# PJM's Evolving Resource Mix and System Reliability

PJM Interconnection
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## Contents

## Prologue

Beginning in 2015, PJM Interconnection has produced a series of papers examining how aspects of its operations, planning and markets could and should evolve given the changing landscape of the electric power industry. On October 12, 2015, PJM produced a paper entitled "Virtual Transactions in the PJM Energy Markets"[1] recommending enhancements to the mechanisms by which virtual transactions occur in the PJM markets. On May 6, 2016, PJM published its paper "Resource Investment in Competitive Markets," [2] in which PJM compared the efficiency of resource entry and exit in competitive and traditionally-regulated environments.

This paper, the latest in the series of work products, evaluates the changing resource mix in PJM given environmental regulations, the preponderance of low-cost natural gas, the increasing penetration of renewable resources and demand response, and the potential for retirements of nuclear power resources. Specifically, the paper examines whether the resource attributes necessary to maintain system reliability will continue to be available in sufficient quantities within various potential future resource portfolios. In addition, the paper raises questions about whether PJM should evaluate operating and planning for potential system events beyond those that drive traditional reliability criteria. More specifically, the paper questions whether there are additional objectives for system resilience that could be achieved by enhancing operational and planning procedures and requirements while taking into account actions PJM already has taken, such as implementation of Capacity Performance.

PJM will focus on additional subject areas associated with the evolving electricity industry as part of separate, future efforts. This paper does not explore, for example, the economics of any particular resource type, the growing trends around the desires of states to subsidize certain resources or resource types to ensure their continued operation, nor the impacts of such subsidies on wholesale markets. This paper also does not address the future evolution of the planning process with respect to whether and how the transmission planning process should include system resilience as a criteria and/or a driver of the need for additional system infrastructure. Finally, this paper does not address any specific areas involved with the evolution of how prices are formed in the capacity, energy or ancillary service markets. PJM will continue to focus on these subjects and will produce additional work products.

This current paper integrates into the context of the other subject areas by answering questions concerning whether the evolving resource mix is resulting in a loss of diversity that will lead to future reliability problems. Acting FERC Chairman Cheryl LaFleur[3] commented at the FERC technical conference following the 2014 polar vortex:

> *The second big thing that all of a sudden everyone is asking about the markets just in the last to 24 months is what about fuel diversity? What about fuel diversity? Well the markets have a single clearing price product. That's how they were set up. They were not set up to buy tranches of this and tranches of that. But if there are elements of what the baseload product resources provide that are being under-valued in the market that need to somehow use the market to try to solve that, I think that also is well worth the effort. Because it seems we are hearing a consistent theme that there is something that is being under-valued when we just go to the short term gas lowest price, and I urge you. We will work with you on that…*

[1] http://www.pjm.com/~/media/committees-groups/committees/mc/20151019-webinar/20151019-item-02-virtual-transactions-in-the-pjm-energy-markets-whitepaper.ashx

[2] PJM Value of Markets Paper - http://www.pjm.com/~/media/about-pjm/newsroom/2016-releases/20160506-pjm-posts-value-of-markets.ashx

[3] Federal Energy Regulatory Commission Technical Conference on April 1, 2014

The paper represents PJM's effort to understand fuel diversity and its impact to reliability. This paper also presents additional questions to be investigated with respect to operating and planning for certain components of system resilience. Further work is required to complete the picture of how PJM's operations, planning and markets should continue to evolve to address these other issues. PJM looks forward to engaging with members, regulators and other stakeholders on these important issues going forward.

# Executive Summary

## *Introduction*

Recent growth in the amount of natural gas-fired and renewable generation has raised questions about "fuel diversity" on the PJM Interconnection system. Considering the retirement of coal-fired generation and to a lesser extent the threat of nuclear generation retirement, stakeholders have questioned whether the system is losing too many resources which historically have been referred to as "base load"[4] generation capability and whether the system is – or could become – so dependent on natural gas or renewable resources that operational reliability is adversely impacted. In response to those concerns, PJM conducted this analysis to evaluate fuel diversity through the lens of reliability and to identify a range of resource mixes that effectively manage reliability risk.

This paper does not analyze market or economic impacts of fuel diversity, nor does it address public policy issues, such as environmental or job impacts of different resource mixes. The paper's focus is on the reliability aspects of fuel mix diversity, including fuel security. The paper offers insight, from a grid operator's perspective, for policymakers to consider when assessing the impacts of a changing resource mix and poses questions about new impacts to evaluate.

## *Approach and Risk Analysis*

In light of the increasing contribution of natural gas-fired generation and retirement of coal-fired generation, PJM has undertaken several natural gas analyses to assess potential system reliability implications. All the studies generally concluded that the existing and planned natural gas pipeline infrastructure would be adequate for current and future anticipated electric system needs.[5]

Today's resource profile in PJM is both reliable[6] and diverse – with a combination of natural gas, coal, nuclear, renewables, demand response and other resource types. Historical events discussed in this paper highlight that a more diverse system is more likely to have increased flexibility and adaptability to (1) mitigate the risk associated with equipment design issues or common modes of failure[7] in similar resource types, (2) address fuel price volatility and fuel supply disruptions and (3) reliably mitigate risk caused by weather and other unforeseen system shocks. In this way, resource diversity can be considered a system-wide hedging tool that helps ensure a steady, reliable supply of electricity.

PJM's assessment of the reliability services provided by different resource types builds upon work initiated by the North American Electric Reliability Corporation (NERC) and the power industry to define "essential reliability services," which comprise a subset of generator reliability attributes. Key generator reliability attributes defined and analyzed as part of this paper include frequency response, voltage control, ramp, fuel assurance, flexibility, black start, environmental restrictions and equivalent availability factor.[8]

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4 In this paper, "base load" generation refers to units that typically do not cycle due to unit limitations or market economics.

5 U.S. Department of Energy Report: Natural Gas Infrastructure Implications of Increased Demand from the Electric Power Sector, https://energy.gov/sites/prod/files/2015/02/f19/DOE%20Report%20Natural%20Gas%20Infrastructure%20V_02-02.pdf

6 See the definition of reliability at the beginning of the Background section in this paper.

7 A common mode failure is one event that causes multiple systems or system components to fail.

8 See the Defining Generator Reliability Attributes section of this paper for the definition of these terms.

PJM analyzed each resource type's ability to provide generator reliability attributes based on the resource type's physical capabilities and PJM's operational experience. For the expected near-term resource portfolio[9] and future portfolios,[10] PJM calculated the capability of each resource type to provide reliability services as well as the total amount of each reliability attribute available in different resource portfolios. Each potential future portfolio was assessed based on its ability to provide two components of reliability: resource adequacy and operational reliability.

Resource adequacy addresses the amount of capacity needed to serve a forecasted peak load while meeting the required Loss of Load Expectation[11] (LOLE) criterion.[12] To ensure resource adequacy, each potential portfolio was tested against the LOLE criterion. The portfolios were subjected to a second LOLE test to account for intermittent output from wind and solar resources and currently limited storage capabilities. This second test ensured that portfolios with large unforced capacity shares of intermittent resource were able to serve load during hours that their outputs would be significantly lower than their capacity obligations. Portfolios that failed the second LOLE test were considered "infeasible."

Operational reliability addresses the grid's day-to-day operational needs and is measured by a portfolio's capability to provide the defined key generator reliability attributes. To assess operational reliability, PJM created a "composite reliability index" using the calculated capability of each resource type to provide the generator reliability attributes. The analysis used the index 1) to identify portfolios at risk of failing to provide adequate levels of the key generator reliability attributes and 2) to quantify and assess the reliability of a given potential resource portfolio across four operational states (i.e., normal peak conditions, light load, extremely hot weather and extremely cold weather). Portfolios with the lowest composite reliability indices were deemed "at risk" for underperformance in terms of providing the defined key generator reliability attributes. These portfolios do not exhibit, or only partially exhibit, numerous generator reliability attributes in one or more of the studied operational states.

The paper does not identify all possible feasible resource mixes, nor does it define an optimal mix. Rather, the analysis used this risk assessment to evaluate a range of potential resource portfolios based on their abilities to provide generator reliability attributes benchmarked against the generator reliability attribute capability of the expected near-term portfolio.

### *Summary of Analysis Results*

Among the key findings of the analysis:

- The expected near-term resource portfolio is among the highest-performing portfolios and is well equipped[13] to provide the generator reliability attributes.

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[9] The expected near-term PJM resource portfolio was established by projecting the composition of the generation mix in PJM out to 2021. The projection reflects near-term trends in announced generator deactivations and added capacity from the PJM Generation Interconnection Queues. More detail on this approach is in the Appendix.

[10] The analysis used recent trends in PJM's generator interconnection queues and deactivation announcements to develop 360 potential future portfolios. More detail on this approach is in the Appendix.

[11] The LOLE criterion defines the adequacy of capacity for the entire PJM footprint so that there are sufficient capacity resources to ensure, load exceeds available capacity, on average, only once in 10 years.

[12] See Federal Energy Regulatory Commission Order 747 – https://www.ferc.gov/whats-new/comm-meet/2011/031711/E-7.pdf

[13] Based on the requirements of the PJM Open Access Transmission Tariff, the PJM Operating Agreement, the PJM Reliability Assurance Agreement and applicable NERC reliability standards

- As the potential future resource mix moves in the direction of less coal and nuclear generation, generator reliability attributes of frequency response, reactive capability and fuel assurance decrease, but flexibility and ramping attributes increase.
- A marked decrease in operational reliability was observed for portfolios with significantly increased amounts of wind and solar capacity (compared to the expected near-term resource portfolio), suggesting de facto performance-based upper bounds on the percent of system capacity from these resource types. Additionally, most portfolios with solar unforced capacity[14] shares of 20 percent or greater were classified infeasible because they resulted in LOLE criterion violations at night. Nevertheless, PJM could maintain reliability with unprecedented levels of wind and solar resources, assuming a portfolio of other resources that provides a sufficient amount of reliability services.
- Portfolios composed of up to 86 percent natural gas-fired resources maintained operational reliability.[15] Thus, this analysis did not identify an upper bound for natural gas. However, additional risks, such as gas deliverability during polar vortex-type conditions and uncertainties associated with economics and public policy, were not fully captured in this analysis. Risks with respect to natural gas may lie not in capability to provide the generator reliability attributes but rather in these other uncertainties.
- More diverse portfolios are not necessarily more reliable; rather, there are resource blends between the most diverse and least diverse portfolios which provide the most generator reliability attributes.

### *Fuel Security and Resilience*[16]

The analysis discussed in this paper was initiated by questions about "fuel diversity" on the PJM system and whether the system could become so dependent on natural gas or renewable resources that operational reliability would be adversely impacted. Fuel diversity itself does not ensure reliability. According to the results of PJM's analysis reported in this paper, the composition of a resource portfolio could negatively impact that portfolio's ability to provide an appropriate level of generator reliability attributes. The adequate level of fuel diversity allows increased flexibility and adaptability.

Nevertheless, the analysis shows that many of the potential future resource portfolios are likely to be reliable because they are likely to provide adequate amounts of the defined key generator reliability attributes. This observation holds true even for potential resource mixes that are heavily reliant on natural gas-fired generation and thus lack fuel diversity. For the purpose of this paper, the terms fuel security and energy security can be used interchangeably. (In addition, as mentioned previously, this paper does not focus on the economic impact of fuel security.)

"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

[14] Unforced capacity (UCAP) is installed capacity rated at summer conditions that is not on average experiencing a forced outage or forced derating; it is calculated for each generation Capacity Resource based on EFORd data for the 12-month period from October to September without regard to the ownership of or the contractual rights to the capacity of the unit. Manual 18: PJM Capacity Market, Attachment A: Glossary of Terms, Revision 36, Effective Date: 12/22/2016.

[15] The potential 86-percent-natural-gas portfolio would occur if all the coal and nuclear resources in the expected near-term portfolio retired and were replaced exclusively by natural gas. Portfolios composed of natural gas unforced capacity shares greater than 86 percent were not considered in the analysis because there is no reasonable expectation that any such portfolios could actually materialize.

[16] Resilience, in the context of the bulk electric system, relates to preparing for, operating through and recovering from a high-impact, low-frequency event. Resilience is remaining reliable even during these events.

address. Resilience is the capability of an energy system to tolerate disturbance and to continue to deliver energy services to consumers. Relying too heavily on any one fuel type may negatively impact resilience because resources do not provide generator reliability attributes equally. External drivers have impacted and could continue to impact the resource mix.

### *Moving Forward*

The capability of resource types to provide various generator reliability attributes may change in the future because of changes in technology or regulations. Therefore, operations, market compensation and regulatory structures may need to shift to ensure that adequate levels of generator reliability attributes are maintained in future resource mixes. PJM will need to assess diversity and security going forward and work through either existing processes and market enhancements or develop new solutions to ensure that sufficient generator reliability attributes will be available.

PJM and its stakeholders should continue to examine resilience-related low-probability and high-impact events which can cause significant reliability impacts. PJM will continue to identify the highest risks to reliability from the anticipated resource mix changes to determine potential techniques to identify and mitigate natural gas infrastructure vulnerabilities – given the current and expected rapid growth in natural gas generation. Although each resource type carries with it sizable exposure to low-probability high-impact events, the ever-growing increase of natural gas as a fuel source makes continued examination of dependence on natural gas particularly appropriate. PJM also will continue to identify means to mitigate the exposure to "realistic" interruption events, which are not extreme but part of the daily physical or political landscape.

However, unlike the reliability services used in this analysis, criteria for resilience are not explicitly defined or quantified today. Some questions PJM and its stakeholders should consider include:

- Does PJM's current set of business practices ensure that PJM's evolving resource mix will result in continued reliable operations?
    - Are there reliability attributes that are missing from this analysis, and what, if any, generator reliability attributes are important but currently being undervalued in PJM?
    - During high-dependency / high-risk periods, should PJM schedule the system differently to consider fuel security concerns?
    - How can distributed energy resources and renewable resources provide additional reliability or resilience services through, for example, advances in inverter and storage technologies?
- How could PJM's business practices include resilience?
    - Should PJM plan for and operate to a set of extreme contingencies that maintain an adequate operating margin under normal operations? Extraordinary situations?
    - Should PJM and the natural gas pipelines coordinate, study and operate to joint electric and natural gas contingencies?[17]
    - Could black-start requirements and restoration strategy better consider resilience, for example, in how PJM defines black-start resources, critical load and requirements for cranking paths?

PJM's established planning, operations and markets functions have resulted in a PJM resource mix that is reliable. The current resource mix is also diverse.[18] PJM recognizes that the benefits of fuel mix diversity include the ability to withstand

[17] http://www.nerc.com/comm/RISC/Related%20Files%20DL/ERO_Reliability_Risk_Priorities_RISC_Reccommendations_Board_Approved_Nov_2016.pdf

equipment design issues or common modes of failure in similar resource types, fuel price volatility, fuel supply disruptions and other unforeseen system shocks. PJM will continue to leverage the proven approach of the well-developed stakeholder process both to ensure future resource mixes support continued reliable operations and to further define criteria for resilience.

[18] http://www.pjm.com/markets-and-operations.aspx

## Background

Recent growth in the share of generation fueled by natural gas and renewables has raised questions about "fuel diversity" on PJM Interconnection system. Considering the retirement of coal-fired generation and to a lesser extent the potential threat of nuclear generation retirement, stakeholders have questioned whether the system is losing too many resources which historically have been referred to as "base load"[19] generation capability and whether the system is – or could become – so dependent on natural gas or renewable resources that reliability would be adversely impacted. Many have attempted to define fuel diversity through economic and political lenses. This paper analyzes fuel diversity through a reliability lens to identify the risks associated with a range of potential resource mix portfolios.

The electricity resource mix has shifted throughout PJM's history, and the PJM system has proven reliable in the face of change. Adequacy and security are two key aspects of reliability.[20] The PJM planning process and Capacity Market maintain resource adequacy by ensuring sufficient resources to meet demand under extreme conditions. Security is maintained by operating the system in a way that anticipates the possibility of failure of key system elements in order to minimize the loss of service to large groups of customers.[21] While effective transmission planning is an integral aspect of reliability, it is not in the scope of this paper. Rather this paper focuses on supply resources, and their operational attributes that contribute to system reliability.

Fuel diversity in the electric system generally is defined as utilizing multiple resource types to meet demand. A more diversified system is intuitively expected to have increased flexibility and adaptability to: 1) mitigate risk associated with equipment design issues or common modes of failure in similar resource types, 2) address fuel price volatility and fuel supply disruptions, and 3) reliably mitigate instabilities caused by weather and other unforeseen system shocks.[22] In this way, fuel diversity can be considered a system-wide hedging tool that helps ensure a stable, reliable supply of electricity.

Diversity often is a mechanism to enhance energy security, which is defined as "the uninterrupted availability of energy sources at an affordable price."[23] The International Energy Agency notes the temporal context of energy security:

> *Long-term energy security mainly deals with timely investments to supply energy in line with economic developments and sustainable environmental needs. Short-term energy security focuses on the ability of the energy system to react promptly to sudden changes within the supply-demand balance. Lack of energy security is thus linked to the negative economic and social impacts of either physical unavailability of energy, or prices that are not competitive or are overly volatile.*

The concept of diversity spans many industry sectors. In any application, diversity consists of three basic properties: variety, balance and disparity.[24] As each of these properties increase, diversity also increases. This paper adapted these properties to describe PJM's view of electric system diversity:

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[19] In this paper, "base load" generation refers to units that typically do not cycle due to unit limitations or market economics.

[20] https://learn.pjm.com/Media/about-pjm/newsroom/fact-sheets/reliability-fact-sheet.pdf

[21] PJM operators make adjustments in real time so that the system is prepared and protected in the event of a sudden, unexpected disturbance or failure.

[22] Examples of system shocks are described in the Historical Events that Demonstrate the Importance of System Diversity section and in the Appendix.

[23] International Energy Agency. https://www.iea.org/publications/freepublications/publication/moses_paper.pdf

[24] Stirling, Andy. (2008). *Chapter 1 - Diversity and Sustainable Energy Transitions: Multicriteria Diversity Analysis of Electricity Portfolios.* Analytical Methods for Energy Diversity & Security, Elsevier Global Energy Policy and Economics Series.

- Variety is a measure of how many different resource types are on the system. A system with more resource types in its generation mix has greater variety.
- Balance is a measure of how much grid operators rely on certain resource types. Balance increases as the reliance on different resource types in a generation mix is becoming more evenly distributed.
- Disparity is a measure of the degree of difference among the resource types relative to each other. Disparity can relate to the geographic distribution of resource types – generation resources that are evenly distributed across the system are more disparate than concentrated pockets of generation resources. Disparity also relates to operational characteristics of resources – a system with resource types that have different operational characteristics is more disparate than a system in which all of the resource types have similar operational characteristics.

### *Diversity of the PJM System*

PJM has a variety of different resource types in its diverse resource mix. For the purposes of this paper, PJM grouped resources into 11 classifications [25] (Coal, natural gas steam, natural gas combustion turbine, oil steam, oil combustion turbine, nuclear, solar, wind, hydro, battery/storage, and demand response).

The resource mix within PJM has become more evenly balanced over time. In 2005, coal and nuclear resources generated 91 percent of the electricity on the PJM system.[26] Over time, policy initiatives, technology improvements, and economics spurred a shift from coal to natural gas and renewable generation. From 2010 to 2016 in PJM, coal-fired units made up 79 percent of the megawatts retired,[27] and natural gas and renewables made up 87 percent of new megawatts placed in service.[28] PJM's installed capacity in 2016 consisted of 33 percent coal, 33 percent natural gas, 18 percent nuclear, and 6 percent renewables (including hydro).[29]

Trends in the PJM Capacity Market suggest that shifts in the resource mix will continue to occur (Figure 1).

[25] The analysis grouped units by majority fuel types, and as such, may not exclusively represent every type or combination of fuel, prime mover and technology type.

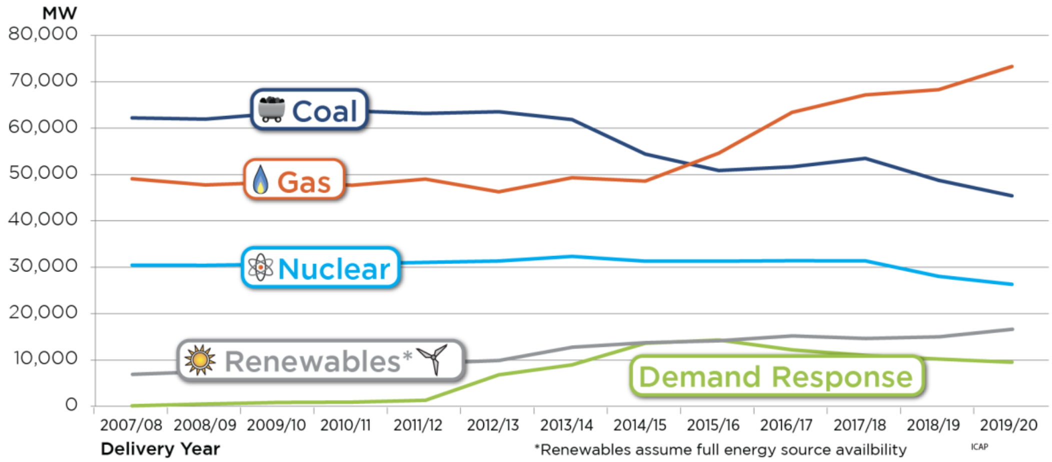
[26] PJM GATS System Mix - https://gats.pjm-eis.com/gats2/PublicReports/PJMSystemMix

[27] PJM Generation Deactivation data; posted at http://www.pjm.com/planning/generation-deactivation/gd-summaries.aspx

[28] PJM Generation Queues (http://www.pjm.com/planning/generation-interconnection/generation-queue-active.aspx). Queue project megawatts are based on "MW placed in service" with Status Codes of IS, UC-ISP, or Active-ISP. MW in service represents the new generation capability added to the system; actual capacity interconnection rights may be lower based on limitations for certain fuel types or rights as specified in individual interconnection agreements.

[29] PJM Capacity by Fuel Type 2016 - http://www.pjm.com/~/media/markets-ops/ops-analysis/capacity-by-fuel-type-2016.ashx ; 'Renewables' is inclusive of Hydro.

**Figure 1. PJM Cleared Installed Capacity by Delivery Year**

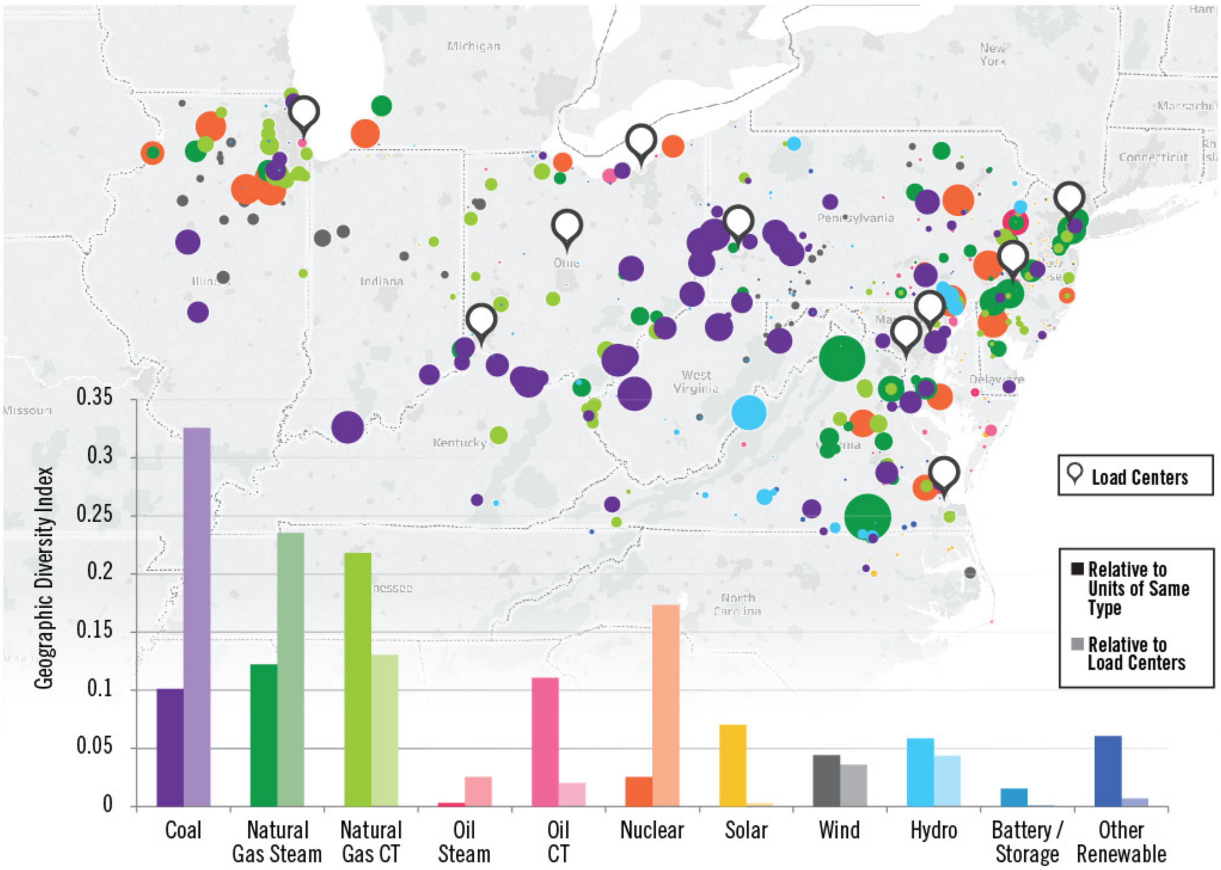



The disparity among PJM resource types can be grouped into two main categories: geographic and operational characteristics. PJM's geographic diversity has increased as the PJM footprint expanded. Figure 2 depicts the geographic diversity of the different resource types in PJM. The geographic diversity indices[30] capture the dispersion of units of the same resource type and the distance of a resource type from load centers.[31] Coal units have a low index relative to each other because they tend to be clustered near fuel sources, while at the same time have a high index relative to load because they tend to be far from load centers. In contrast, natural gas and oil combustion turbines (CTs) tend to be dispersed relative to each other, but close to the load centers. Geographic diversity can act as a system wide hedge to reduce potential reliability impacts of local supply/infrastructure disruptions by leveraging resources across the footprint.

[30] The geographic diversity index titled "Relative to Units of Same Resource Type" was calculated using MW weighted distances between units of the same resource type. The geographic diversity index titled "Relative to Load Centers" was calculated using MW weighted and load weighted distances between units of the same resource type and the load centers.

[31] Loads for the top ten metropolitan areas in the PJM footprint are assumed to be proportional to the 2016 Gross Metro Product (GMP) shares of those areas.

**Figure 2. Geographic Diversity**[32]

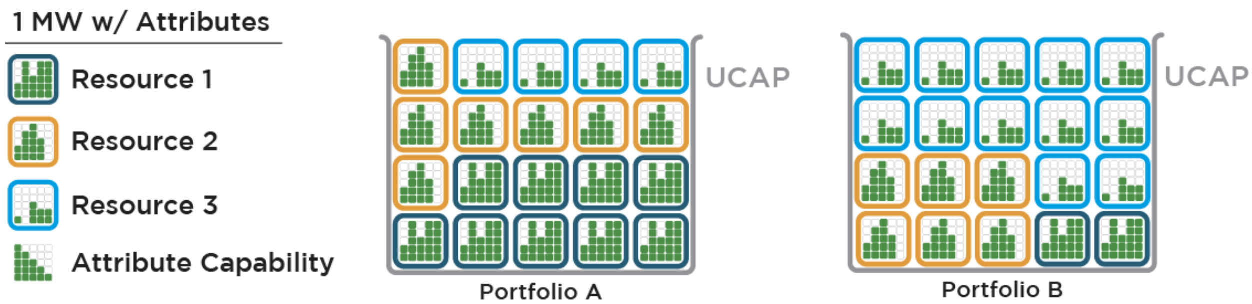



A disparate mix of resource types has different operational characteristics that aid in maintaining system reliability. In this paper, these operational characteristics are referred to as generator reliability attributes. A benefit of diversity is having the ability to leverage the capabilities of different resources types when they are most needed. However, not all resource types are equal in their ability to provide generator reliability attributes necessary for system operation, or in their ability to be resilient during times of system stress.[33] Figure 3 illustrates how the generator reliability attributes of different resource types and the shares of these resource types in a portfolio impact the total amount of generator reliability attribute capability. Each resource in Figure 3 has different generator reliability attribute capabilities. Differences in generator reliability attribute capabilities, and the resource mix in each portfolio, result in Portfolio B having less total capability to provide generator reliability attributes than Portfolio A.

[32] Loads for the top ten metropolitan areas in the PJM footprint are assumed to be proportional to the 2016 Gross Metro Product (GMP) shares of those areas.

[33] The Generator Reliability Attributes will be discussed in detail in the Reliability section.

**Figure 3. Generator Reliability Attribute Primer**

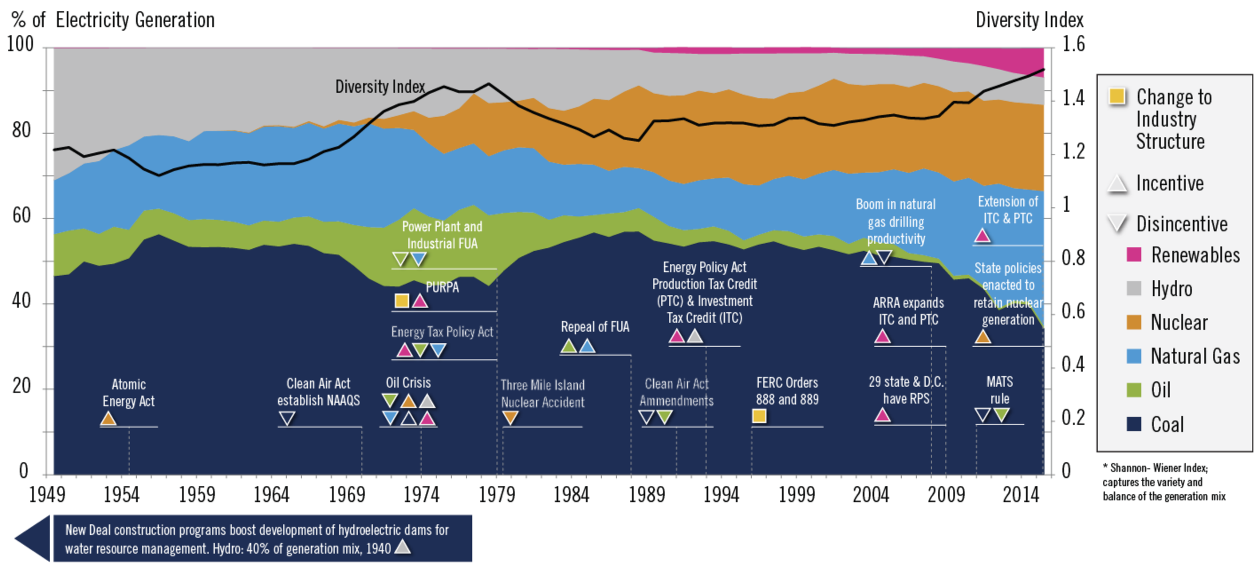



### *Historical Drivers of Fuel Diversity in the United States*

Historical drivers of resource mix change are an important part of understanding fuel diversity issues. The evolution of the resource mix in the United States is a product of technological development, economics, government policy and geopolitical forces. Figure 4 relates key historic drivers of the shifting composition and relative diversity of the U.S. resource mix.[34] Policy drivers often target specific resource types. Many of these drivers influence both fuel diversity itself, and create additional drivers. For example, tax incentives and state Renewable Portfolio Standards increased the amount of renewable resources. The increased demand for renewables resulted in more research and development to reduce manufacturing costs and increase unit efficiency, making renewable resource development more viable.

[34] The Diversity Index was calculated as a Shannon-Wiener Index. This accounts for number generation resources in each year, and the share of those resources in the fleet, and show the relative diversity of the generation mix in each year.

**Figure 4. Generation Mix Driver Timeline**




| | | | |
|---|---|---|---|
| **NOTE:** This graphic is not an exhaustive representation of all drivers related generation mix change. The intent was to capture examples of major drivers, with a focus on policies and events that targeted specific resource types. | | | |
| NAAQS | National Ambient Air Quality Standards | ARRA | American Recovery & Investment Act |
| PURPA | Public Utility Regulatory Policies Act of 1978 | RPS | Renewable Portfolio Standard |
| FUA | Power Plant and Industrial Fuel Use Act of 1978 | MATS | Mercury and Air Toxics Standards |

Exploring fuel diversity from a historical perspective makes clear that "the only thing constant is change."[35] Policies have and will continue to incent or dis-incent specific fuel types depending on the economic, geopolitical, or social climate at that time. The maintenance of national energy security has and will continue to be an important policy driver. PJM must prepare and adjust as these policies continue to directly impact the composition of the resource mix.

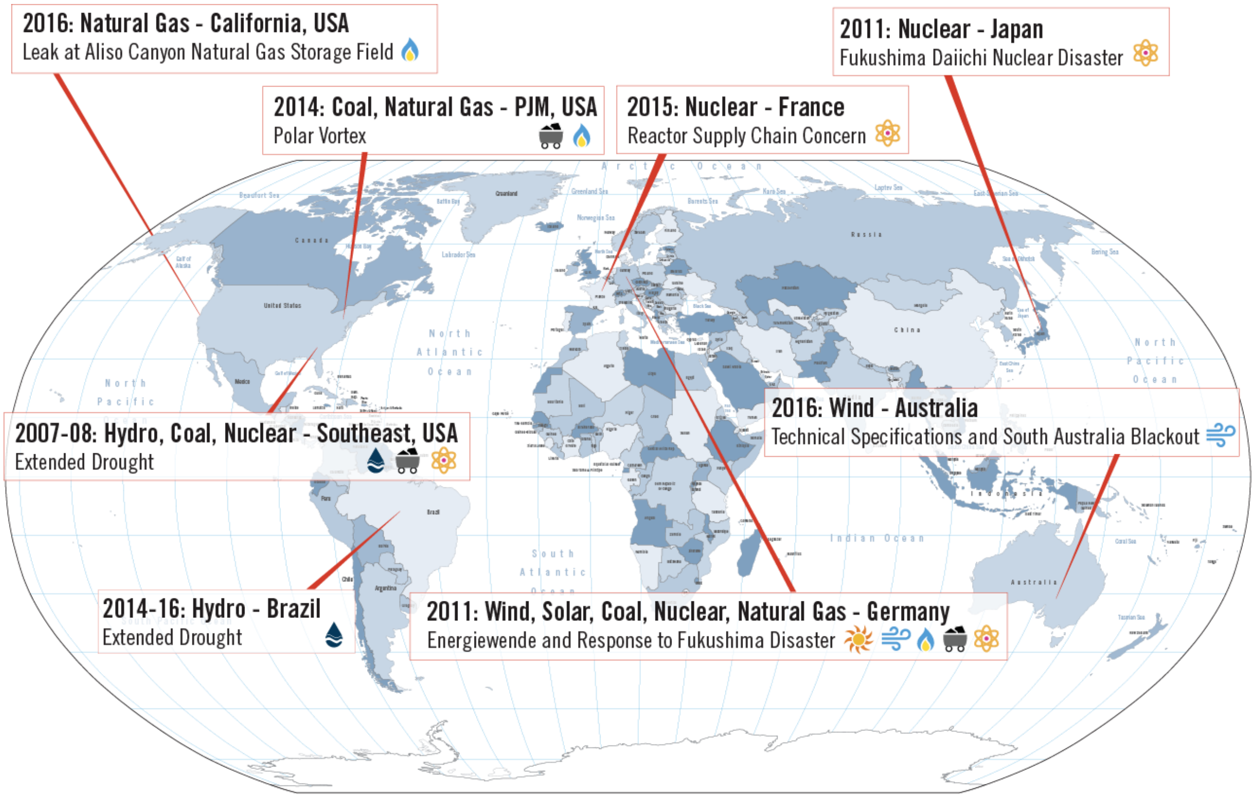
### *Historical Events that Demonstrate the Importance of System Diversity*

Global events emphasize the importance of assessing the risks associated with current or future resource mixes. All resource types are susceptible to issues that could compromise reliability and fuel security. Figure 5 provides examples of historical events that exposed the risks associated with different resource types.[36] These events were caused by natural occurrences, such as extreme weather events, and unforeseen whole-system vulnerabilities, such as new technical specifications for all nuclear units based on an event at a specific plant.

[35] Heraclitus, Greek philosopher, circa 500 B.C.

[36] See the Appendix for case studies of historical events.

**Figure 5. Historical Events World Map**




No generation resource is free from risks that can negatively impact the electric power sector. These risks are global, and can affect any geography or political construct. Additional risks of increasing concern include man-made, purposely malicious attacks[37] designed to inflict maximum disruption to electric grid operations. The reaction to, and impacts from, events that reduce reliability and fuel security can be widespread and long-lasting.[38] Although most of these events are unpredictable, PJM must be prepared. Measures beyond traditional capacity procurement or economic dispatch may be needed to reduce risks associated disruptive events and maintain system reliability and resilience.

## Reliability

PJM's analysis of reliability, as related to fuel diversity and security, builds upon the work initiated by the North American Electric Reliability Corporation (NERC) and the power industry to define essential reliability services, which comprise a subset of generator reliability attributes.

An awareness of the existing level of generator reliability attributes is required to understand how retirements of conventional generation (e.g., coal and nuclear) and replacement of capacity with natural gas generators and variable energy resources will impact reliable operation of the bulk electric system. At the same time, resources on the distribution system are increasing because of demand response programs and growth of distributed energy resources.

[37] Examples of man-made attacks include, but are not limited to, High Altitude Electromagnetic Pulse, coordinated cyber or physical attacks, etc.

[38] See the Appendix for examples of historic events and impacts.

Although each fuel source produces real power - megawatt-hours (MWh) that are ultimately consumed by customers - each also contributes to overall grid reliability by providing generator reliability attributes.

PJM has undertaken various initiatives to analyze, develop, or modify system requirements that, directly or by extension, maintain acceptable levels of generator reliability attributes. The initiatives include Capacity Performance, enhanced standards for inverter-based resources, centralized forecasts (wind, solar and distributed energy resources), business rules which support dispatchability of variable energy resources, "Pay for Performance" regulation service, 15-minute interchange intervals, and the PJM Renewable Integration Study.[39]

### *Defining Generator Reliability Attributes*

To better quantify the generator reliability attributes that contribute to grid reliability, PJM compiled information from various NERC initiatives that defined Interconnected Operations Services[40] and Essential Reliability Services,[41] as well as information from renewable integration studies, the PJM ancillary service markets,[42] the PJM Capacity Performance Initiative,[43] the PJM Advanced Technology Pilot program[44] and feedback from PJM staff, PJM members, and other industry experts. The resulting generator reliability attributes are defined and described below.

Figure 6 shows a matrix of the generator reliability attributes[45] based on 2016 capabilities and PJM operational experience for different resource types to include Coal, Natural Gas Steam, Natural Gas CT, Oil Steam, Oil CT, Nuclear, Solar, Wind, Hydro, Battery/Storage and Demand Response.

The capability to provide various generator reliability attributes may change in the future as a result of changes in technology or resource mix driven by regulation. The matrix is intended primarily to group units by fuel type, and as such, may not exclusively represent every combination of fuel, prime mover and technology type. Should the actual, future fuel mix evolve such that the potential exists for the quantity of generator reliability attributes to fall below that which is necessary to maintain reliable grid operations, then operations, market incentives and regulatory structures may need to shift to provide incentives to ensure adequate levels of these attributes are maintained.

[39] http://www.pjm.com/~/media/committees-groups/subcommittees/irs/postings/pjm-pris-final-project-review.ashx

[40] http://www.nerc.com/docs/pc/IOSrefdoc.pdf

[41] http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf

[42] PJM Balancing Manual (M12) http://www.pjm.com/~/media/documents/manuals/m12.ashx

[43] http://www.pjm.com/~/media/committees-groups/committees/mic/20160119-special/20160119-capacity-performance-parameter-limitations-informational-posting.ashx

[44] http://pjm.com/markets-and-operations/advanced-tech-pilots.aspx

[45] See the Generator Reliability Attribute section in the Appendix for further explanation.

## Figure 6. Generator Reliability Attribute Matrix

● = Exhibits Attribute
◒ = Partially Exhibits Attribute
○ = Does Not Exhibit Attribute

| Resource Type | Essential Reliability Services (Frequency, Voltage, Ramp Capability) | | | | | Fuel Assurance | | Flexibility | | | Other | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Frequency Response (Inertia & Primary) | Voltage Control | Ramp | | | | | | | | | | |
| | | | Regulation | Contingency Reserve | Load Following | Not Fuel Limited (> 72 hours at Eco. Max Output) | On-site Fuel Inventory | Cycle | Short Min. Run Time (< 2 hrs.)/ Multiple Starts Per Day | Startup/ Notification Time < 30 Minutes | Black Start Capable | No Environmental Restrictions (That Would Limit Run Hours) | Equivalent Availability Factor |
| Hydro | ● | ● | ● | ● | ● | ○ | ◒ | ● | ● | ● | ● | ◒ | ● |
| Natural Gas - Combustion Turbine | ● | ● | ◒ | ● | ◒ | ● | ○ | ● | ● | ● | ● | ◒ | ◒ |
| Oil -Steam | ● | ● | ● | ● | ● | ● | ● | ● | ○ | ○ | ○ | ○ | ◒ |
| Coal - Steam | ● | ● | ● | ● | ● | ● | ● | ◒ | ○ | ○ | ○ | ◒ | ◒ |
| Natural Gas - Steam | ● | ● | ● | ● | ● | ● | ○ | ● | ○ | ○ | ● | ◒ | ◒ |
| Oil/ Diesel - Combustion Turbine | ● | ● | ○ | ● | ○ | ○ | ● | ● | ● | ● | ● | ○ | ◒ |
| Nuclear | ◒ | ● | ○ | ○ | ◒ | ● | ● | ○ | ○ | ○ | ○ | ◒ | ● |
| Battery/ Storage | ◒ | ◒ | ● | ● | ○ | ○ | ○ | ● | ● | ● | ◒ | ● | ● |
| Demand Response | ○ | ○ | ◒ | ◒ | ◒ | ◒ | ◒ | ● | ● | ◒ | ○ | ● | ● |
| Solar | ◒ | ◒ | ○ | ○ | ◒ | ○ | ○ | ● | ● | ● | ○ | ● | ● |
| Wind | ◒ | ◒ | ○ | ○ | ◒ | ○ | ○ | ● | ● | ● | ○ | ◒ | ● |

## Generator Reliability Attributes Description

Key generator reliability attributes defined and analyzed as part of this paper include frequency response, voltage control, ramp, fuel assurance, flexibility, black start, environmental restrictions and equivalent availability factor.

### Frequency Response

The frequency of alternating current on an interconnected transmission system (typically 60 Hz in the U.S.) is a key indicator of the system's health and stability. Frequency response is an essential reliability service as defined by NERC, and is provided through the interaction of three components – synchronous inertia,[46] primary frequency response[47] and secondary frequency response.[48] Frequency will be impacted by any imbalance between load and generation, deviating upward when generation exceeds demand, and deviating lower when generation is insufficient to meet demand. Frequency response components work together to arrest frequency changes caused by an imbalance between generation and demand, and to return the system to scheduled frequency.

The initial rate at which system frequency changes depends on the amount of inertial response available at the time of the event. Historically, the majority of inertial response has been supplied by large synchronous generators[49] such as coal-fired steam units. Once the frequency change has been arrested, primary and secondary frequency response resources can provide additional power to eventually return the system to normal frequency through ancillary services like area regulation and Security Constrained Economic Dispatch (SCED).

Nuclear plants may be prohibited from providing primary frequency response based on their licenses. Controls on (legacy) non-synchronous solar and wind generation are not capable of providing frequency response. However, newer non-synchronous generators,[50] such as wind and solar, have the ability to provide frequency response with smart inverters, which can be programmed to provide frequency response for very short periods using power electronics. Future resource capabilities likely will change based on the outcome of the Federal Energy Regulatory Commission (FERC) Notice of Proposed Rule Making entitled Essential Reliability Services and the Evolving Bulk-Power System—Primary Frequency Response.[51] In the NOPR, the FERC proposes requiring all new interconnected resources to provide frequency response. PJM's analysis assumes that, in future mixes, these resources will be capable of providing primary frequency response. Market changes may be needed, however, to incent non-synchronous generators to provide primary frequency response because, to do so, they need to operate below their maximum output.

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46 Synchronous Inertia - Due to electro-mechanical coupling, a generator's rotating mass provides kinetic energy to the grid (or absorbs it from the grid) in case of a frequency deviation $\Delta f$ arresting frequency decline and stabilizing the electric system. The contribution of inertia is an inherent and crucial feature of rotating synchronous generators.

47 Primary Frequency Response - involves the autonomous, automatic, and rapid action of a generator, or other resource, to change its output (within seconds) to rapidly dampen large changes in frequency.

48 Secondary Frequency Response, also known as automatic generation control, is produced from either manual or automated dispatch from a centralized control system. It is intended to balance generation, interchange and demand by managing the response of available resources within minutes as opposed to primary frequency response, which manages response within seconds. Secondary frequency response is accounted for in the Ramping generator reliability attribute.

49 Synchronous generator is an alternating-current generator whose average speed of normal operation is exactly proportional to the frequency of the system to which it is connected.

50 Non-Synchronous generator is an alternating-current generator whose average speed of normal operation is independent of the frequency of the system to which it is connected.

51 (Docket No. RM16-6-000), issued November 17, 2016, http://ferc.gov/whats-new/comm-meet/2016/021816/E-2.pdf

## Voltage Control

The second key indicator of the health and stability of the interconnection is system voltage. Voltage control, also an essential reliability service, is the ability of a generator to either inject or absorb "reactive power" either prior to or after a system disturbance (such as a generator or transmission facility tripping out of service) in order to maintain or restore system voltages to prescribed levels. Unlike real power (megawatts), reactive power (mega Volt Ampere reactive or MVAR) cannot be transmitted over long distances. For this reason, reactive power reserves must be geographically dispersed, located in close proximity to customer load. If sufficient reactive reserves are not maintained locally, disturbances can result in instability and potentially localized or wide-area blackouts. Typically, synchronous generator's voltage control is dependent upon reactive power control and physical moving parts of a generating machine.[52] New nonsynchronous generators are equipped with smart inverters to provide dynamic reactive power and voltage control capabilities as mandated by FERC Order 827.[53]

## Ramping

Ramping is the ability of a generator to increase or decrease real power (megawatts) in response to changes in system load, interchange schedules or generator output, in order to maintain grid reliability and compliance with applicable NERC standards. The generator reliability attribute of ramping is further defined by several attributes:

- **Regulation:** An amount of energy reserves from a resource that is responsive to automatic generation control, and is sufficient to provide normal regulating margin and frequency control as required in PJM Manual 12: Balancing Operations.[54]
- **Contingency reserve (synchronized reserves/non-synchronized reserves)**: The provision of capacity that may be deployed to respond to a contingency that results from a large mismatch between generation and demand, typically resulting from a loss of a generator.
- **Load following (dispatchable):** A generator that adjusts its power output as demand for electricity fluctuates throughout the day.

Load following capability varies by technology and/or fuel type. Modern utility-scale wind and solar plants typically can control their output from the full (currently available) power level down to zero. Conventional generators typically have minimum load levels below which they cannot reduce power. Minimum loads may be 40 percent or higher for coal plants, and nuclear plants typically offer limited load following capability. Because some combustion turbines must be block-loaded for emissions reasons, they offer no load following capability. Ramping control is typically faster and more accurate for the new natural gas combined cycle, wind and solar plants than for legacy fossil-fired or nuclear plants, although the capability for intermittent resources such as wind and solar plants to provide ramping capability is significantly limited by the uncertain availability of their fuel source. Such resources could therefore be extremely capable of providing ramping capability in the downward direction, but the upward direction is potentially constrained.

Traditionally, nuclear units in the PJM footprint have not been dispatchable or configured for load following. Reductions to nuclear units are done in a methodic and planned fashion, and the units typically take several hours to ramp down and to

[52] http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF_Draft_Concept_Paper_Sep_2014_Final.pdf

[53] https://www.ferc.gov/whats-new/comm-meet/2016/061616/E-1.pdf

[54] http://www.pjm.com/~/media/documents/manuals/m12.ashx

ramp back up. During emergency conditions, nuclear units would ramp down faster, but ramping up still would occur in a slower, more controlled fashion over several hours.

As a result of negative Locational Marginal Prices (LMP) market signals, some nuclear units have begun to operate in a load following manner much like a large steam unit. These nuclear resources have been able to operate as dispatchable resources in a range between 85 percent and 100 percent of their economic maximum.

As penetration of variable energy resources increases, additional load following capability is required from other resources in order to reliably offset rapid changes in output from renewable resources.

An August 2016 study conducted by the U.S. Department of Energy's National Renewable Energy Laboratory concluded that a portfolio mix consisting of greater than 30 percent renewable energy resources such as wind and solar "will cause other generators to ramp and start more quickly."[55]

### Fuel Assurance

For PJM operations, fuel assurance is defined as the ability of a resource to maintain economic maximum energy output for 72 hours, based on the definition of fuel limited resources within the PJM Manual 13: Emergency Operations Attachment C.[56] Fuel assurance considers the capability of the resource to store fuel on-site in order to limit the exposure to a single common event. It is necessary in order to provide the energy and reserves needed to maintain system reliability, independent of external delivery infrastructure or rapidly changing weather patterns.

### Flexibility

Flexibility is the ability of a resource to cycle, its total time required to start (including notification time), minimum run time and the number of starts per day.

- Cycle is the ability of a unit to start up and shutdown more than once in every 24-hour period.
- Startup/Notification Time: the sum total duration of notification and startup time of less than or equal to 30 minutes.
- Minimum Run Time/multiple starts per day: minimum run times less than or equal to two hours per start.

Flexible generators can come on or off-line and run for short periods of time when system load, interchange, or generator output is rapidly changing, which is most common during early morning periods or late afternoon periods.

Flexibility also is needed to maintain system reliability during minimum load periods, peak load periods, periods of rapidly changing variable energy resources, during transmission or capacity emergency conditions, or due to real-time changes in load profile and/or unit availability after day-ahead resource commitments are communicated.

The level of generator flexibility varies by technology and/or fuel type. Combustion turbines, hydro units and diesel generators typically provide the most flexibility, while fossil steam and nuclear units provide the least flexibility.

[55] http://www.nrel.gov/docs/fy16osti/64472-ES.pdf

[56] http://www.pjm.com/~/media/documents/manuals/m13.ashx

Both wind and solar resources have the flexibility to be dispatched in the downward direction in response to system constraints or minimum generation situations. Due to the variability of the sun and wind, however, their return to previous output cannot be assured, limiting the flexibility of these resources.

### Other

The "other" category of generator reliability attributes captures other relevant and noteworthy attributes. It includes:

- **Black start capability:** A unit that can start independent of a grid electrical source and that can supply electricity to the grid for the purposes of restoring the electric power grid and other generation resources following a widespread loss of the electric power grid. Typically, combustion turbines, hydro, diesel generators, as well as batteries, can be black start capable.
- **Environmental restrictions:** Typically a regulatory restriction, environmental restrictions may limit the number of hours a unit can produce power. Resources such as solar, batteries/storage and demand response have very few, if any, applicable environmental restrictions. Coal, natural gas, and nuclear steam units, as well as wind and hydro units, to some degree, have some environmental restrictions, which, as a rule, have limited impact on system operations. Coal and natural gas resources generally have limits on air emissions that can affect operations; nuclear units at times have encounter limits on cooling water, including pond/river levels and temperatures. Wind turbines shut down automatically during periods of high winds and sometimes are affected by bird or bat migration patterns. Hydro units have pond level and minimum flow requirements. Generation assets that burn liquid fuels tend to have the most restrictions, particularly tied to their air permits.

  **Equivalent availability factor:** The equivalent availability factor recognizes the equivalent demand forced outage rate, which is a measure of the probability that generating unit will not be available due to a forced outage or forced deratings, when there is a demand on the unit to generate.[57] For solar and storage, the equivalent availability factor is also calculated as a capacity factor, using outage data from eDART which is an electronic, internet-based tool used by PJM and member company operations for outage tracking[58] in lieu of generator availability data (GADs), since NERC GADs reporting requirements only apply to conventional resources larger than 20 MW.[59] For wind, the equivalent availability factor is calculated as a ratio of reductions/outages plus outages to generated megawatts in order to more accurately take into account wind conditions. For demand response resources, equivalent availability factor was determined by actual performance during prior load management events.

  For purposes of comparison in the matrix presented in Figure 6 above, generator equivalent availability factors are grouped as follows: >90 percent (exhibits attribute), 80-90 percent (partially exhibits attribute), and <80 percent (does not exhibit attribute).

## *Contributions from Other Resources*

Although this paper is primarily focused on fuel security for grid-connected generating resources, other resources such as Demand Response and Distributed Energy Resources also have to be accounted for. The characteristics of each of these are described in more detail below.

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[57] https://www.pjm.com/~/media/documents/manuals/m18.ashx

[58] http://www.pjm.com/markets-and-operations/etools/edart.aspx

[59] http://www.nerc.com/pa/rapa/gads/pages/default.aspx

## Demand Response

Demand response is an end-use customer who changes electric usage from normal levels in response to high real-time electricity prices or when system reliability is jeopardized.

PJM has approximately 8,500 MW of demand response committed for the 2016/2017 delivery year. The capacity commitment is primarily for limited demand response (6,800 MW), which has obligation to respond only June through September for up to six hours per event for 10 events per delivery year. The remainder is composed of extended summer demand response, annual demand response and annual Capacity Performance demand response.

Demand response is transitioning from seasonal products to annual Capacity Performance products. Demand response can participate voluntarily in the energy and ancillary service markets. Table 1 summarizes demand response participation in PJM energy and ancillary services markets.

**Table 1. Demand Response Participation in PJM Markets**

| | Energy (MW) | Sync Reserve (MW) | Regulation (MW) |
|---|---|---|---|
| Maximum | 2500 | 400 | 36 |
| Summer Peak | 1000 | 180 | 36 |
| Typical | 100 | 60 | <15 |

For demand response, the attributes identified in Figure 6 above are based how demand response participates within the PJM market based on current PJM business rules and market conditions (prices).

## Distributed Energy Resources

According to the NERC DER Task Force Report from November of 2016: "A distributed energy resource (DER) is any resource on the distribution system that produces electricity or actively alters the balance of demand or generation, and that is not otherwise included in the formal NERC definition of the bulk energy system."[60]

A grid operator's visibility of behind-the-meter real-time DER behavior is limited because today behind-the-meter DER is not required to supply telemetry data (such as output) to the grid operator. While telemetry for some utility-scale DER units may be available, the process for obtaining the data varies based on the local electric distribution company. Many DERs are solar photovoltaic generators that produce power only during specific times of day. Output from these solar units is not coincident with system peak loads during certain times of year. Depending on the level of penetration, DERs could require increased de-commitment/re-dispatch of centrally dispatched resources or off-system schedules to meet the balancing obligations. Recently proposed improvements to integration requirements for DER and implementation of a solar forecast within PJM are intended to lessen the impact on existing resources and improve market efficiency.

Most existing DERs were not designed to provide active voltage control and frequency response. Technology exists to allow DERs to provide these essential reliability services.[61] However, there is currently limited coordination between DER installations and bulk power system requirements enumerated in NERC standards.[62] This is because, in most cases,

[60] NERC DER Task Force Report - http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/May%202016%20Meeting%20Materials.pdf

[61] As specified in IEEE 1547 http://grouper.ieee.org/groups/scc21/1547_revision/1547revision_index.html

[62] Such as PRC-024-2 at http://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-024-2.pdf

DERs do not meet NERC registration criteria under the current NERC functional model,[63] which does not require most DERs to register as a Generator Owner or Generator Operator. As such, NERC standards would not apply to these entities.

### *Generator Reliability Attribute Quantification*

The reliability attribute matrix ( Figure 6 above) summarizes the capabilities of each resource type to provide services that are essential to system reliability. Using detailed analysis of generator operational data, each reliability attribute was quantified[64] to assess the capability of each resource type to provide each reliability service, and determine the total amount of each attribute available in different resource portfolios.

Importantly, the quantification approach was not based on energy dispatch models and does not capture the amount of each generator reliability attribute provided by resources that are online at any moment in time. The analysis does not capture the system requirement for each generator reliability attribute because the needs of the electric system are dynamic and dependent on the economic dispatch of resources. Instead, the quantification of the generator reliability attributes was based on the attribute capability of each resource type and the resource share of unforced capacity[65] in each portfolio. The total quantity of each attribute in a resource portfolio is the maximum amount available.

There were three main steps in quantifying the generator reliability attributes:

- Evaluate the capability of each resource type to provide generator reliability attributes, as outlined by PJM in Figure 6, and determine the total amount of each attribute in the system today.
- Develop resource type-specific capability factors for each generator reliability attribute that can be applied to the unforced capacity (UCAP) of each resource type in a resource portfolio. These factors were calculated based the attribute capabilities in the system today with the purpose of relating quantities of attributes to different UCAP amounts of each resource type.
- Apply the attribute capability factors to estimate amounts of each attribute and percent of total attribute capability provided by each resource type in potential future portfolios.

Current PJM operational data and experience were used quantify each reliability attribute in the system today. This served as the basis for the resource type-specific capability factors used to estimate the attribute capabilities of different portfolios. Additional detail about how each of the reliability attributes was quantified and converted into factors is detailed in the Appendix.

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63 http://www.nerc.com/pa/comp/Pages/Registration-and-Certification.aspx

64 The quantification methodology is explained in more detailed in the Appendix.

65 There are numerous ways the industry quantifies generation and capacity. Below are a few examples to help explain these terms and provide comparison:

Generation or energy – MWh, same for all resources

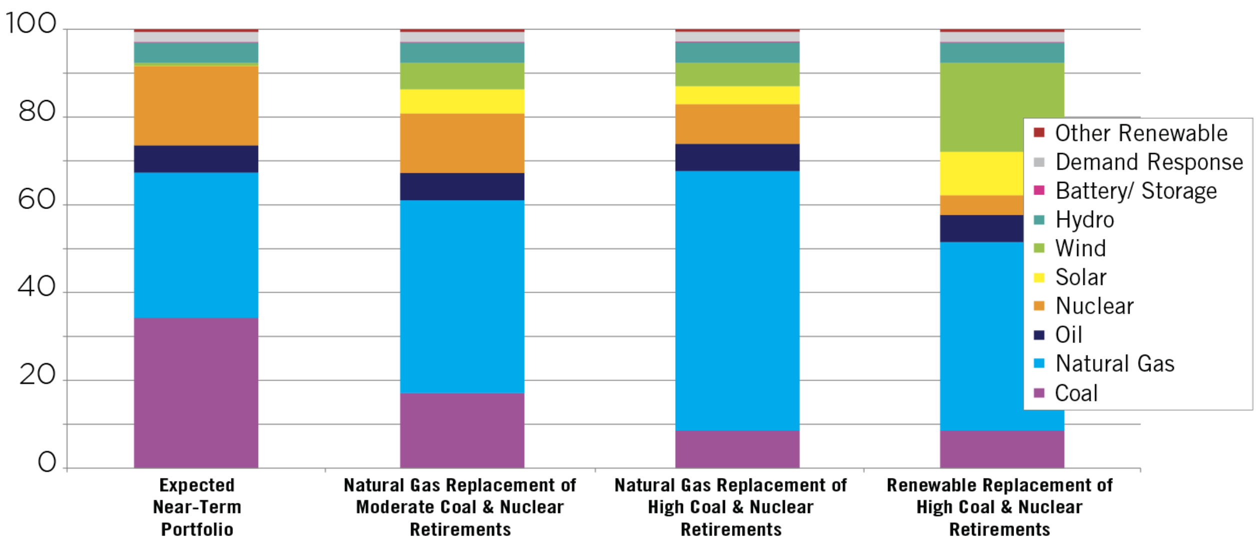
- Nameplate rating – MW, maximum sustained capability
- Unforced capacity (UCAP) – MW, value of a capacity resource in the PJM Capacity Market. For generating units, the unforced capacity value is equal to installed capacity multiplied by (1- unit's EFORd). For demand resources and energy efficiency resources, the unforced capacity value is equal to demand reduction multiplied by Forecast Pool Requirement.
- Example: Wind – 100MW ICAP = 13MW UCAP = 0.3 TWh per year (assuming 30 per cent net capacity factor)
  - Generator portfolio with 20 per cent of UCAP from wind compared with current portfolio:
  - 20 percent: 33,413 MW UCAP = 257,025 MW nameplate = 675.5 TWh energy per year (assuming 30 percent net capacity factor)
  - Current: 1085 MW UCAP = 8346 MW nameplate =21.9 TWh energy per year (assuming 30 per cent net capacity factor)

As the fuel mix was adjusted based on possible future scenarios, the analysis shows how much of each reliability attribute was lost or gained. These results show the impact on reliability for each possible future fuel mix scenario. Resource portfolios with reduced amounts of reliability attributes will have less capability to rely on during real-time operations to meet system needs, and may be at increased reliability risk. Such scenarios would require PJM and stakeholders to consider new technology requirements or market mechanisms to incent enhanced capability for the reliability services of concern.

Figure 7 compares the resource share of unforced capacity in PJM's expected near-term portfolio[66] and three sample future portfolios.[67] Figure 8 compares the total quantity of each reliability attribute in each portfolio, with the expected near-term portfolio as a baseline. The axis in Figure 8 is the generator reliability attribute ratio, which indexes the total amounts of attribute capability in the sample portfolios relative to that of the expected near-term portfolio. Values less than 1.0 indicate that there is less total attribute capability relative to the baseline. Values greater than 1.0 indicate there is greater total attribute capability relative to the baseline.

Figure 7 and Figure 8 depict the first major takeaway from quantifying the reliability attributes. As the resource mix moved in the direction of less coal and nuclear generation, there was a decrease in Fuel Assurance attribute capability and an increase in Flexibility attribute capability. These shifts were driven by differing capabilities of the resource types that comprise each portfolio. Natural gas, wind, and solar do not exhibit the same level of fuel assurance capability as do coal and nuclear. They do exhibit higher levels of the flexibility capability, however.

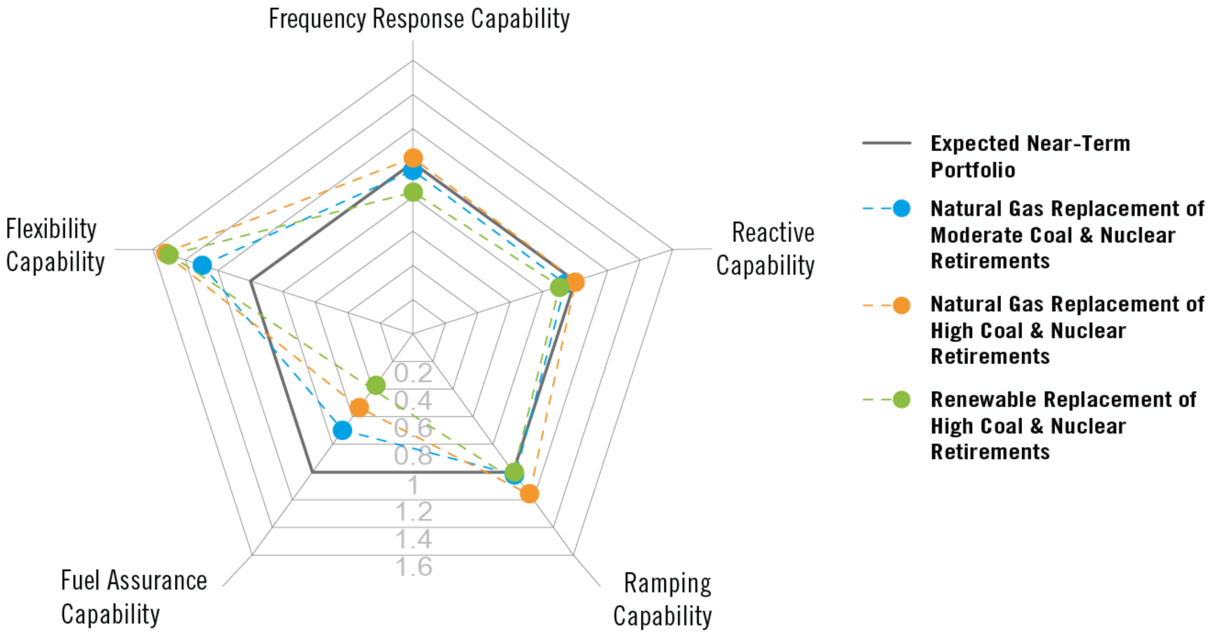
**Figure 7. Illustrative Resource Portfolios - Percent of Total Unforced Capacity**




[66] The 'Expected Near-Term PJM Portfolio' was established by projecting the composition of PJM's generation fleet out to 2021, and is described in more detail in the Risk Analysis Section.

[67] These are sample portfolios from the 360 potential future portfolios, which are described in the Risk Analysis section and the Appendix.

**Figure 8. Shift of Generator Reliability Attributes in Changing Portfolios**[68]




The heat maps in Table 2 compare the percent of total attribute capability provided by each resource type in the baseline portfolio and sample future portfolios. Table 2 illustrates the second major conclusion from quantifying the reliability attributes: as the amount of coal and nuclear resources in future portfolios decreases, the percent of total attribute capability provided by natural gas resources increases, indicating an increased reliance on natural gas resources to provide reliability attributes. The shift in reliance was most evident in the sample portfolio labeled "Natural Gas Replacement of High Coal & Nuclear Retirements." Compared to the baseline, natural gas resources contribute 69 percent of total Reactive Capability, a large shift from 39 percent.

Additionally, the highlighted boxes around specific attribute categories in Table 2 further illustrates that there was a reduced amount of total attribute capability relative to the baseline portfolio. For example, the sample portfolio labeled "Renewable Replacement of High Coal & Natural Gas Retirements" had less total capability for frequency response, reactive, ramp, and fuel assurance attributes relative to the baseline portfolio, and increased reliance on natural gas to provide these attributes.

[68] The axis values in Figure 8 are reliability attribute ratios, which index the total amounts of capability for each attribute in the sample portfolios relative to the total amount in the baseline portfolio. The attribute ratios for the baseline portfolio =1.0. Values less than 1.0 indicate that there is less total attribute capability relative to the baseline. Values greater than 1.0 indicate there is greater total attribute capability relative to the baseline.

**Table 2. Shift in Reliance on Resource Types to Provide Generator Reliability Attributes**

| | Unforced Capacity | Frequency Response Capability | Reactive Capability | Ramp Capability | Fuel Assurance Capability | Flexibility Capability | Unforced Capacity | Frequency Response Capability | Reactive Capability | Ramp Capability | Fuel Assurance Capability | Flexibility Capability |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Expected Near-Term Portfolio** | | | | | | **Natural Gas Replacement of Moderate Coal & Nuclear Retirements** | | | | | |
| **Coal** | 34.2% | 19.7% | 35.5% | 27.9% | 32.9% | 5.8% | 17.1% | 12.8% | 18.9% | 15.3% | 25.1% | 2.2% |
| **Natural Gas** | 33.1% | 31.2% | 39.0% | 47.9% | 7.6% | 50.4% | 44.0% | 38.1% | 55.0% | 61.2% | 13.5% | 51.5% |
| **Oil** | 6.2% | 15.5% | 6.8% | 5.6% | 21.4% | 15.9% | 6.2% | 14.7% | 7.3% | 5.5% | 22.5% | 12.3% |
| **Nuclear** | 18.1% | 9.7% | 13.3% | 0.0% | 22.7% | 0.0% | 13.6% | 7.7% | 10.6% | 0.0% | 22.9% | 0.0% |
| **Solar** | 0.1% | 1.5% | 0.0% | 0.0% | 0.0% | 0.1% | 5.5% | 2.8% | 0.6% | 0.0% | 0.0% | 3.9% |
| **Wind** | 0.6% | 3.0% | 0.2% | 0.1% | 0.0% | 1.3% | 6.1% | 5.6% | 2.2% | 0.6% | 0.0% | 9.4% |
| | **Renewable Replacement of High Coal & Nuclear Retirements** | | | | | | **Natural Gas Replacement of High Coal & Nuclear Retirements** | | | | | |
| **Coal** | 8.6% | 10.0% | 10.7% | 7.6% | 21.4% | 0.9% | 8.6% | 9.0% | 8.8% | 6.4% | 18.6% | 1.0% |
| **Natural Gas** | 43.0% | 43.5% | 61.1% | 65.3% | 20.3% | 40.9% | 59.2% | 45.2% | 69.3% | 72.8% | 21.6% | 58.7% |
| **Oil** | 6.2% | 15.5% | 8.3% | 6.1% | 24.8% | 10.0% | 6.2% | 14.5% | 6.8% | 4.9% | 23.3% | 10.4% |
| **Nuclear** | 4.5% | 3.2% | 4.1% | 0.0% | 16.1% | 0.0% | 9.0% | 4.8% | 6.7% | 0.0% | 20.0% | 0.0% |
| **Solar** | 9.9% | 2.8% | 1.2% | 0.1% | 0.0% | 5.7% | 0.1% | 2.8% | 0.0% | 0.0% | 0.0% | 0.0% |
| **Wind** | 20.3% | 5.6% | 8.4% | 2.3% | 0.0% | 25.5% | 9.3% | 5.6% | 3.2% | 0.9% | 0.0% | 12.4% |

NOTE: Hydro, battery/storage, demand response and other renewables are excluded from this graphic because their contribution to the total amount of reliability services is consistent in each example portfolio.

Evaluating the total amount of generator reliability attributes in different resource portfolios aids in understanding the potential impact of generation mix change. The quantified generator reliability attributes were used to create a composite reliability index that was applied in a reliability risk model for 360 potential future generation portfolios and is discussed in the next section.

## Risk Analysis

This analysis examined the reliability risk of various potential resource portfolios.[69] Two components of reliability risk were studied: 1) resource adequacy reliability and 2) operational reliability, defined as the capability to provide the generator reliability attributes identified in Figure 6 and quantified in the previous section. Resource adequacy addresses the amount of capacity needed to satisfy a forecasted peak load while meeting the Loss of Load Expectation criterion, whereas the generator reliability attributes supply the grid's day-to-day operational needs. These generator reliability attributes are generally not included in PJM's resource adequacy studies. Note that there can be multiple portfolios that meet PJM's resource adequacy criterion but that may not have adequate ability to provide operational reliability.

To examine future portfolio compositions, recent trends in PJM's generator interconnection queue and deactivation announcements were used to develop 360 potential portfolios. Each prospective portfolio was evaluated for its ability to provide adequate levels of the generator reliability attributes and was benchmarked against PJM's projected 2021 capacity mix.[70] Portfolios that are best able to provide the generator reliability attributes under four operational states were identified.

### *Method*

PJM developed a methodology to determine the relative operational reliability and assess the risk of each prospective portfolio. Figure 9 shows the steps associated with the Risk Analysis Methodology.

**Figure 9. Risk Analysis Methodology**


In the first step, a baseline portfolio is established by projecting the composition of PJM's current resource mix out to 2021.[71] The baseline portfolio is developed to meet the industry standard resource adequacy "one day in 10 year" criterion, known as the Loss of Load Expectation (LOLE)[72]. To ensure that the portfolio has adequate capacity to meet the LOLE,

[69] PJM performed the risk analysis based on unforced capacity provided by resources within a portfolio. Energy was not considered in this section.

[70] Greater detail on how portfolio capabilities are calculated is located in the Appendix.

[71] The baseline portfolio was projected out to 2021 to account for near-term trends in announced retirements and added capacity from the PJM Generation Queue. More detail on this approach is in the Appendix.

[72] ReliabilityFirst Standard BAL-502-RFC-02 – http://www.nerc.com/files/BAL-502-RFC-02.pdf

the total megawatt amount of unforced capacity within the portfolio was set equal to a fixed megawatt reliability requirement and the installed reserve margin[73] is allowed to vary.

Next, a set of alternative portfolios was created by incrementally retiring coal and nuclear units and replacing them with natural gas, solar and wind resources. All other resource types were held constant at the baseline level. Each alternative portfolio was derived such that it meets the "one day in 10 year" LOLE criterion. Since today's capabilities in storage are limited, and cannot account for large changes in wind and solar generation, the portfolios were subjected to a second LOLE test to account for intermittency in output from wind and solar. This second test ensured that portfolios with large unforced capacity shares of intermittent resource were able to serve load during hours that the output of these resources was significantly lower than their capacity credits. Portfolios that failed this second LOLE test were considered infeasible.

After imposing the second LOLE test, the feasible portfolios were assessed for their ability to provide the generator reliability attributes displayed in Figure 6 under four operational states: normal peak conditions, light load, extremely hot weather and extremely cold weather. Reliability indices that quantify the performance[74] of each portfolio against the baseline portfolio's performance were created under each operational state. These reliability indices were averaged to create a composite reliability index.[75]

The composite reliability index (CRI) measured a portfolio's capability to supply all of the generator reliability attributes across the four operational states, relative to the baseline portfolio. Low composite reliability indices indicated reduced capability of a portfolio to provide the generator reliability attributes. As portfolios became less capable to provide the generator reliability attributes that meet system needs during real-time operations, operational reliability risk increased. Therefore, to identify trends in portfolio compositions that potentially pose operational reliability risk that may necessitate additional technology requirements or market mechanisms, the portfolios were placed into performance categories based on composite reliability index values.

Table 3 describes the reliability criteria used to classify each performance category.

### Table 3. Performance Classification

| Performance | Classification Criterion | Technology Requirements or Market Mechanisms Necessary to Ensure Adequate Reliability Services |
|---|---|---|
| Infeasible | Violates LOLE | Highly likely |
| At-Risk-for-Underperformance | CRI < 0.90 | Highly likely |
| Less-than-Baseline | 0.90 < CRI < 1 | Likely |
| Greater-than-Baseline | CRI > 1 | Unlikely |
| Desirable | RI > 0.95 in all operational states | Highly unlikely |

[73] The Installed Reserve Margin is the installed capacity percent above the forecasted peak load required to satisfy the LOLE. PJM typically has resources in the form of capacity or energy-only that exceeds the IRM requirement and were not considered as part of the Risk Analysis Methodology.

[74] Greater detail on how portfolio performance is quantified is described in the Appendix.

[75] Each resource's capability to provide the generator reliability attributes is calculated using the quantification method explained in the reliability attribute quantification section.

Finally, to test the hypothesis that greater fuel diversity results in greater reliability, the Shannon-Wiener diversity index was compared to the composite reliability indices of the portfolios. The Shannon-Wiener diversity index is a commonly used measure of diversity that PJM adapted to measure two of the three components of fuel diversity described in the background section: 1) the variety of fuel types in a portfolio and 2) how balanced the share of unforced capacity is among the fuel types.[76] The third component of fuel diversity, disparity, was captured by the composite reliability index.

In summary, this analysis provides information regarding the capability of potential portfolios to provide operational reliability across a range of operational states and also regarding the relationship between fuel diversity and reliability.

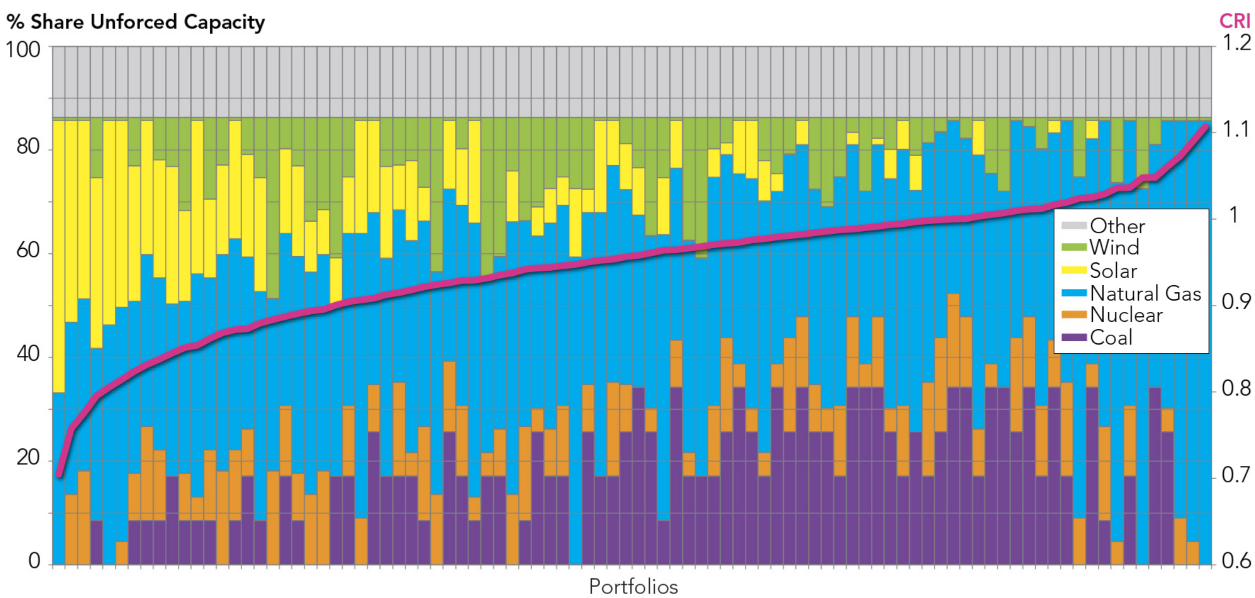
## *Results*

### Composite Reliability Index

Composite reliability indices of the portfolios considered in this analysis ranged from 0.70 to 1.11 with the baseline portfolio's CRI equal to 1.00. This range indicated that the lowest performing portfolio's ability to provide the full range of generator reliability attributes was approximately 30 percent less than that of the baseline portfolio. Likewise, the highest performing portfolio's measured capability was nearly 11 percent greater than the baseline.

Figure 10 displays the overall trend between the composite reliability index and various resource portfolios. The composition of the portfolios was tracked on the primary vertical and is represented by the stacked bar graph. The corresponding composite reliability index for each portfolio was tracked on the secondary vertical and is represented by the red line.

**Figure 10. Portfolio Composition and Composite Reliability Index**




The composite reliability indices varied across portfolios and were dependent upon the composition of the portfolio. Despite variation, broad trends emerged by resource type:

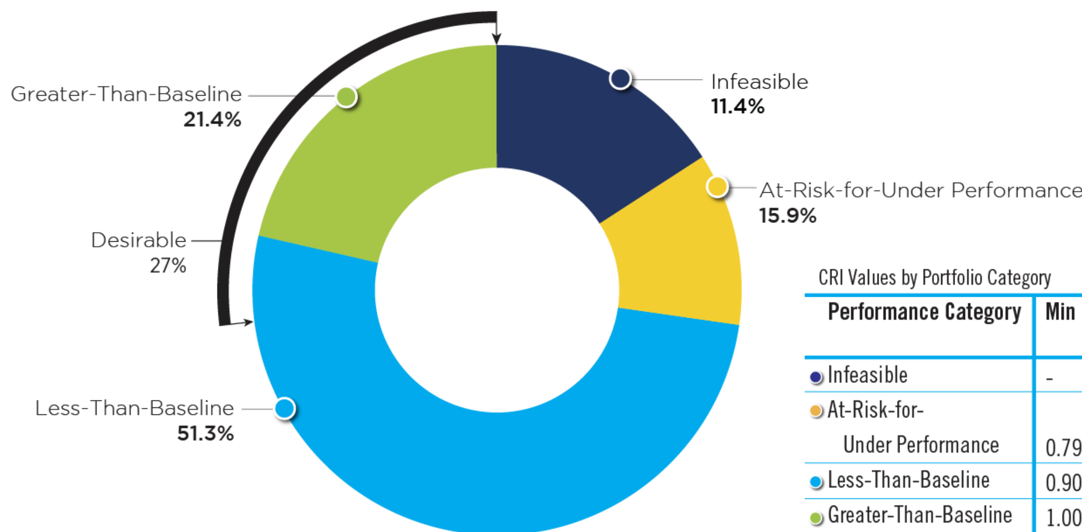
76 The Shannon Wiener Index only captures the variety and balance aspects of diversity, discussed in the Background section. The disparity aspect of diversity is accounted for in the differing generator reliability attribute capabilities of each resource type.

- Portfolios with the largest unforced capacity shares of wind and solar tended to have the lowest composite reliability indices. This indicates that these portfolios have reduced capability in the some of the generator reliability attribute categories, specifically the Essential Reliability Services and Fuel Assurance, relative to the baseline portfolio.
- Composite reliability indices generally improved as unforced capacity shares of nuclear, coal and natural gas increased. This is due to these fuel types collectively exhibited the majority of the generator reliability attributes displayed in Figure 6.
- When coal and nuclear units were retired and replaced, portfolios with the highest composite reliability indices tended to be ones in which natural gas is the predominant replacement resource. This is because natural gas provides a broad range of the generator reliability attributes.

## Composition of the Performance Categories

To identify trends in portfolio compositions that potentially pose operational reliability risk that may necessitate additional technology requirements or new market mechanisms, the portfolios were placed into performance categories based on composite reliability index values. Figure 11 describes the distribution of the composite reliability indices.

**Figure 11. Distribution of the Performance Categories**




CRI Values by Portfolio Category

| Performance Category | Min | Max | LOLE Criterion |
|---|---|---|---|
| ● Infeasible | - | - | Failed |
| ● At-Risk-for-Under Performance | 0.79 | 0.90 | Met |
| ● Less-Than-Baseline | 0.90 | 0.99 | Met |
| ● Greater-Than-Baseline | 1.00 | 1.11 | Met |
| ■ Desirable | 0.95 | 1.11 | Met |

## Infeasible

The determination of a portfolio's feasibility in this analysis was independent of its composite reliability index values. Only portfolios that failed to meet the second LOLE test were categorized as infeasible. Most portfolios with an unforced capacity share of solar above 20 percent violated LOLE and were therefore categorized as infeasible. This outcome is the result of an inability for these portfolios to serve load during hours in which solar resources' output is significantly below its 38 percent capacity credit (for example, during high-load winter days at hours with no sunlight or high levels of cloud cover). It is important to note that not all portfolios with an unforced capacity share of solar greater than 20 percent violated the second LOLE test. Some portfolios with unforced capacity shares of solar greater than 20 percent benefited from the over-performance of wind at times when the solar resources' output was significantly below its 38 percent capacity credit.[77] As a result, these portfolios did not violate LOLE.

### At-Risk-for-Underperformance

A low composite reliability index indicated that a portfolio either did not exhibit or only partially exhibited several of the generator reliability attributes across the four operational states. As a portfolio's ability to provide the generator reliability attributes decreased, the risk of that portfolio underperforming increased. Portfolios in this category were highly likely to necessitate additional technology requirements and/or new market rules to ensure adequate reliability services. Therefore, portfolios unable to provide at least 90 percent of the composite reliability index of the baseline portfolio were considered at-risk-for-underperformance.

A majority of the portfolios with composite reliability indices low enough to be categorized as at-risk-for-underperformance were portfolios in which most of the coal and nuclear units are retired and replaced primarily by wind. These portfolios tended to underperform in three of the four studied operational states: base load, extremely hot and extremely cold weather. This poor performance was generally driven by low measured capability of these portfolios to provide Synchronous Inertia, Voltage Control, Ramp Capability and Fuel Assurance.

### Less-Than-Baseline

The less-than-baseline category was comprised of more than 50 percent of the portfolios, all of which had composite reliability indices within 10 percent of the baseline. Portfolios within this category tended to have relatively low reliability indices under the two extreme weather scenarios, but better performance under the other two operational states. These portfolios were less equipped to provide the reliability attributes, but still benefited from strong performance of several resources in providing the generator reliability attributes.

The performance of portfolios in this category was largely due to the incremental replacement of coal with increasing unforced capacity shares of solar or wind, and a moderate share of natural gas. Unlike coal, these resources either did not exhibit, or only partially exhibited generator reliability attributes that are stressed during extreme weather conditions such as Ramp Capability and Fuel Assurance. These portfolios were not classified as at-risk-for-underperformance, but they did not provide the same level of generator reliability attributes as the baseline. A trend toward portfolios that fall within this category would indicate that PJM and its stakeholders should consider new technology requirements and market rules to address potential operational reliability shortfalls.

### Greater-Than-Baseline

Portfolios in the greater-than-baseline category were those with composite reliability index values higher than 1.00. These portfolios had increased capability to provide the generator reliability attributes than the baseline because of the operational characteristics of the resources in those portfolios. It is unlikely that these portfolios will have reduced capability to provide generator reliability attributes under the four operational states. Therefore, they were not likely to necessitate additional technology requirements or new market mechanisms to incent adequate generator reliability attribute capability.

This category represented 21.4 percent of the analyzed portfolios and was generally composed of portfolios in which coal and natural gas[78] accounted for majority unforced capacity shares with moderate levels of nuclear, solar and wind

[77] The composition of each portfolio within the performance categories is graphically depicted in the Appendix.

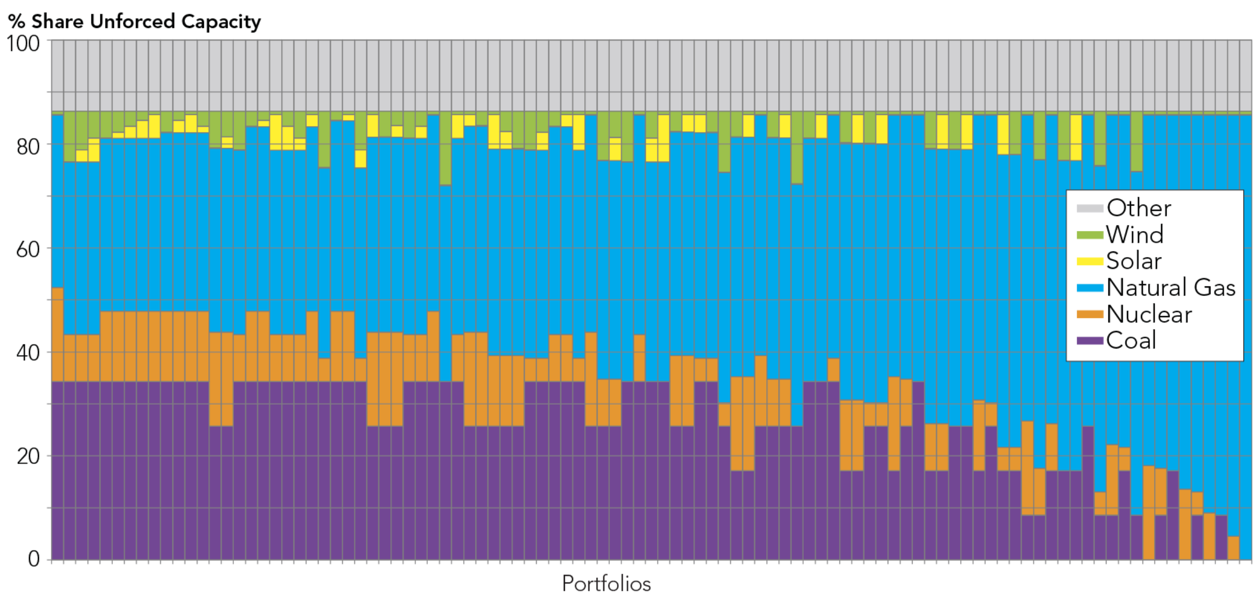
unforced capacity. Gains in generator reliability attribute capability were due to the fact that the predominant resources in the greater-than-baseline category – natural gas and coal – collectively exhibited the majority of generator reliability attributes displayed in Figure 6. The attribute shortcomings of natural gas and coal were met by other resource types in a portfolio. For example, natural gas has reduced capability for onsite fuel because it is extremely dependent on delivery infrastructure, while nuclear has ample onsite fuel capability. Coal units have reduced capability for Flexibility attributes, but are in portfolios with other resources that have shorter minimum run times and shorter startup times.

### "Desirable" Portfolios

Under some circumstances, a portfolio's high composite reliability index was due to over-performance in one or more of the operational states, despite under-performing under another operational state. Therefore, portfolios that consistently exhibited high levels of the generator reliability attributes under each operational state were considered best equipped to provide the generator reliability attributes. Portfolios that had the capability to provide 95 percent or more of the baseline's capability under each studied operational state were categorized as desirable.

Twenty-seven percent of the studied alternative portfolios met this criterion. Figure 12 depicts the composition of the desirable portfolios.

**Figure 12. "Desirable" Portfolios**




Natural gas and, to a lesser degree, coal, individually exhibit a broad range of the generator reliability attributes. Therefore, portfolios with large shares of both natural gas and coal exhibited a majority of the generator reliability attributes. As a result, these resources tended to represent a majority unforced capacity share in the portfolios classified as desirable. However, coal and natural gas did not fully exhibit all of the generator reliability attributes and benefited from the addition of wind, solar and nuclear unforced capacity. Thus, most of the desirable portfolios were composed of relatively large

[78] Natural gas resources within each portfolio include both steam and combustion turbines in the same ratio as the baseline expected near-term portfolio: 60 percent and 40 percent, respectively.

unforced capacity shares of coal and natural gas, with moderate unforced capacity shares of wind, solar and nuclear to provide the full range of generator reliability attributes.

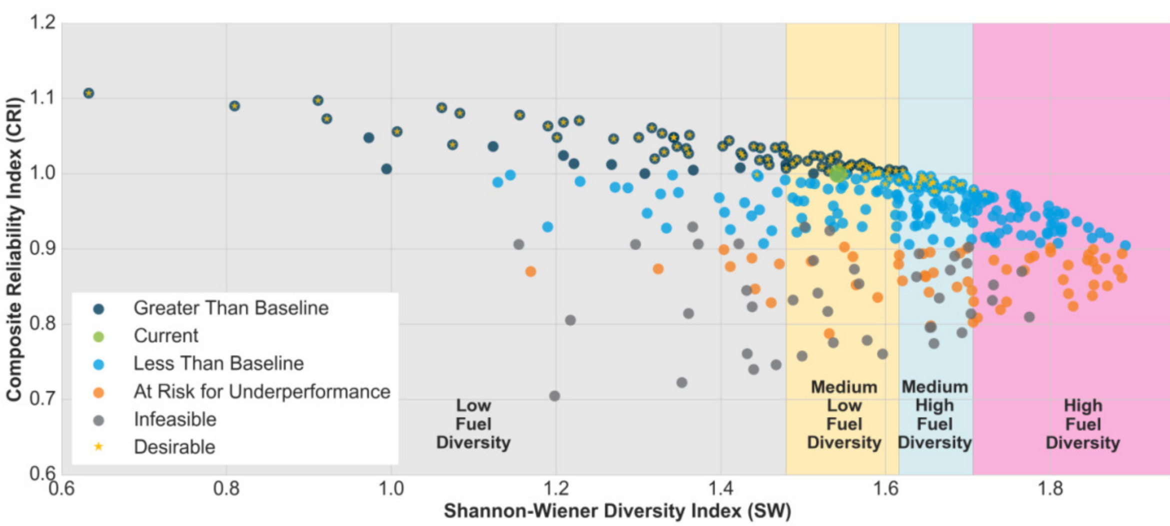
Because wind and solar exhibited limited capability in providing certain generator reliability attributes, upper bounds for wind and solar unforced capacity shares were identified within the desirable category. The upper bound for wind occurred in a portfolio in which a large unforced capacity share of nuclear was retired and replaced exclusively by unforced capacity of wind and natural gas. Similarly, the upper bound for solar within the desirable category occurred in a portfolio in which a large unforced capacity share of nuclear was replaced exclusively by solar and natural gas unforced capacity. Note that, to be included in the desirable category, portfolios with moderate unforced capacity shares of wind and/or solar required relatively large shares of both coal and natural gas. Although an upper bound was identified for wind and solar, a number of portfolios with unprecedented wind and solar unforced capacity shares in PJM were included in the desirable category.

Natural gas generation, on the other hand, performed well across a broad range of reliability attributes. Specifically, the potential portfolio with the greatest share of natural gas, 86 percent, showed no decreases in performance under the four operational states and was included in the desirable category. As mentioned earlier, portfolios composed of natural gas unforced capacity shares greater than 86 percent were not considered in the analysis because they were implausible. Therefore, a performance-based upper bound for natural gas was not identified by the analysis. Operational risk with respect to natural gas, however, may exist in other aspects not considered by this risk analysis. These aspects include infrastructure, economics, policy, and resilience.

### *Composite Reliability Index and the Shannon-Wiener Diversity Index*

To better understand the relationship between fuel diversity and reliability, the composite reliability indices were analyzed against the Shannon-Wiener Diversity Index. Figure 13 displays the relationship between the Shannon-Wiener diversity indices and the composite reliability indices.

**Figure 13. CRI vs. Shannon-Wiener Diversity Index**




Fuel diversity alone is not an indication of reliability. Because not all fuel types have the same capability to provide the generator reliability attributes, the relationship between fuel diversity and the generator reliability attributes is dependent upon the composition of the fleet. As depicted in Figure 13, several portfolios with low diversity had high composite reliability indices. However, there were also many portfolios with low diversity that had low composite reliability indices.

The capability of capacity resources to exhibit the full range of generator reliability attributes determined the reliability of a portfolio, rather than how many fuel types were in a portfolio or how balanced the share of unforced capacity was among the fuel types.

## Fuel Security and Resilience

Although resource portfolios with low diversity may have high reliability indices because they are likely to provide adequate amounts of the defined key generator reliability attributes, "heavy" reliance on one resource type raises questions about electric system resilience, which are beyond questions about already-accepted measures of reliability attributes as have been discussed in this paper. Resilience is the capability of an energy system to tolerate disturbance and to continue to deliver energy services to consumers.

History has shown that, despite having a system that meets reliability standards and requirements, rare extreme events, such as those experienced in PJM and other parts of the world, may produce negative impacts to the system that threaten the ability to continue to deliver energy services. Such events may trigger higher-than-average unit unavailability rates that are not captured by the reliability risk analysis. Therefore, PJM analyzed for a polar vortex[79] sensitivity to show an example of such an impact. This sensitivity analysis is described in Appendix IV: Risk Analysis.

The resilience of the portfolios identified as desirable by the risk analysis was tested by subjecting the desirable portfolios to a polar vortex event. Such an event may trigger higher-than-average unavailability rates for fuel types such as natural gas, coal and solar. To determine these potential higher-than-average unavailability rates, generator performance data from high load days during Winter 2014/2015 and Winter 2015/2016 were analyzed by fuel type. The maximum unavailability rates during those days were applied to the portfolios in the desirable region. Reliability indices and composite reliability indices were recalculated.

Only 34 of the 98 portfolios which were classified as desirable were resilient when subjected to a polar vortex event. This sensitivity specifically captured the increased risk of natural gas delivery under extremely cold and high load conditions. The polar vortex sensitivity highlights the importance of resilience, which is not captured by the generator reliability attributes that were considered in this study.

A resilient energy system can anticipate, minimize the impact of and quickly recover from shocks. It also can provide alternative means of satisfying energy service needs in the event of changed external circumstances.[80] In addition to delivering energy services reliably during strained system conditions to which probabilities can be attached (e.g., plant outages, weather variability), a resilient energy system also must be resistant to larger scale shocks to which it is difficult to attach probabilities and that can exceed NERC planning N-1-1 and operations N-1 criteria.[81] [82]

[79] Large portions of the United States experienced abnormally low temperatures caused by a polar vortex in early January 2014. Coinciding with the hour of peak demand, on January 7, approximately 22 percent of total generation capacity in PJM was not available.

[80] http://www.ukerc.ac.uk/publications/building-a-resilient-uk-energy-system-research-report.html

[81] http://www.nerc.com/_layouts/PrintStandard.aspx?standardnumber=TPL-001-4&title=Transmission System Planning Performance Requirements&jurisdiction=United%20States

[82] During real-time, the electric system must be operated so that it can continue to operate reliably following the failure of any one element on the system, e.g., a generating unit or a transmission line. For planning purposes, the grid must be planned and built so that it is capable of withstanding the unexpected loss of one transmission element followed by the loss of a second element.

Ultimately, the most desirable portfolios are those portfolios that are able to adequately supply all generator reliability attributes and that show resilience in the face of other risks associated with rare extreme events.

### *Previous Natural Gas and Renewables Studies*

Owing to the increased natural gas dependency, PJM, ISO-New England, the Midcontinent Independent System Operator, New York ISO, the Ontario Electric System Operator and the Tennessee Valley Authority, part of the Eastern Interconnection Planning Collaborative (EIPC), with the financial support of the U.S. Department of Energy, commissioned an independent analysis of the robustness of pipeline infrastructure in their regions to meet future electric demand under a variety of scenarios. The EIPC's Gas-Electric System Interface Study,[83] completed in 2015, represented a first of its kind comprehensive analysis of the gas infrastructure's capability to serve the future needs of electric generation over a region that encompasses 35 states and the province of Ontario.

Overall, the EIPC analysis demonstrated that, even under a high-gas-demand scenario, a robust pipeline infrastructure is available through 2023 to serve generation through the overwhelming majority of the PJM footprint. Limited potential locational constraints were identified during the peak heating season in eastern PJM, with most issues associated with generators dependent on the local gas distribution company. Modeling of gas-side contingencies, such as a pipeline break, found that affected generators were spread across many pipelines, thus limiting the impact of a single contingency. Additionally, dual-fuel capability was found to be available, deliverable and economically advantageous in PJM, providing additional resilience to mitigate the risk of gas pipeline contingencies on the electric grid. Although, the EIPC analysis found a robust infrastructure from a physical viewpoint, it also highlighted notable differences between the available infrastructure and the contractual availability and allocation of that infrastructure to meet the needs of the power generation sector.

PJM studied as well the potential impacts of increased dependence on renewable resources, specifically solar and wind. The PJM Renewable Integration Study,[84] conducted by GE Energy Consulting in 2014, investigated operational, planning and energy market effects of large-scale wind/solar integration and made recommendations for possible facilitation/mitigation measures. The study found that "the PJM system, with adequate transmission expansion and additional regulating reserves, will not have any significant issues operating with up to 30 percent of its energy provided by wind and solar generation." Recommendations were made to increase the regulation requirement to compensate for the increased variability resulting from wind and solar generation, develop a methodology to adjust renewable capacity market value, improve the wind and solar forecast through use of mid-range (shorter-term) forecasts, and explore improvements to ramp-rate capability of the existing base load fleet.

### *Risks to Resilience*

Grid resilience is increasingly important considering the number of associated risks – cybersecurity, more extreme weather events, increasing dependence on natural gas pipelines, aging infrastructure and resource category retirements. Add to those more reliance on the internet of things,[85] data and interconnected systems, which create an increased risk of cyber incidents. Preparedness, hardening, robustness, redundancy and autonomy are all components of a comprehensive view of grid resilience.

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[83] Information and documents regarding the EIPC Gas-Electric Interface Study: http://www.eipconline.com/gas-electric.html

[84] PJM Renewable Integration Study information and documents: http://www.pjm.com/committees-and-groups/subcommittees/irs/pris.aspx

[85] Internet of things - http://www.mckinsey.com/industries/high-tech/our-insights/the-internet-of-things

Although PJM's established planning, operations and markets functions should ensure that future portfolios would maintain adequate levels of reliability services and fuel security, external drivers – such as economics and public policies – have impacted, and could further impact, the mix of resources in the future. The resource mix could evolve in a way that results in less-than-adequate generator reliability attributes and fuel security because a vast majority of resources could be unavailable because, collectively, they rely either on a single technology or a single fuel.

While redundancy in technology or fuel source helps to mitigate this risk, backup or dual fuel capability currently tends to be limited to supporting sustained operation for a matter of days and, therefore, is dependent on resupply. However, recent studies, including the Black Sky/Black Start Protection Initiative, suggest that 30 days of fuel inventory would be required to adequately respond to Black Sky type events.[86] Although practical for nuclear, oil and coal resources, such a requirement would be a more significant challenge for natural gas plants, which could become a challenge in the future. With no identified maximum plausible penetration of natural gas resources that reach the point of presenting reliability concerns (see the Risk Analysis section above), natural gas resources could continue to replace uneconomic coal and nuclear units at very high levels. While these high levels of natural gas capacity do not suggest direct reliability issues, a very high dependence on one fuel type may create other resilience issues, such as those vulnerabilities identified by the natural gas industry, as discussed later in the paper.[87]

### *Role of Capacity Performance*

In April 2015, in an effort to address the risks of fuel security associated with individual generating plants, PJM revised how capacity resources were defined and compensated in the capacity market. The new capacity product, called Capacity Performance, incents generators to commit to more stringent performance requirements. This includes the "firming" of fuel supply (through firm gas service contracts, firm service contracts with greater flexibility or the installation of dual-fuel capability), as well as investment in operations and maintenance to shorten minimum run times and increase operational flexibility. However, while Capacity Performance improves individual generator availability, to be resilient PJM must take account of the possibility of larger-scale disruptions of the natural gas supply system.

The Capacity Performance product was introduced in response to several changing conditions on the grid – including an unprecedented fuel switch from coal to natural gas and sharply lower wholesale electricity prices, which inhibited needed investments in plant maintenance, upgrades and modernization – all of which profoundly affected the availability of generation, particularly during cold weather. PJM's studies of generator performance during the cold weather of January 2014 highlighted that changes were needed in performance requirements, incentives and charges for non-performance to ensure adequate availability during peak days.

PJM has been transitioning into the Capacity Performance construct since 2015 by procuring more of the Capacity Performance product with each annual Reliability Pricing Model (RPM) Auction. In the 2017 RPM Base Residual Auction for the 2020/2021 Delivery Year, 100 percent of the capacity procured will be Capacity Performance. While there has not yet been an operational test of this new product, PJM has seen improved operational flexibility in capacity resources and increased investment by generators to meet the stricter performance requirements. These improvements map to some of the attributes identified in the Generator Reliability Attributes Matrix, such as fuel assurance and flexibility.

[86] EIS - The Black Sky/Black Start Protection Initiative (BSPI™), http://www.eiscouncil.com/App_Data/Upload/BSPI.pdf

[87] DOE – AGA - Natural Gas Resiliency - https://energy.gov/sites/prod/files/2015/01/f19/AGA.Resiliency%20Metrics%20workshop.pdf

Through stricter performance requirements, incentives and charges for non-performance, Capacity Performance holds capacity resources accountable to make the necessary investments and operational improvements required to ensure delivery of energy when needed most. For example, these investments include firming fuel supply, investing in dual-fuel capability (which combines back-up oil fuel with primary natural gas fuel), increased staffing, capital investments for better operational flexibility, and cold-weather testing on alternate fuels. These investments are based on risks to performance that a resource can anticipate, plan for, budget for and implement.

Capacity Performance is, therefore, designed to address the risks of fuel security associated with individual generating plants by incenting the "firming" of fuel supply through firm gas service contracts, or firm service contracts with greater flexibility, or the installation of dual fuel capability, which combines back-up oil fuel with primary natural gas fuel. The flexibility of dual fuel units has to be balanced with the additional emissions restrictions and this will require continued collaboration with affected resources and regulatory agencies such as the Environmental Protection Agency. However, in order to be resilient, PJM needs to take account of the possibility of larger-scale disruptions of the natural gas supply system.

Although Capacity Performance places the risk of non-performance squarely on the generator – even for events occurring outside the control of the generator (such as loss of fuel supply due to pipeline ruptures or localized extreme weather events), the risks generators assume are those that are captured within the sphere of traditional NERC standards (i.e., N-1-1 planning or N-1 operational events). However, another set of systemic risks can affect the entire fleet and are beyond those traditional NERC standards. While PJM currently studies some of these types of contingencies in planning and operations, consistent with NERC standards, PJM also should examine plausible actions based on potential systemic risks, which are characterized as high-impact, low-probability events, the occurrence of which cannot be predicted with certainty and are beyond what any one resource reasonably can anticipate and mitigate through capital investments and operational improvements. Given the changing nature of the fleet and a new set of threats that were not anticipated under the current NERC standards, prudent planning and operations requires the anticipation and mitigation of potential future occurrence of events, such as:

- sustained supply-chain issues
- environmental actions that limit operations of an entire fleet of fossil generators
- a nuclear disaster, which causes regulatory reaction for new and existing nuclear fleet
- a single incident causing major, multiple pipeline or supply disruptions for the natural gas fleet or oil fleet
- a major impact to a large portion of the transmission infrastructure that forces an outage lasting for days, such as a major natural disaster that impacts large sections of grid including resources and the infrastructure that connects the resources to consumers

### *Extreme Contingencies and Resilience*

Capacity Performance has appropriately placed a degree of risk of non-performance on generators – irrespective of whether the driving factor was technically within the generator's control or involved its own facility and potentially others near it. Nevertheless, the high-impact systemic events described above also need attention. Currently, NERC does not require mitigating common mode failures or natural gas interdependency risks. NERC defines an N-1 contingency based on the failure of a single piece of equipment or equipment electrically connected.[88]

Resilience, in the context of the bulk electric system, relates to preparing for, operating through and recovering from a high-impact, low-frequency event,[89] such as those listed above. Resilience is remaining reliable even during these high impact, low frequency events. For PJM, resilience means the ability of the system to withstand or timely recover from high risk events beyond the control of individual generators and ensuring sufficient system flexibility in light of a changing generation mix.

To develop a resilient bulk electric system that will operate reliably in response to and be resilient in the face of a wide range of probable contingencies, NERC standards require Planning Coordinators and Transmission Planners to analyze extreme events, such as loss of a large gas pipeline into a region or multiple regions that have significant gas-fired generation. Currently, if such an analysis concludes there is a probability of cascading outages caused by the occurrence of extreme events, an evaluation is conducted of possible actions to reduce the likelihood or mitigate the consequences and adverse impacts of the event(s).[90] The NERC ERO Reliability Risk Priorities report[91] identifies additional risk scenarios that should be assessed but go beyond current NERC criteria. While some of these additional risk scenarios may result in developing standards, many are recommended as assessments only. These risks include changing the resource mix, bulk-power system planning, resource adequacy and performance, extreme natural events, physical security and cybersecurity vulnerabilities. Some themes and takeaways from the Reliability Risk Priorities report focus on enhancing resilience and recovery and a focus on natural gas deliverability.

While PJM itself studies many of these extreme contingencies and events, there are no required triggers for taking action outside an actual failure.

As part of the planning process, PJM analyzes 26 such extreme contingencies, reflecting gas pipeline outages or pipeline compressor failure contingencies in the PJM footprint that would result in 1,000 MW or more of generation loss. In addition, PJM analyzes four temperature-threshold gas contingencies, which simulate a local gas distribution company interrupting non-firm natural gas generation customers in order to serve heating demand at a pre-determined temperature threshold. Such extreme contingencies are incorporated into the PJM Winter Peak Reliability Analysis.[92]

PJM also analyzes expected gas pipeline contingencies and any credible disruptive events on the natural gas interstate pipeline system in the operations horizon. This is done as part of seasonal, monthly and ad hoc assessments to provide

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[88] http://www.nerc.com/files/concepts_v1.0.2.pdf

[89] NERC High Frequency, Low Impact Report – June 2010 - https://energy.gov/sites/prod/files/High-Impact%20Low-Frequency%20Event%20Risk%20to%20the%20North%20American%20Bulk%20Power%20System%20-%202010.pdf

[90] NERC TPL-001-4 R3.5 http://www.nerc.com/_layouts/PrintStandard.aspx?standardnumber=TPL-001-4&title=Transmission%20System%20Planning%20Performance%20Requirements&jurisdiction=United%20States

[91] ERO Reliability Risk Priorities, November 2016 - http://www.nerc.com/comm/RISC/Related%20Files%20DL/ERO_Reliability_Risk_Priorities_RISC_Reccommendations_Board_Approved_Nov_2016.pdf

[92] PJM Manual M14B, Attachment D3 http://www.pjm.com/~/media/documents/manuals/m14b.ashx

situational awareness to PJM Transmission Operations, modeling 50 such contingencies within the PJM Energy Management System.[93]

PJM takes a conservative approach in both planning and operations when defining extreme gas contingencies. The compressor failure contingencies assume that all generation downstream of the gas contingency on the same gas infrastructure is lost, regardless of a secondary gas transmission feed or dual-fuel capability. The temperature threshold gas contingencies assume that all non-firm gas generation in a transmission zone cannot operate due to gas interruption, even if multiple pipelines supply the local distribution company.

In actuality, not all gas units would be lost simultaneously, or instantaneously, as part of such contingencies. The available timeframe for PJM operators to respond to generators coming off line following a gas pipeline contingency can vary significantly as the duration of time is dependent on a variety of factors, including the location and severity of the failure on the pipeline system, the pressure within the pipeline at the time of the incident, the firmness of the gas service the generator procured and whether alternative pipeline transmission is available to the generator. The time period between gas infrastructure failure and a generator coming off line potentially could range from several minutes to several hours in cases where no redundant backup gas supply capability exists and one or more of the factors identified above came into play. If such a contingency were to occur, PJM would start effective non-gas generation, direct some resources to swap to an alternate fuel or request that the generator be serviced from a secondary pipeline (if possible), and quickly implement emergency procedures as necessary to maintain system reliability. Depending upon the location of the gas infrastructure failure in relation to the gas generation, PJM would have several minutes to a few hours to take corrective action in response to a contingency.

### A Prudent Approach

PJM meets all of the requirements of the current NERC standards and assesses many of these risk areas in both planning and operations. A prudent approach, consistent with the NERC standard entitled Transmission System Planning Performance Requirements (TPL-001-4 R3.5), would be to take the next step after developing mitigating steps and action plans: implement some of the corrective actions for some of the widespread events in order to enhance the system's resilience and recovery.

PJM will continue to manage potential reliability issues through the system planning processes, either by reinforcing the system with transmission upgrades or by increasing reserve margins to ensure adequate resources are available. PJM and its stakeholders, however, should examine low probability and high impact events which cause significant reliability impacts and consider additional measures to ensure grid resilience.

## Moving Forward

PJM's established planning, operations and markets functions have resulted in a resource mix that is reliable. The current resource mix is also diverse – with a combination of natural gas, coal, nuclear, renewables, demand response and other resource types. PJM recognizes that the benefits of resource diversity include the ability to withstand equipment design issues or common modes of failure in similar resource types, fuel price volatility, fuel supply disruptions and other

[93] In addition, through the Eastern Interconnection Planning Collaborative, PJM analyzed the future load forecast compared to the natural gas pipeline infrastructure anticipated to be in service in 2018 and 2023 and then tested that system through analyzing the impact of the largest contingencies on both the pipeline and electric grids. The reviews of that analysis were presented to stakeholders through the EIPC analysis.

unforeseen system shocks. However, external drivers have impacted, and could continue to impact, the makeup of the resource mix.

PJM's analysis shows that, depending on the composition of a resource portfolio, there could be negative impacts to the ability of that portfolio to provide an adequate level of reliability services, because all resource types are not equal in the generator reliability attributes they provide. Resource diversity itself, however, is not a measure of reliability. Relying too heavily on any one fuel type may create a fuel security or resilience issue because the level of resource mix diversity does not correlate directly with a resource portfolio's ability to provide sufficient generator reliability attributes. But, a moderate level of diversity helps to ensure the system's ability to withstand unforeseen system shocks – either operational disturbances caused by contingencies beyond those studied and planned for today or both man-made and natural disasters.

The capability of resource types to provide various generator reliability attributes may change in the future because of changes in technology or regulations. Operations, market compensation and regulatory structures may, therefore, need to shift to provide incentives to ensure that adequate levels of generator reliability attributes are maintained in future resource mixes. PJM will continue to leverage a proven approach of utilizing its well-developed stakeholder process both to ensure future resource mixes support continued reliable operations and to define criteria for resilience.

In parallel with inter-regional and national efforts, PJM and its stakeholders should continue to examine resilience-related low-probability and high-impact events which can cause significant reliability impacts. Resilience is becoming a more prominent topic for the power industry and other industries. As the grid operator, responsible for coordinating the movement of wholesale electricity in all or parts of 13 states and the District of Columbia for more than 65 million people, PJM recognizes its responsibility to actively participate in and/or lead this conversation. Risks are changing and PJM recognizes the need to be part of the discussion to quantify and mitigate these risks

However, unlike the reliability services used in this analysis, criteria for resilience are not explicitly defined or quantified today. Some questions PJM and its stakeholders should consider include:

- Does PJM's current set of business practices ensure that PJM's evolving resource mix will result in continued reliable operations?
  - Are there reliability attributes that are missing from this analysis? What, if any, generator reliability attributes are important but currently being undervalued in PJM?
  - Should all generator reliability attributes have a required quantity? How should this be determined? Based on total portfolio capability? Procured in the day-ahead market? Scheduled as part of real-time dispatch?
  - During high-dependency / high-risk periods, should PJM schedule the system differently to consider fuel security concerns, such as scheduling a unit on its alternate fuel or carry extra reserves?
  - How can distributed energy resources (including demand response and microgrids) and renewable resources provide additional reliability or resilience services through improvements such as improved inverter and storage technologies?
- How could PJM's business practices consider resilience?
  - How should resilience be defined and measured as part of planning and operations?

- Should PJM plan for and operate to a reasonable set of extreme contingencies to provide an adequate operating margin? Under normal operations? Situationally dependent?
- Should PJM and the natural gas pipelines coordinate, study and operate to joint electric and natural gas contingencies?[94] Should PJM also consider this for other critical infrastructure industries such as telecommunications and water?
- Could PJM's black-start requirements and restoration strategy better consider resilience, for example, in how PJM defines black-start resources, critical load and requirements for cranking paths? Are PJM's system restoration plans too reliant on single-unit or single-cranking-path solutions that do not properly account for fuel security and fuel transportation risks?

PJM has a unique perspective to inform these discussions. Based on industry standards, best practices, thought leadership and emerging threats, industry-wide action as well as PJM action is needed.

[94] http://www.nerc.com/comm/RISC/Related%20Files%20DL/ERO_Reliability_Risk_Priorities_RISC_Reccommendations_Board_Approved_Nov_2016.pdf