEP) is required to ensure adequate transmission reinforcements to at least meet a zone's Capacity Emergency Transfer Objective (CETO).

ASSUMPTIONS

Transmission Modeling

Announced Retirements: Transmission constraints that are greater than or equal to 230 kV

Escalated Retirements: Individual transmission constraints were not modeled; transfers into eastern PJM were limited based on CETO with a 15% transfer margin adder

30 PJM Pre-Scheduling Operations Manual 10, Section 2: Generator Outage Reporting. https://www.pjm.com/-/media/documents/manuals/m10.ashx.

31 In this case, "fuel supply" refers to the NERC Fuel Supply Cause Code.

To recognize the impact of transmission constraints in the simulations, PJM used a zonal transfer limit approach based on a transmission zone's CETO to ensure that there is no load shed beyond the 1 day in 25 years loss of load expectation RTEP criterion. Given the historical west-to-east transfer limitations in the PJM system as well as the natural gas and oil concentration in the eastern portion of PJM's system, these transfer limits were enforced only in the eastern PJM zones.

The assumption underlying this approach is that PJM would expand its transmission system to transfer power to meet a zone's CETO plus a 15 percent additional transfer capability to account for the nature of transmission reinforcement, which tends to exceed the necessary requirements. Details about PJM's CETO procedure are included in PJM Manual 20, PJM Resource Adequacy Analysis.[32]

Interchange

PJM assumed interchange transaction quantities reflecting the economical interaction between PJM and neighboring systems consistent with real-time operations. A historical analysis was performed to determine an upper bound for imports into PJM and exports out of PJM using the 2017/2018 cold snap data.

PJM observed a maximum scheduled import of approximately 3,300 MW and exports of approximately 5,700 MW. As part of the analysis, PJM restricted the maximum economical import and export amounts to 2,700 MW, out of which 1,500 MW of imports were modeled to recognize external capacity that is pseudo-tied into PJM. Limiting the imports and exports by design ensured that the analysis was an evaluation of the impact of fuel security on PJM resource adequacy.

ASSUMPTIONS

Scheduled Interchange

Total interchange with neighboring systems limited to +/-2,700 MW

Demand Response

The quantity of DR PJM modeled for the study is based on results from the 2021/2022 Base Residual Auction (Auction). Results from the Auction are summarized in **Table 5**. All of the cleared DR meets Capacity Performance requirements and is therefore available in the winter.

The Auction cleared amount was then reduced by the "replacement" rate of 32 percent. The replacement rate is the proportion of DR cleared in the Auction that is replaced through incremental auctions by other resources prior to the Delivery Year. The latest three-year average replacement rate is 32 percent.

ASSUMPTIONS

Demand Response

7,092 MW modeled locationally based on MW cleared by zone and nodal modeling

Table 5: 2021/2022 PJM Capacity Market Auction Results

Capacity Market Auction Cleared Demand Response	Installed Capacity†
Annual	9,795
Post-Replacement	6,660
Fixed Resource Requirement (FRR) Alternative	432
Total	**7,092**

†When referring to DR, the amount of load to be curtailed.

32 https://www.pjm.com/~/media/documents/manuals/m20.ashx.

The quantity of DR committed through the Fixed Resource Requirement Alternative was then added to the Auction results to yield the total DR amount of 7,092 MW. In the study simulations, DR was modeled as being activated as a pre-emergency action.

Renewable Generation Modeling

PJM used historical hourly data from winter 2017/2018 to develop profiles for existing wind, solar, pumped storage and run-of-river hydro generation. Generators in the interconnection queue without historical profiles were given zonal-average profiles by resource type, scaled to the proposed resource-specific installed capacity.

ASSUMPTIONS

Renewable Modeling

2017/2018 cold snap profile

Emissions Limitations

PJM did not explicitly model emissions limitations as part of the fuel security analysis, as PJM does not typically encounter emissions limitations as a generator constraint within operations, particularly during the winter season. PJM has processes and procedures to identify if a unit has limitations other than fuel, such as environmental limitations, in order conserve run hours during emergency conditions.[33] PJM would use the maximum emergency dispatch operating procedure, allowing PJM dispatchers to preserve runtime that would otherwise be consumed through normal economic dispatch by manually dispatching environmentally limited resources to optimize the amount of load served. If conserving run hours is insufficient to mitigate the emergency, PJM has defined procedures to work with asset owners to request temporary waivers from regulatory authorities[34] in order to maintain reliable system operations.

33 PJM Manual 13: Emergency Operations 6.4 Fuel Limitation Reporting https://www.pjm.com/-/media/documents/manuals/m13.ashx.

34 PJM Manual 13: Emergency Operations Attachment M: Procedure for Obtaining a Temporary Environmental Variance https://www.pjm.com/-/media/documents/manuals/m13.ashx.

Distributed Energy Resources and Energy Efficiency

The impacts of distributed energy resources (DER) and energy efficiency are recognized in the loads used in both the typical and extreme winter load. The PJM load forecast model explicitly recognizes existing behind-the-meter solar generation and expected additions. Non-solar DER is recognized in the load forecast to the extent that it has operated in the past and reduced the historical loads that are inputs to the forecast model. In addition, the load forecast model recognizes expected energy efficiency trends.

ASSUMPTIONS

Distributed Energy Resources

Impacts of DER are explicitly accounted for in the load forecast

Energy Efficiency

Energy efficiency is explicitly accounted for in the load forecast

Transmission Outages

Transmission outages were not considered as part of the fuel security study as there were no applicable long-term outages in the 2023/2024 time frame. In addition, significant longer-duration planned transmission outages are generally not scheduled during the winter, unless necessitated by an identified reliability issue.

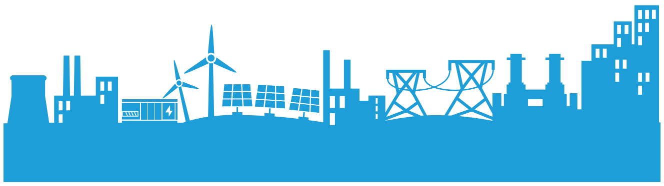
Fuel Prices

Fuel prices can fluctuate daily during cold weather conditions. In order to calculate such price fluctuations for the study horizon, PJM gathered forward natural gas prices to match the study period. Historic fuel price volatility trends were captured using representative typical and extreme winter load conditions. Volatility trends were derived by computing the commodity price differences between current day (Day_N) and next day (Day_{N+1}) for the duration of the trend. Typical and extreme weather volatility trends were then applied to monthly futures prices to derive daily 2023/24 fuel prices. (See the Technical Appendix for an example.)

ASSUMPTIONS

Fuel Prices

2023/2024 futures prices adjusted by day-to-day fluctuations in price (volatility)



Analysis Results

Evaluating System Performance in the Scenarios

PJM analyzed 324 scenarios, each with different combinations of assumptions and sensitivities as described in the "Assumptions" section. In order to evaluate system performance in each scenario, PJM examined the level of emergency procedures triggered over the 14-day period studied in each hourly simulation of security constrained unit commitment and economic dispatch. Each emergency procedure, in order of increasing severity, is described in **Figure 12**.

Figure 12: Emergency Procedures

Normal Operations	**No Emergency Procedures** Normal economic dispatch
Demand Response Deployed	**Pre-Emergency Action** Demand response deployment
Reserve Shortage	**Emergency Warning** An operational reserve shortage is triggered when 10-minute Synchronized Reserves are less than the largest generator in PJM. Depending on system conditions, a reserve shortage will trigger additional emergency procedures such as voltage reduction warnings and manual load shed warnings.
Voltage Reduction	**Emergency Action** Voltage reduction action enables load reductions by reducing voltages at the distribution level. PJM estimates a 1-2% load reduction resulting from a 5% load reduction in transmission zones capable of performing a voltage reduction.
Load Shed	**Emergency Action** Manual load shed action enables zonal or system-wide load shed. This is the last step of all emergency procedure actions.

An overview of results is provided in the following sections. The Technical Appendix contains more detailed analysis of seven scenarios, using a common overview template to illustrate the differences in operational impact across scenarios. The seven examples represent a cross-section of results that were presented as part of the stakeholder process.

Reading the Analysis Results

The results of the analysis are summarized in **Figure 13**, **Figure 14** and **Figure 15**. Each box represents a single scenario, which is color-coded by the most severe emergency procedure observed. Boxes include all operational procedures up to and including the one indicated by color. For instance, a yellow-colored box would indicate an operational reserve shortage, with some level of demand response already having been deployed; voltage reduction and manual load shed would not have occurred.

Column and row labels contained within the summary figures indicate the following:

- **Winter Load:** Typical (134,976 MW peak) or extreme (147,721 MW peak)
- **Non-Firm Gas Availability:** 62.5 percent or 0 percent available
- **Dispatch:** Economic dispatch or a maximum emergency dispatch
- **Moderate/Limited Refueling:** Amount of oil refueling
- **Single 1/Single 2/Looped 1/Looped 2:** Names assigned to simulated pipeline disruptions. Each pipeline disruption was simulated independently – no scenario introduced multiple pipeline disruptions
- **Medium/High:** Severity of simulated pipeline disruptions

Additional details of the assumptions are provided within the "Assumptions" section of this paper and in the Technical Appendix.

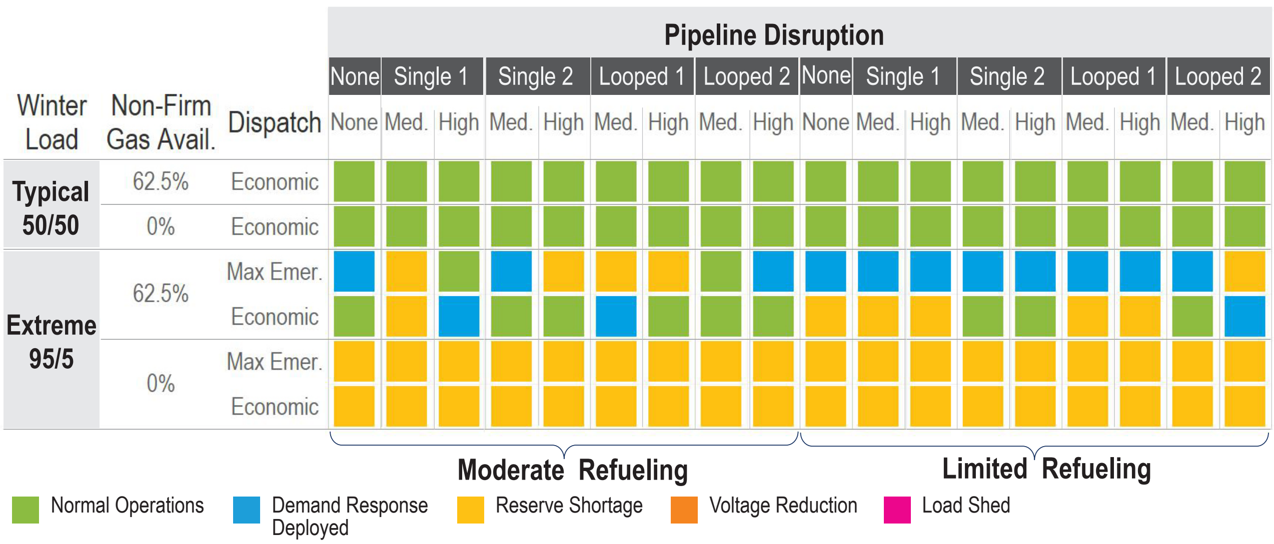
Announced Retirements, Typical and Extreme Winter Load

The results of scenarios for the announced retirements portfolio, which accounts for announced retirements as of Oct. 1, 2018,[35] and new generation slated to be in operation by 2023, are shown in **Figure 13**. No emergency procedure actions were triggered on the system in any of the 36 typical winter load scenarios, even when simulating high-impact pipeline disruptions with limited oil refueling and no non-firm gas available.

Of the 72 extreme winter load scenarios, normal operations were observed in 11 (15 percent), demand response was deployed in 14 scenarios (20 percent), and a combination of demand response and operational reserve shortages were triggered in 47 scenarios (65 percent). PJM noted that in extreme scenarios, demand response is called on more often, for longer durations and is assumed to have responded. Though these operational procedures were triggered, the grid would remain reliable and able to continue to deliver electricity without the need for voltage reduction or manual load shed actions.

Even under the most severe announced retirement scenarios, in which significant amounts of generation would be unavailable due to fuel delivery issues, the PJM system remained reliable and able to operate through disruptions and reliably serve load, which demonstrates PJM's finding that there is no imminent threat to reliability.

Figure 13: Results: Announced Retirements, Typical and Extreme Winter Load



Escalated Retirements, Typical and Extreme Winter Load

In order to simulate additional stress on the system, PJM analyzed two separate portfolios in which generation retirements were escalated beyond what is announced for 2023 – termed escalated 1 and escalated 2. As noted in the "Assumptions" section, both portfolios meet PJM's installed reserve margin reliability requirement.[36] Escalated 1 modeled generation retirements of 32,216 MW by 2023, with 16,788 MW of capacity added to meet the installed reserve margin requirement of 15.8 percent. Recognizing that as units retire, market signals would slow the rate of further retirements, escalated 2 modeled generation retirements of 15,618 MW by 2023 with no capacity replacement. Additional details are provided in the "Assumptions" section and the Technical Appendix.

35 Retirements announced by Oct. 1, 2018.

36 In the escalated 1 scenario, 16,788 MW of replacement resources were added to meet the 15.8 percent installed reserve margin reliability requirement. In the escalated 2 scenario, a level of retirements (15,618 MW) was assumed that resulted in meeting the 15.8 percent installed reserve margin reliability requirement and therefore no replacement resources were added.

The results of the 216 escalated retirement scenarios are summarized in **Figure 14**. When the escalated retirement portfolios are combined with typical winter load (72 scenarios), PJM's analysis does not indicate the need for emergency actions such as voltage reduction and manual load shed.

On the other hand, when the escalated retirement portfolios are combined with extreme winter load (144 scenarios), PJM's analysis indicates the system may be at risk for voltage reduction and manual load shed actions in addition to demand response deployment and reserve shortage. The numbers within the magenta boxes in **Figure 14** indicate the total hours of manual load shed action in each scenario. The numbers in the magenta boxes in **Figure 15** indicate the magnitude (in gigawatt-hours) of manual load shed action in each scenario.

- ***Of the 144 extreme winter load scenarios, 65 (45 percent) displayed demand response deployment and reserve shortage alone.***

The remaining scenarios showed the need for additional emergency actions indicating that the reliability of the system was at risk:

- ***Voltage reduction was the most severe action needed in 6 of the 144 extreme winter load scenarios (4 percent).***
- ***The most extreme of the emergency procedures, manual load shed, was observed in 73 of the 144 extreme winter load scenarios (51 percent).***

It should be noted that the load shed hours are generally locational in nature. The results, based on the specific scenarios modeled, indicate that some load shedding somewhere in the system would be needed under some extreme scenarios. This does not mean that there would be widespread outages across PJM. Moreover, with the variety of tools available to PJM and its members, the load shed would not necessarily affect a single area for the entire duration of the load shed but could potentially be rotated to minimize customer impact should an extreme scenario come to fruition.

Figure 14: Results: Escalated Retirements, Typical and Extreme Winter Load (with Hours of Load Shed)

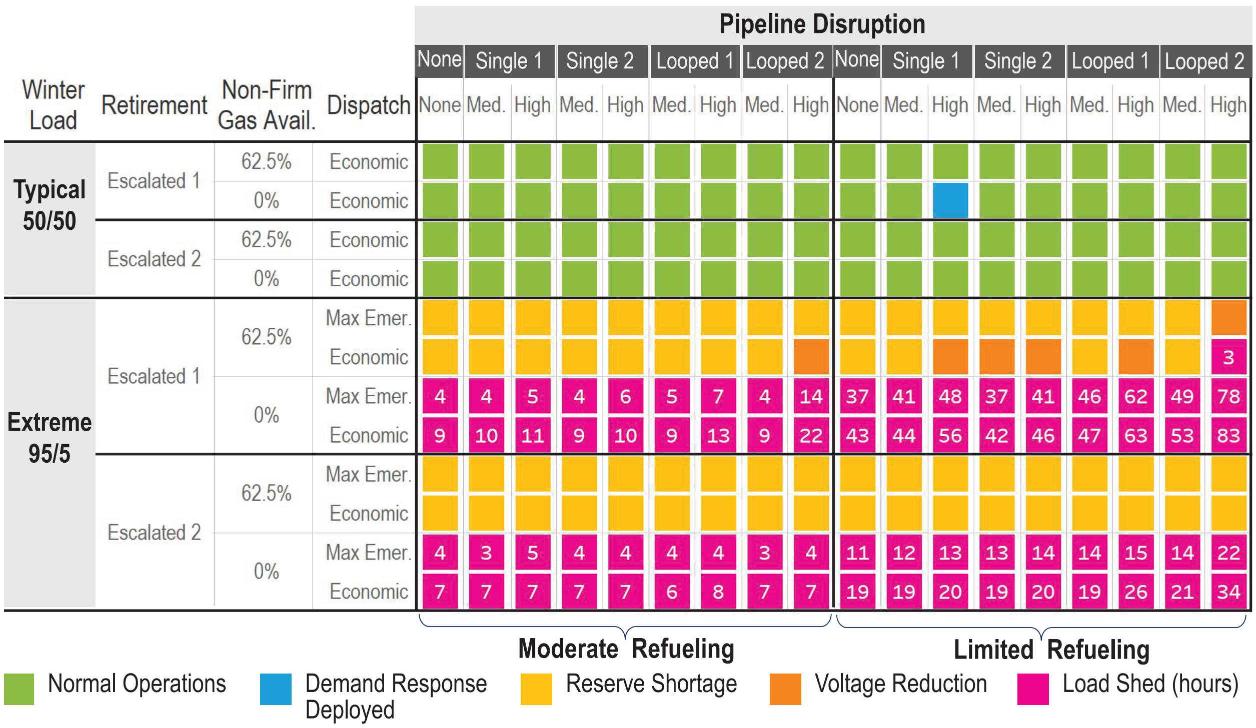
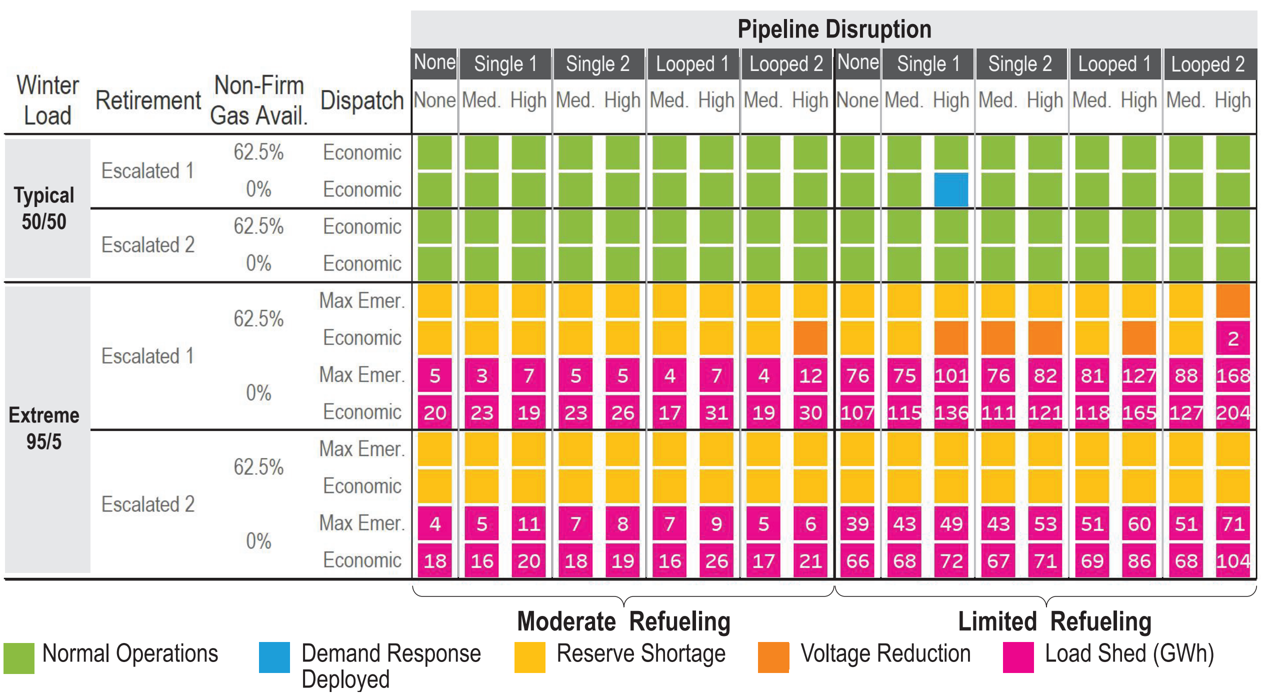


Figure 15: Results: Escalated Retirements, Typical and Extreme Winter Load (with GWh of Load Shed)



Locational and Area Observations

Figure 16 and **Figure 17** highlight locational impacts observed in the analysis results. Each pie chart corresponds to a single scenario with assumptions outlined within the rows and columns. In **Figure 16** the size of the pie chart corresponds to the total hours of manual load shed in each scenario, ranging from 3 hours to 83 hours. In **Figure 17** the size of the pie chart corresponds to the total gigawatt hours of manual load shed in each scenario, ranging from 2 GWh to 204 GWh.

For the purposes of this analysis, three PJM areas were defined as East, West and South (see **Figure 6**). Within each area, there are typically multiple transmission zones that represent individual utilities. In **Figure 16** and **Figure 17**, blue indicates the portion of load shed that was confined to specific locations (i.e., locational). Orange indicates the portion of load shed that occurred in multiple areas of PJM.

Figure 16: Escalated Retirement Scenarios – Volume (GWh) of Manual Load Shed: Locational and Multiple Area

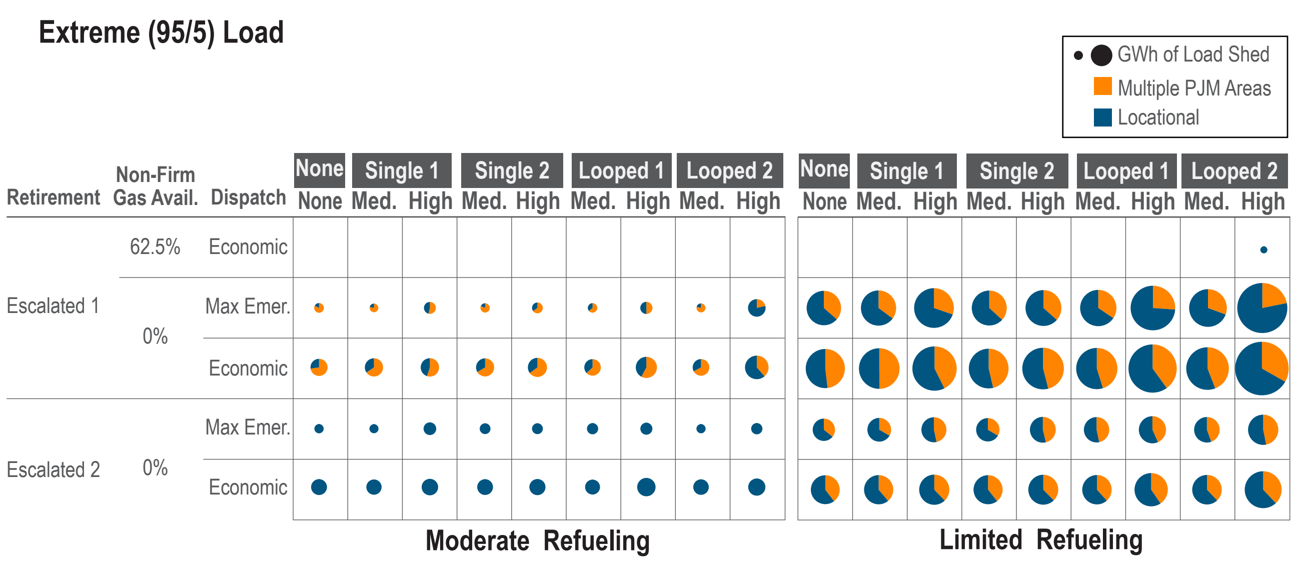
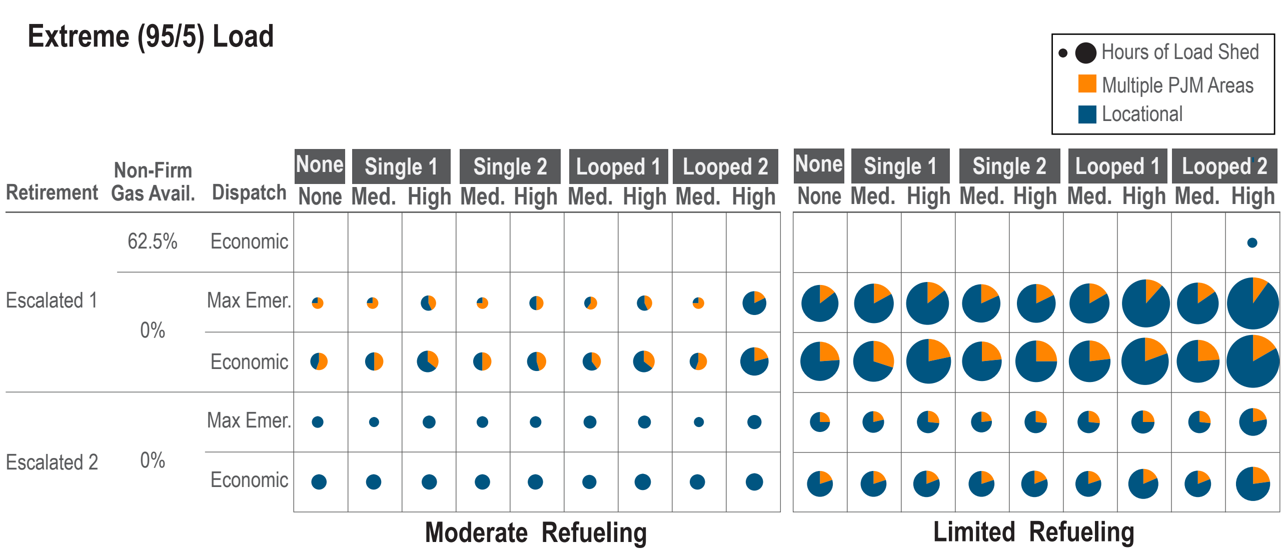


Figure 17: Escalated Retirement Scenarios – Hours of Manual Load Shed: Locational and Multiple Area



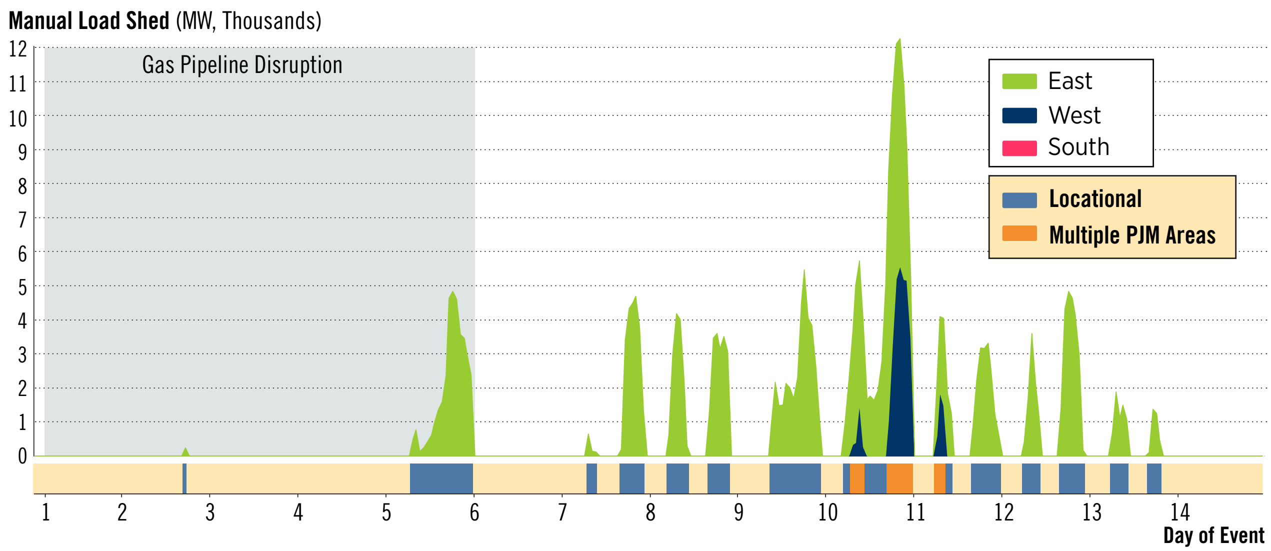
For the purposes of this study, PJM multiple-area load shed means that for a given hour in the simulation, manual load shed was observed in more than one area of PJM. Locational load shed means that, for a given hour in the simulation, manual load shed was only observed in one area of PJM. (See **Figure 6** for a map of PJM areas and transmission zones.)

In the majority of hours in which load shed was observed, the load shed occurred in specific locations as opposed to more than one PJM area. Across the escalated retirement simulations, the majority of load shed volume (in gigawatt hours) occurred during the hours of highest load across the 14 days.

As the severity of scenarios increased with changes to key input assumptions of refueling rate, level of non-firm gas and severity of pipeline disruptions, the volume of locational load shed increased and transitioned to multiple-area load shed as more sites ran out of on-site fuel. By looking at **Figure 16**, **Figure 17** and the details in **Figure 18**, the trend is reinforced, as load shedding transforms from locational to multiple-area based on changes in key input assumptions.

An example of the locational and multiple-area load shed trends observed is provided in **Figure 18**, which shows hourly load shed data for the most extreme load shed scenario of 204 GWh. The scenario assumptions are: extreme winter load, escalated 1 retirement portfolio, 0 percent non-firm gas availability, economic dispatch, limited refueling, and looped 2, high-impact pipeline disruption.

Figure 18: Hourly Load Shed for Most Extreme Load Shed Scenario



In this scenario, locational load shed in PJM East only is observed toward the end of the disruption period. As the duration of the cold weather event continues, with non-firm gas unavailable and units running out of on-site fuel, more locational load shed occurs. During day 10, the peak load of the 14 days, load shed volume also peaks and occurs in multiple areas of PJM. Further information pertaining to this scenario is included in the Technical Appendix.

Impacts of Key Input Assumptions on Results

The analysis results highlight the impact of certain input variables on the emergency procedures triggered. Elements such as availability of oil deliverability, availability of non-firm gas service, pipeline configuration and utilization of operational procedures become increasingly important as the system is exposed to more stresses.

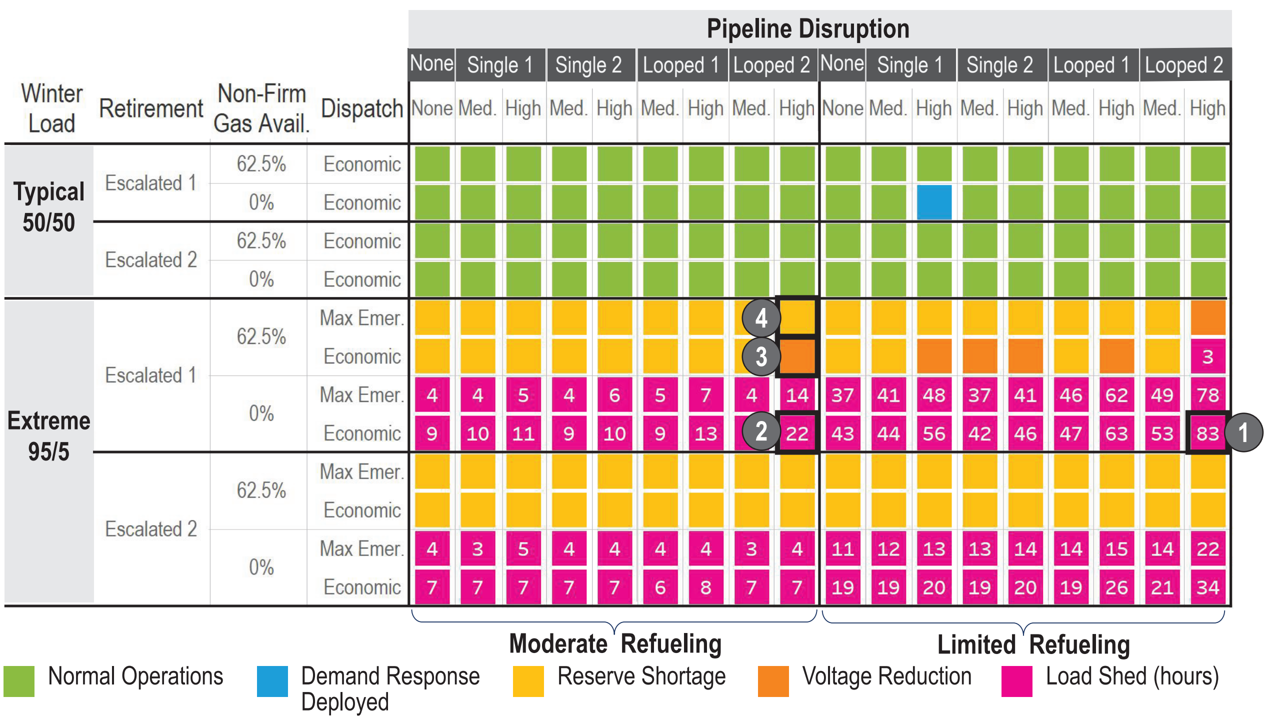
Figure 19 illustrates how the total hours of load shed can be reduced or eliminated as input variables change. For example, for the scenario with 83 hours of load shed (escalated 1, extreme winter load, looped 2, high-impact pipeline disruption, 0 non-firm gas available, economic dispatch, limited refueling) total load shed hours decrease from 83 hours to 22 hours when the refueling variable changes from limited to moderate (Step 1 to Step 2).

The 22 hours of load shed were eliminated and only voltage reduction was required as the non-firm gas variable changed from 0 MW to 10,000 MW (Step 2 to Step 3).

The need for voltage reduction was eliminated as Maximum Emergency Operating Procedures were used in lieu of Economic Dispatch, resulting in only a Reserve Shortage (Step 3 to Step 4).

Additional details regarding the impacts of key assumptions follow.

Figure 19: Illustration of Assumption Changes on Results

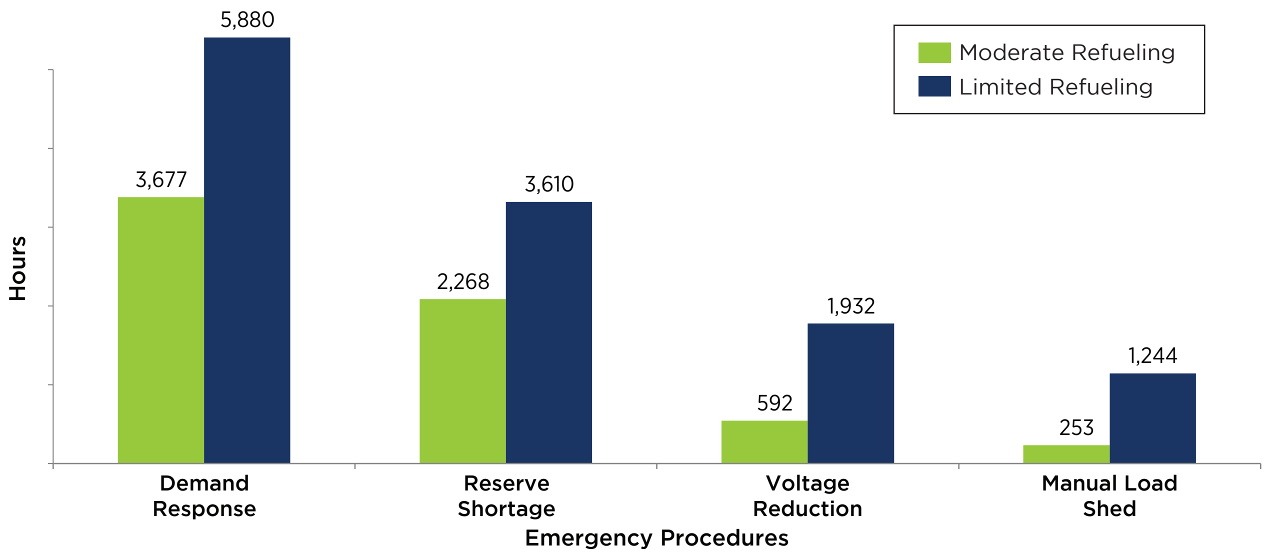


Oil Replenishment

Whether or not refueling logistics can support the increased demand for oil during an extreme winter event was a key question raised after the 2017/2018 cold snap. The impact of refueling was tested in the analysis by varying two levels of refueling – moderate and limited.[37] This proved to be one of the most important factors determining to what extent emergency procedures were triggered in each scenario.

In comparing scenarios that had the same input assumptions except for the level of oil replenishment, more emergency procedures were triggered in scenarios with limited refueling compared to moderate refueling. This was most evident in scenarios with other extreme input assumption sensitivities. **Figure 20** provides an aggregate comparison of total hours[38] of emergency procedures across all scenarios with moderate refueling versus all scenarios with limited refueling.

Figure 20: Impact of Refueling Assumptions on Emergency Procedures



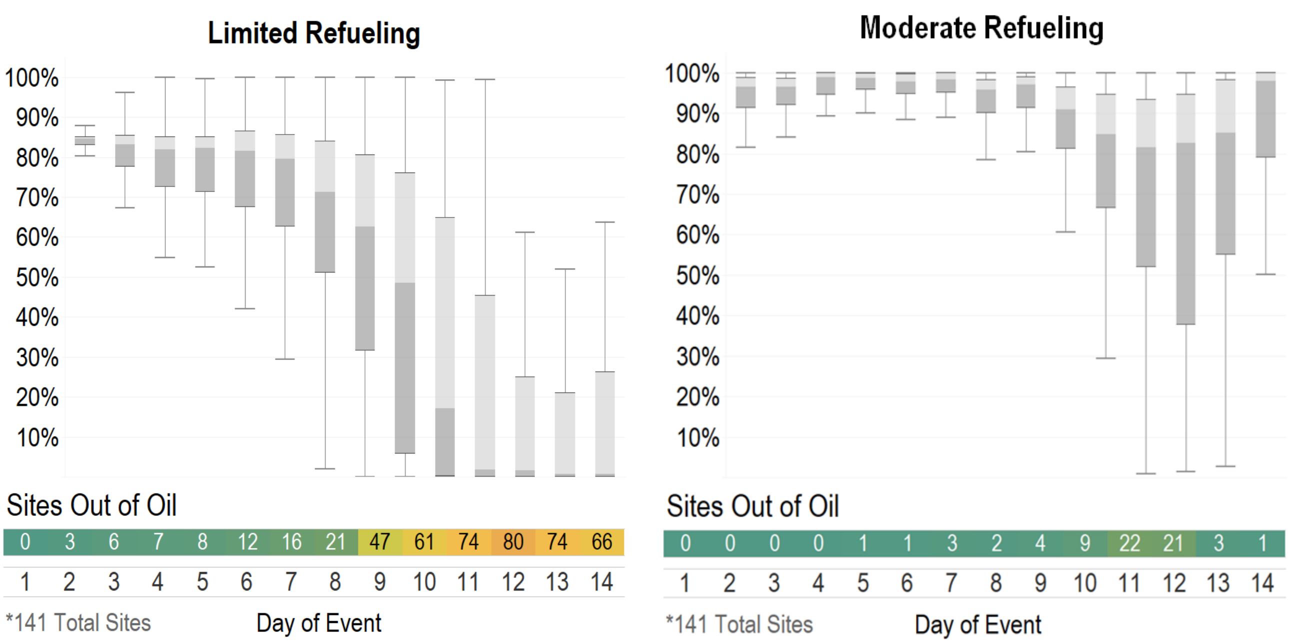
37 Refueling assumptions are described in detail in the "Assumptions" section.

38 Simulation hours for all 324 scenarios totaled 108,864.

Figure 21 provides a more detailed comparison of two scenarios with the same input assumptions except for the level of oil refueling. The box and whisker plots in **Figure 21** show site-specific[39] inventory levels (in percent of maximum on-site inventory) throughout the simulation, summarized by day.

The heat maps in **Figure 21** under the box and whisker plots indicate, by day, the number of sites where oil inventories were depleted throughout the simulation. The scenario with moderate refueling resulted in higher inventory levels and a smaller number of units running out of oil compared to the scenario with limited refueling. The overall impact of increased oil replenishment resulted in an additional 59 sites maintaining adequate inventories for operation on day 12 of the simulation.

Figure 21: Impact of Oil Refueling Assumptions

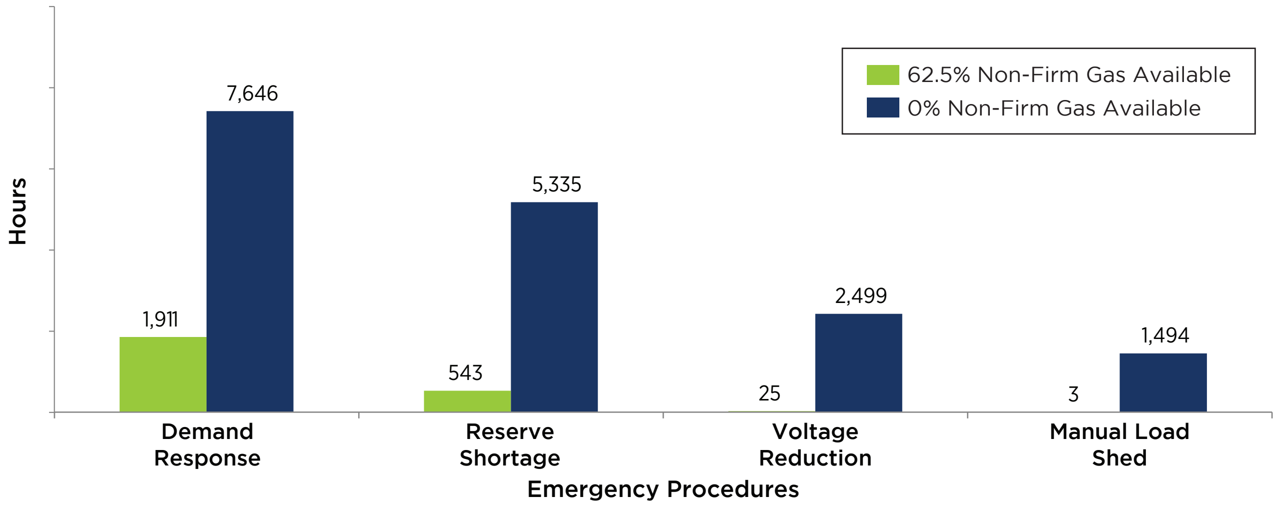


39 "Site-specific" refers to on-site fuel inventories for individual generating units or that are shared by a group of generating units.

Non-Firm Gas Availability

Another extremely important input variable was the level of non-firm gas availability. In comparing scenarios that had the same input assumptions except for the level of non-firm gas availability, more emergency procedures were triggered in scenarios with no non-firm natural gas available as compared to 10,000 MW (62.5 percent) available. **Figure 22** provides an aggregate comparison of total hours of emergency procedures across all scenarios with 62.5 percent non-firm gas availability versus all scenarios with no non-firm gas availability.

Figure 22: Impact of Non-Firm Gas Availability Assumptions on Emergency Procedures

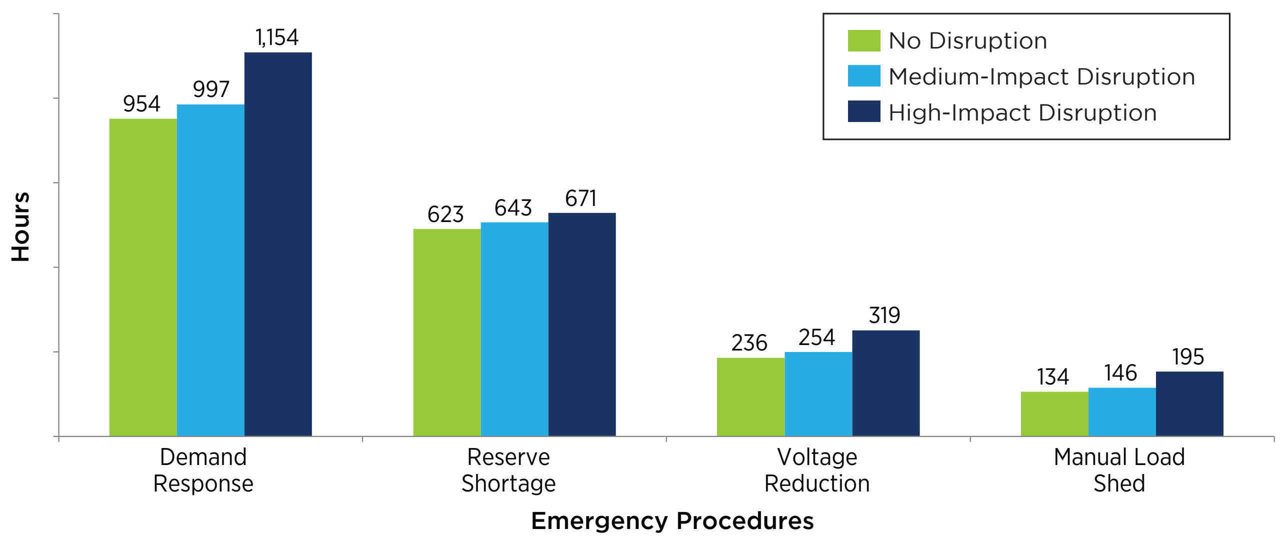


Natural Gas Pipeline Disruptions

The scenarios that included natural gas pipeline disruptions triggered marginally more emergency procedures compared to scenarios with no disruptions. There was a small difference in severity between scenarios with medium-impact disruptions as compared to high-impact disruptions. This is evident in **Figure 23**, which provides an aggregate comparison of total hours of emergency procedures across all scenarios with pipeline disruptions to all scenarios with no pipeline disruptions.[40] Overall, the pipeline disruptions had a smaller impact on the triggering of emergency procedures than oil replenishment and non-firm gas availability. This can be attributed to the locational nature of the pipeline disruptions and that some of the units affected by the disruptions are dual-fuel and capable of switching to oil as an alternate fuel.

PJM will continue to evaluate gas pipeline contingency impacts as additional natural gas generation is connected to the grid and will stay engaged in the FERC resilience docket as coordinated gas/electric generator interconnections may help mitigate the impact of gas pipeline contingencies on the grid.

Figure 23: Impact of Natural Gas Pipeline Disruptions on Emergency Procedures



Natural Gas Pipeline Configuration

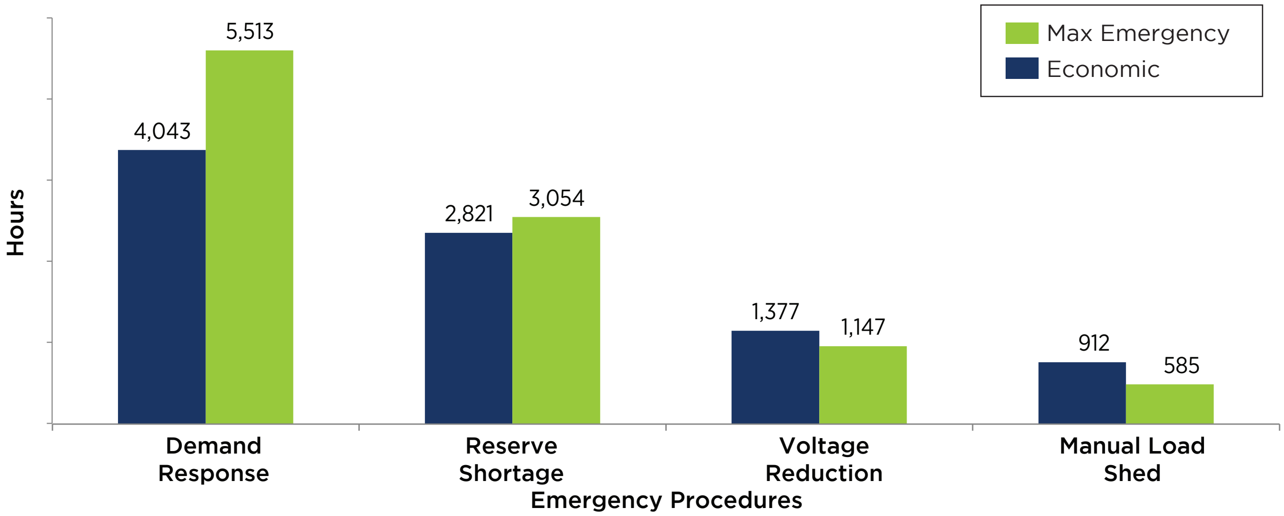
The results of scenarios with medium-impact disruptions reflect that looping provides additional redundancy, which improves gas deliverability during disruptions. This is because a level of firm gas would continue to flow during a medium-impact disruption to a looped pipeline, whereas no firm gas would flow during a medium-impact disruption to a single pipeline.

40 The hours of emergency procedures shown in **Figure 23** are adjusted to account for the difference in the number of scenarios with no pipeline disruption compared to the number of scenarios with pipeline disruptions in order to provide an apples-to-apples comparison.

Maximum Emergency Operational Procedure

To illustrate the value of existing PJM operational procedures, PJM simulated the use of maximum emergency dispatch to conserve on-site oil supplies. In scenarios where maximum emergency dispatch was used, the severity of emergency procedures decreased. **Figure 24** provides an aggregate comparison of total hours of emergency procedures across all extreme winter load scenarios with economic dispatch to all extreme winter load scenarios with maximum emergency dispatch.[41]

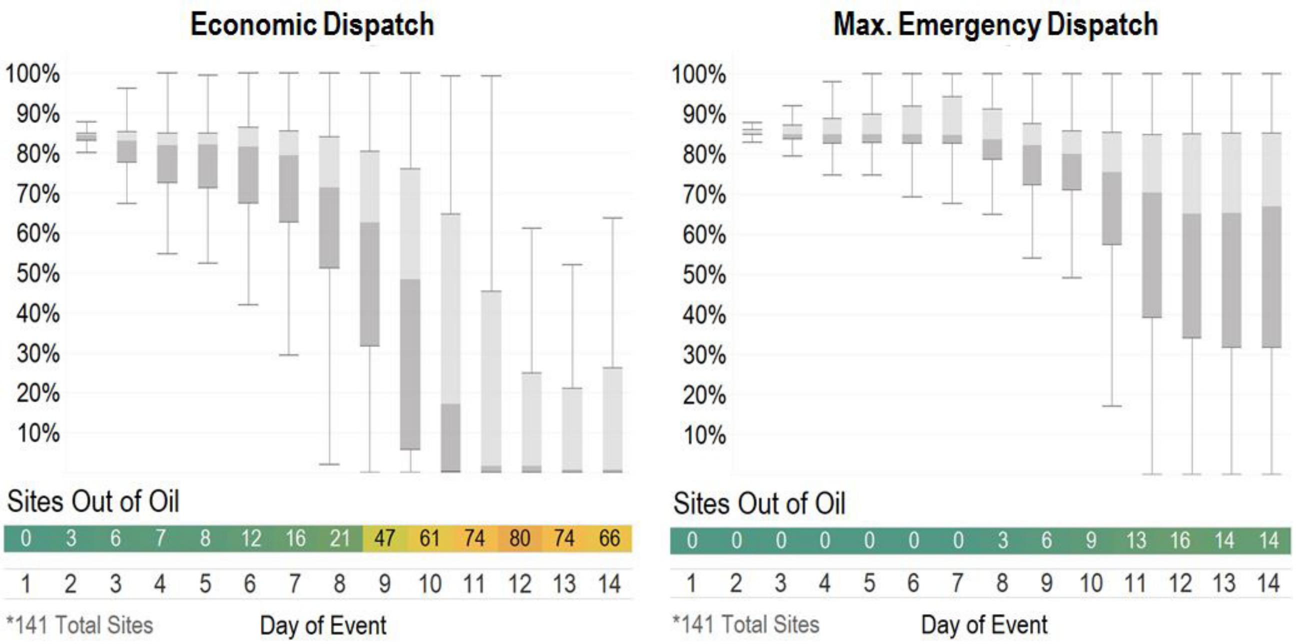
Figure 24: Impact of Dispatch Assumptions on Emergency Procedures



41 Max emergency dispatch was only simulated under extreme winter load, so scenarios with typical winter load are not included in this comparison.

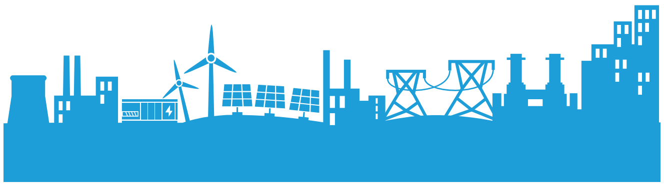
Figure 25 provides a more detailed comparison of two scenarios with the same input assumptions except for the dispatch to show the impact of maximum emergency dispatch on conserving fuel inventories. The box and whisker plots show site-specific[42] inventory levels (in percent of maximum on-site inventory) throughout the simulation, summarized by day. The heat map below the box and whisker plot in **Figure 25** indicates the number of sites at which oil inventories were depleted throughout the simulation, summarized by day.

Figure 25: Impact of Maximum Emergency Operational Procedure



The scenario using maximum emergency dispatch resulted in higher inventory levels and a smaller number of units running out of oil compared to the scenario using economic dispatch. In this scenario, the overall impact of the maximum emergency dispatch resulted in an additional 64 sites maintaining adequate inventory for operation on day 12 of the simulation.

42 "Site-specific" refers to on-site fuel inventories for individual generating units or that are shared by a group of generating units



Conclusion

In PJM's March 2017 paper, PJM's Evolving Resource Mix and System Reliability, PJM concluded that the current fuel portfolio is reliable, diverse and among the highest performing of those studied. It is well supplied with the required generator reliability attributes. Additionally, it found that the PJM system can remain reliable with the addition of more natural gas and renewable resources. However, the paper did not address the resilience and fuel security of the grid under these changing circumstances. Therefore, in April 2018, PJM undertook an analysis to study the fuel security aspect of resilience.

As part of the fuel security analysis, PJM looked five years into the future, using a 2023/2024 system model, to analyze 324 different scenarios ranging from typical operations to extreme scenarios, considering elements like generation retirements, customer demand, fuel delivery and fuel disruptions.

This extensive analysis concluded the following:

- The PJM system is reliable today and will remain reliable into the future.
- The analysis results showed some risks and vulnerabilities associated with fuel security.
- The key variables that have the most impact are:
  - On-site fuel inventory
  - Oil deliverability
  - Availability of non-firm natural gas service
  - Location of a pipeline disruption
  - Pipeline configuration

As the grid operator, it is important for PJM to talk about how to address known risks and vulnerabilities to the PJM system. Due diligence should be performed to understand the potential solutions and to balance cost and risk.

Next Steps

While there is no imminent threat, fuel security is an important component of ensuring reliability and resilience – especially if multiple risks materialize simultaneously. The findings underscore the importance of PJM exploring proactive measures to value fuel security attributes, and PJM believes this is best done through competitive wholesale markets. In order to enhance the fuel security of the grid into the future, PJM believes market-based mechanisms for retaining or procuring resources with the necessary fuel secure attributes should be explored.

As noted above, there remain significant issues for policymakers to consider regarding the level of resilience that should be expected to be borne by customers of the grid. PJM is hopeful that the FERC resilience docket may provide some policy guidance in this area. Nevertheless, the market design should, in PJM's view, be adapted to incorporate locational fuel security requirements with determinations of the exact point in time and set of conditions to trigger use of those mechanisms also subject to additional discussion and ultimate consideration by policymakers.

Throughout 2019, PJM will work with its stakeholders to examine the findings of this report and explore market-based solutions to address concerns about long-term fuel security.

It would be desirable, in PJM's view, for that stakeholder process to include, but not be limited to:

- Developing a detailed and prescriptive definition of fuel secure attributes
- Determining the required quantity and location of fuel secure resources
- Developing the mechanism to ensure fuel secure resources are appropriately valued
- Developing market rules as necessary to implement any recommended enhancements

In parallel, PJM will continue to work with the gas pipeline industry to improve coordination in communications and evaluate and refine contingencies as additional natural gas generators interconnect and pipeline configurations change, and further improve shared understanding of pipeline and grid operations and how they interface. In addition, PJM will collaborate with the natural gas industry to increase transparency of the secondary gas market. PJM will also collaborate with the fuel-oil and fuel-oil-transportation industries to increase transparency of on-site fuel inventory levels in addition to replenishment rates and capabilities.

As stakeholders address these issues, increasing transparency will need to be part of the discussion.

In addition, PJM will undertake Phase 3 of this analysis, applying this model to scenarios requested by the U.S. Department of Energy to simulate larger-scale disruptions.

PJM will also continue to engage the Federal Energy Regulatory Commission (FERC) in the national consideration of fuel security issues addressed in FERC's resilience docket,[43] specifically:

- The development of a working definition and common understanding of grid resilience
- Additional efforts by FERC to encourage sharing of pipelines' prospective identification of vulnerabilities and threats on their systems and, sharing on a confidential basis in real-time, the pipeline's modeling of such contingencies and communication of recovery plans
- The improvement of generation interconnection coordination with pipelines in order to better align interconnection activities and time lines and minimize potential issues associated with generation facilities located in areas on pipeline systems where reliability or resilience benefits may be suboptimal
- The submittal of any necessary proposed tariff amendments for any proposed market reforms and related compensation mechanisms to address resilience

Additional Information

Detailed information about the approach, methodology and analysis is contained in the Fuel Security Analysis Technical Appendix.

A summary of each scenario can be found in the Fuel Security Scenario Summaries document.

43 https://www.pjm.com/-/media/documents/ferc/filings/2018/20180309-ad18-7-000.ashx