Energy Transition in PJM: Frameworks for Analysis

Dec. 15, 2021

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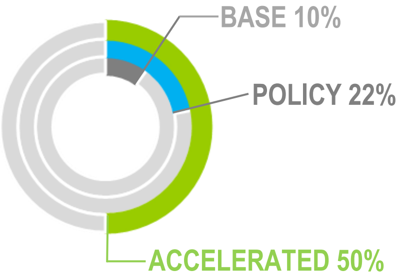
Executive Summary

Driven by PJM's strategic pillars – facilitating decarbonization, planning/operating the grid of the future, and fostering innovation – PJM has embarked on a multiphase, multiyear effort to study the potential impacts associated with the evolving resource mix. This "living study" will identify gaps and opportunities in the current market construct and offer insights into the future of market design, transmission planning and system operations.

The diverse set of PJM state policies were synthesized into three scenarios in which an increasing amount of the annual energy is served by renewable generation (10%, 22% and 50%). An entire year of the energy market was simulated with an hourly resolution.

The market rules of the energy market was simulated "as is" in 2020, and the capacity contributions of renewable resources were evaluated using the Effective Load Carrying Capability (ELCC) methodology. In the study, a qualitative assessment of NERC and power-industry-defined generator reliability attributes was also performed.



State policies were synthetized into three renewable scenarios. The *Base* is a counterfactual scenario with 10% of the annual energy in the PJM footprint coming from renewable generation. In the *Policy* and *Accelerated* scenarios, renewables represent 22% and 50% of the annual energy, respectively. In the *Accelerated* scenario, 70% of the generation dispatched is carbon-free.

This body of work is intended to be a living study, in which assumptions are continually refined based on internal and external stakeholder feedback. The initial findings should not be regarded as expected outcomes, but as bookends to be refined as the study progresses. The results of the study suggest five key focus areas for the PJM's stakeholder community and delineate the subsequent phases of the study.

1 | Correctly Calculating Capacity Contribution of Generators Is Essential

Resource Adequacy addresses whether there is sufficient generation available on the system to reliably meet customer demand. Historically, the hourly risk profile has been tightly coupled with periods of peak demand. The study showed that as the penetration of renewable resources increases, the risk profile shifts toward later hours in the evening, as peak net demand (load minus renewable generation) shifts toward the sunset. The ELCC methodology properly captured the capacity value of renewable resources, and there were no instances of load-shedding events in the energy market simulation.

In general, as the penetration of renewables increases, their capacity value contribution decreases under ELCC. As a result, an additional 78% nameplate capacity on top of the forecast peak load was required to satisfy the 1-in-10-year Loss of Load Expectation (LOLE) in the case with the greatest penetration of renewable resources. At those levels, there were periods of time in which more than a 130% of the instantaneous electricity demand was served by renewable resources. The 30% of surplus generation in excess of the electricity demand was exported to the Eastern Interconnection in the simulation.

> *FERC approved PJM's ELCC methodology in July 2021. Given the profound impact that the ELCC methodology had on the study results, it will be critical for PJM and stakeholders to continuously improve and incorporate sophisticated methods to accurately account for the capacity value contribution of all generation resources.*

2 | Flexibility Becomes Increasingly Important With Growing Uncertainty

In power systems operations, there is always some level of uncertainty driven by deviations from what is forecasted. The study reaffirmed the need for operational flexibility to address the rise in uncertainty – findings include 50% steeper net-load ramping periods, frequent dispatch of generators to their economic minimum and lower capacity factors for thermal resources.

Intuitively, adding zero-marginal-cost renewable resources decreased the average locational marginal pricing (LMP) in all scenarios (by as much as 26%). Consequently, the overall size of the energy market in terms of revenues to resources and charges to load shrunk by a maximum of 40%. The study underscored the need for PJM and stakeholders to continue to work on price formation initiatives to ensure that the flexibility needs of the system are transparently priced in the market.

In general, transparent price signals that are aligned with real-time system conditions will best incentivize optimal operations and investments. However, forward procurements of ancillary service products could complement real-time price signals (just like the capacity market complements the energy market).

> *Procuring flexibility through market-based methods ensures that the true need for ancillary services is transparently priced and competitively procured in a cost-effective manner.*

3 | Thermal Generators Provide Essential Reliability Services and an Adequate Supply Will Be Needed Until a Substitute Is Deployed at Scale

The essential reliability attributes of the generation mix were qualitatively assessed in the study. The comprehensive set of attributes evaluated include inertia, primary frequency response (PFR), reactive capability, ramping, regulation, fuel assurance and black start.

Given that the behavior of inverter-based resources is vastly different from that of traditional spinning-mass generators, the qualitative assessment revealed that, absent any reform, as the penetration of renewable resources increases, there is an overall decline in essential reliability services. The analysis also underscored the need for sophisticated analytical tools and studies to accurately assess grid stability.

> *Today, thermal resources supply essential reliability services. Until a different technology can provide a reliable substitute at scale, an adequate supply of thermal resources will be needed to maintain grid stability. PJM and stakeholders must ensure that the market structure provides the right incentives to maintain an adequate supply of these services.*

In general, due to the massive size of the Eastern Interconnection (seven times the inertia of Texas), there is a long runway before wide-area impacts are expected to materialize. On the other hand, localized issues associated with system strength[1] ("weak grid") will have to be mitigated early into the fuel-mix transition.

4 | Regional Markets Facilitate a Reliable and Cost-Effective Energy Transition

The study underscored the benefits associated with the economies of scale within PJM Interconnection in facilitating the integration of renewable resources. Geographical diversity greatly attenuated the impact of the changing resource mix on the grid's essential reliability attributes. For example, the hourly ramping requirement was cut in half when comparing a geographically diversified versus a highly clustered renewable generation portfolio.

The analysis also showed the advantages of a robust interconnection between systems. PJM's exports increased by 140%, and its interchange with the Midcontinent Independent System Operator (MISO) peaked at more than 20 GW of power flow. At the time when the simulation results for this study were completed (2020), 20 GW of power flow from PJM to MISO represented more than double the maximum historical level. Interestingly, during the Texas winter event of 2021, PJM exported more than 14 GW to MISO, emphasizing once again the importance of the interconnection and overall generation portfolio diversity.

Intuitively, as the power flow in the network changed, so did the congestion patterns, and the simulations showed an overall increase in congestion hours. Renewable curtailments represented 10% of the total renewable generation production. Combined, these results suggest an opportunity for strategic regional transmission expansion, grid-enhancing technologies, and an increased need for storage.

> *The economies of scale, geographical diversity and robust transmission system of PJM Interconnection facilitate a reliable and cost-effective integration of renewable resources. The study results suggest an opportunity for strategic regional transmission expansion, grid-enhancing technologies, and storage.*

5 | Reliability Standards Must Also Evolve

The qualitative analysis of essential reliability services highlighted an opportunity for enhanced coordination between the Federal Energy Regulatory Commission (FERC), the North American Electric Reliability Corporation (NERC) and states. Today, NERC's standards do not apply to resources connected at the distribution network. FERC Order 2222 provides an opportunity for distributed energy resources (DER) to participate in wholesale electricity markets and provide value to the grid, further blurring the conventional boundaries between the transmission and distribution systems. As the penetration of DER increases in the grid, it will be critical to hold DER to an appropriate level of performance, cybersecurity and reliability standards such as IEEE Standard 1547.

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[1] "System strength" denotes the ability of the power system to maintain a healthy voltage waveform. During a disturbance, synchronous generators can provide a temporary burst of energy 10 times greater than its nominal rating. In a strong grid (with a highly dense mesh of transmission lines and synchronous generators), the voltage waveform recovers quickly after a disturbance, enhancing grid stability. In a "weak grid," the impact of a disturbance is exacerbated, leading to potential controller instability and cascading outages.

Similarly, interdependent infrastructure (gas, water, telecommunications, etc.) should also be held to appropriately stringent reliability requirements tailored to their particular industries. Extreme weather events (like the Texas winter event) provide a sobering reminder that reliability cannot be achieved in a vacuum. Interdependent infrastructure will play an ever-important role and should be on comparable footing regarding reliability requirements. These interdependencies were not evaluated as part of the initial renewable integration analysis, but they will become increasingly important as other sectors of the economy (e.g., transportation, heating) become more dependent on the electric power grid.

Reliability cannot be achieved in a vacuum. In order to facilitate a reliable energy transition, the evolution of PJM's markets, operations and transmission planning must be accompanied by the advancement of comparable reliability requirements across interdependent infrastructure.

Analysis Framework

Previous Analyses

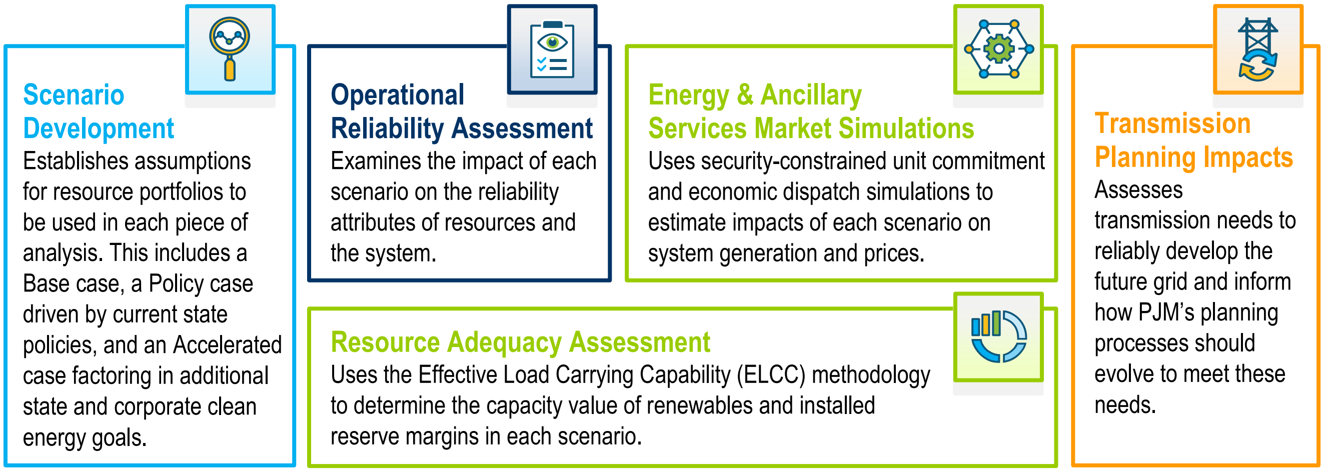
PJM's March 2021 white paper "Reliability in PJM: Today and Tomorrow" provides an overview of bulk power system reliability in terms of four basic building blocks that a grid operator must have in place today and plan to provide in the future: adequate supply, accurate forecasting, robust transmission and reliable operations. That paper was intended to help provide the proper context for discussions on system reliability with policymakers and stakeholders.

It also began a review of how PJM's core functions, market rules, operations and planning processes should evolve to maintain reliability in the face of the changes occurring in the electric industry. PJM has reviewed other renewable integration studies in order to inform its approach and methodology. Many of these studies include robust combinations of analyses that took place over multiple years.[2]

The 2014 "PJM Renewable Integration Study" conducted by GE Consulting, found that the PJM system, with adequate transmission expansion and additional regulation reserves, would not have any significant reliability issues operating with up to 30% of its energy provided by wind and solar generation. The 2017 "PJM's Evolving Resource Mix and System Reliability" report defined several attributes that are critical for system reliability and highlighted the change in reliability attribute needs to support the evolution of the PJM resource mix.

The following sections described in Figure 1 outline key elements of the analysis framework, as well as takeaways from initial phases of PJM's analysis.

Figure 1. Framework for Analyzing Energy Transition in PJM



Scenario Development
Establishes assumptions for resource portfolios to be used in each piece of analysis. This includes a Base case, a Policy case driven by current state policies, and an Accelerated case factoring in additional state and corporate clean energy goals.

Operational Reliability Assessment
Examines the impact of each scenario on the reliability attributes of resources and the system.

Energy & Ancillary Services Market Simulations
Uses security-constrained unit commitment and economic dispatch simulations to estimate impacts of each scenario on system generation and prices.

Resource Adequacy Assessment
Uses the Effective Load Carrying Capability (ELCC) methodology to determine the capacity value of renewables and installed reserve margins in each scenario.

Transmission Planning Impacts
Assesses transmission needs to reliably develop the future grid and inform how PJM's planning processes should evolve to meet these needs.

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[2] Other studies referenced include the NREL "Eastern Renewable Generation Integration Study," MISO "Renewable Integration Impact Assessment," Itron & Analysis Group "NYISO Climate Change Impact Study" and Brattle "New York's Evolution to a Zero Emission Power System."

Scenario Development

The first part of the analysis framework is to develop scenarios that will serve as reference points for studying the impacts of an evolving resource mix in PJM. PJM developed resource expansion and resource retirement assumptions by analyzing government and corporate policies driving clean-energy growth and generation retirements across PJM states, trends in the PJM interconnection queue and industry projections of the evolving system mix.[3] Onshore wind, offshore wind and solar resources are considered for expansion in three scenarios:

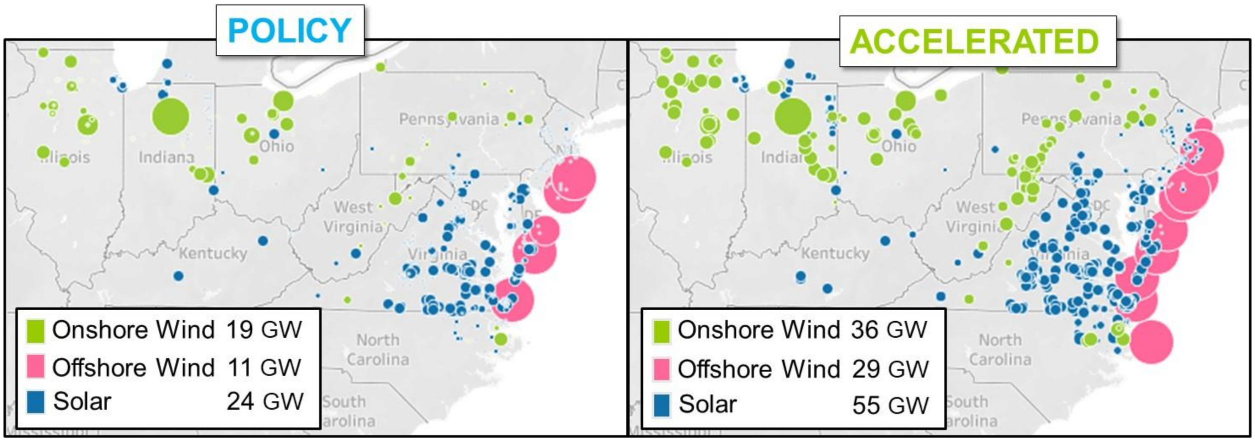
1 | **Base:** The amount of wind, solar, battery energy storage and solar-storage hybrid resources anticipated in the most current Regional Transmission Expansion Plan.

2 | **Policy**: References state and corporate clean-energy targets for 2035,[4] which combined would result in 22% of the energy in the PJM footprint coming from renewable generation, with the ability to provide up to 90% of PJM's instantaneous peak.

3 | **Accelerated:** References additional state and corporate clean-energy targets extending to 2050,[5] which combined would result in 50% of the energy in the PJM footprint coming from renewable generation, with the ability to provide 30% more energy than PJM's instantaneous peak.

The resource expansion is shown in Figure 2. Future phases of this analysis will also consider the expansion of battery energy storage and solar-storage hybrid resources.

Figure 2. Renewable Generation Expansion in Policy and Accelerated Scenarios



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[3] Industry sources: IHS Markit North American Power Market Outlook and EIA Annual Energy Outlook.

[4] The State policies used to inform the scenarios were those in place as of April 2020. Future iterations of the study will continuously use updated versions of such policies.

[5] See footnote 12.

All portfolios included formal deactivation notices as well as state or utility policies or agreements that include the shutdown of fossil generation beyond units that have formally submitted deactivation notices to PJM. Additional fossil generation retirements were included in the Policy and Accelerated cases to offset the additional capacity added by the renewable buildout.

The study assumed that existing nuclear generation resources would complete the Subsequent License Renewal process to remain operational through the policy reference years. Future studies may consider additional retirement sensitivities. The gross load from the long-term load forecast for the year 2035 was used in all three scenarios. The net load varied in each scenario to account for the impact of behind-the-meter solar.[6] In future studies, sensitivities may also include the impacts of high electrification.

Resource Adequacy Assessment

A system with increased variable resources will require new approaches to adequately assess the reliability value of each resource and the system as a whole, which will impact the amount and characteristics of the resources needed to provide sufficient reserves. PJM used the ELCC methodology, recently approved by FERC,[7] to determine the capacity value of renewables and installed reserve margins under each study scenario.

The Capacity Value of Renewables: Effective Load Carrying Capability

The ELCC method was used to assess the resource reliability value (also referred to as capacity value) tied to the concepts of resource adequacy and probabilistic evaluation. Each portfolio under examination had the same gross load but varying amounts of solar (both behind-the-meter and in-front-of-the-meter), onshore wind and offshore wind. These varying penetration levels had an impact on net demand – or the amount that needs to be met after taking into account contributions from renewables – and ultimately on the reliability value of the variable resources.

For traditional resources such as a thermal generator, ELCC is approximately equal to its unforced capacity (UCAP) value (which is determined based on the resource's forced outage rate). For variable resources, such as wind and solar, ELCC methodology is applied to derive a UCAP-equivalent value. ELCC results are driven by those hours with high risk or high loss-of-load probability (i.e., hours experiencing shortage or near-shortage conditions). These risk hours may vary as penetration of the variable resource increases.

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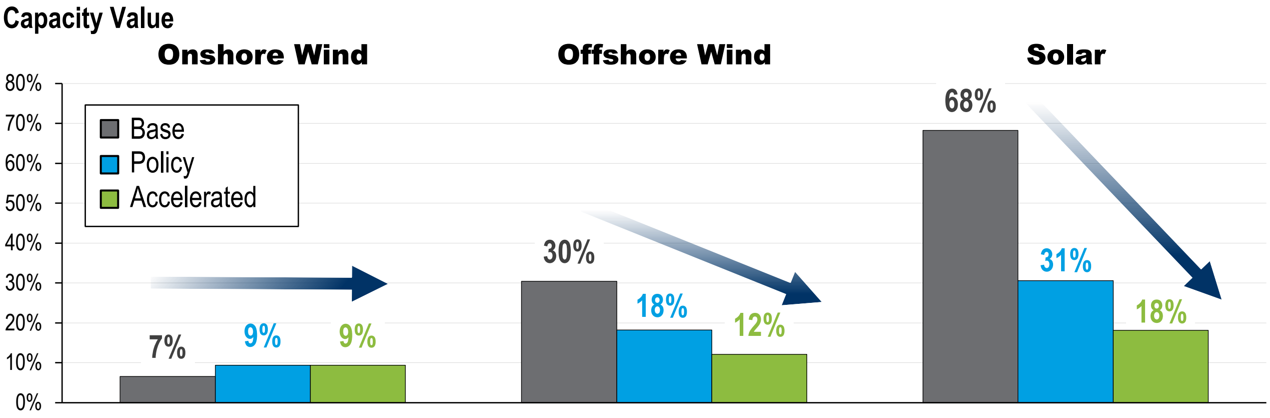
[6] For the Base and Policy scenarios, the IHS Markit behind-the-meter (BTM) solar forecast was used to determine the renewable energy contribution from BTM solar resources. The Base scenario used the expected BTM solar penetration in 2023 from the IHS Markit solar forecast and scaled it up to 2035 load levels. The Policy scenario used the 2035 BTM solar forecast. In order to produce BTM solar values for the Accelerated scenario, guidance was taken from the Energy Information Administration on regional BTM solar growth between 2035 and 2050 to scale up the Policy scenario values.

[7] ELCC replaces the existing methodology of determining the capacity value of renewables, which only considers performance during certain peak hours in the summer. ELCC uses a more robust, probabilistic analysis that considers the contribution to reliability that resources provide during all hours of high risk, including net-peak-demand hours, and accounts for the limited duration of storage resources.

Study results indicate that as renewable penetration increased, risk shifted to hours in which the resources under study do not perform as well. This can be seen in the ELCC results. **Error! Reference source not found.** shows the results as variable resource penetration increases from the Base to Policy to Accelerated cases.

Figure 3. Effective Load Carrying Capability Results by Resource Type



ELCC results were sensitive to the input data, which included both the mix of profiles used and the assumption of resource performance. For instance, many solar resources entering the interconnection queue are hybrids (solar paired with storage), and these would have higher ELCC values depending on the storage capability and dispatch assumptions. Because of these and likely other factors, ELCC values presented should not be considered predictive for future ELCC values. Future analyses will refine the underlying assumptions and integrate energy storage and hybrid resources into the model.

Resource Adequacy Implications

PJM conducts an annual Reserve Requirement Study, which evaluates capacity needs on top of forecasted load in order to meet PJM's Loss of Load Expectation (LOLE) criterion of 0.1 days per year.

Because of the declining reliability value of renewable resources, the percent nameplate above peak load would increase under each progressive scenario. In the Accelerated scenario, an additional 78% nameplate capacity on top of the forecasted peak load was required to satisfy the 1-in-10 year LOLE. At those levels, there were periods of time in which more than 130%[8] of the instantaneous electricity demand was served by renewable resources.

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[8] The 30% of surplus generation in excess of the electricity demand was exported to the Eastern Interconnection.

In PJM's capacity market, known as the Reliability Pricing Model, procurement needs are dictated through the Forecast Pool Requirement, which is the amount of UCAP needed to meet PJM's reliability criteria. Shifting to an ELCC-based concept for determining variable resources' UCAP value provides a better alignment between capacity offers and its ability to produce energy in the hours needed to serve load. PJM's practice prior to ELCC assigned capacity value according to a resource's performance from 2–6 p.m. from June 1 through Aug. 31. This measure ignores the changing hourly risk profile of renewable resources and became detached from reliability value as penetration increased in the analysis. For example, PJM's previous practice would provide solar with too much value relative to its reliability contribution in the Policy and Accelerated cases.

Energy & Ancillary Service Market Simulations

In order to analyze the impacts of increased renewable generation in the PJM wholesale electricity markets, PJM used a production cost model to simulate security constrained unit commitment and economic dispatch over a one-year period for each renewable penetration scenario.[9] The insights PJM intends to gain from comparing the results of these simulations with increasing renewable penetration levels and thermal generation retirements include:

- Impacts on reserve procurement and prices
- Impacts on locational marginal prices and system production cost
- Shifts in generator commitment, revenues, curtailments and interchange
- Ramping needs due to shifts in net demand
- Shifts in system emissions

Locational Marginal Prices

Figure 4 shows the Energy Market dynamics. Across all hours, the average LMP decreases by 26% from the Base scenario to the Accelerated scenario with the highest penetration of renewables. The overall size of the energy market shrunk by 40%, as measured in terms of total system production cost. Reserves were modeled to be consistent with PJM's current business rules.[10] Future analysis will include Operating Reserve Demand Curve (ORDC) modeling consistent with enhanced reserve price formation business rules.

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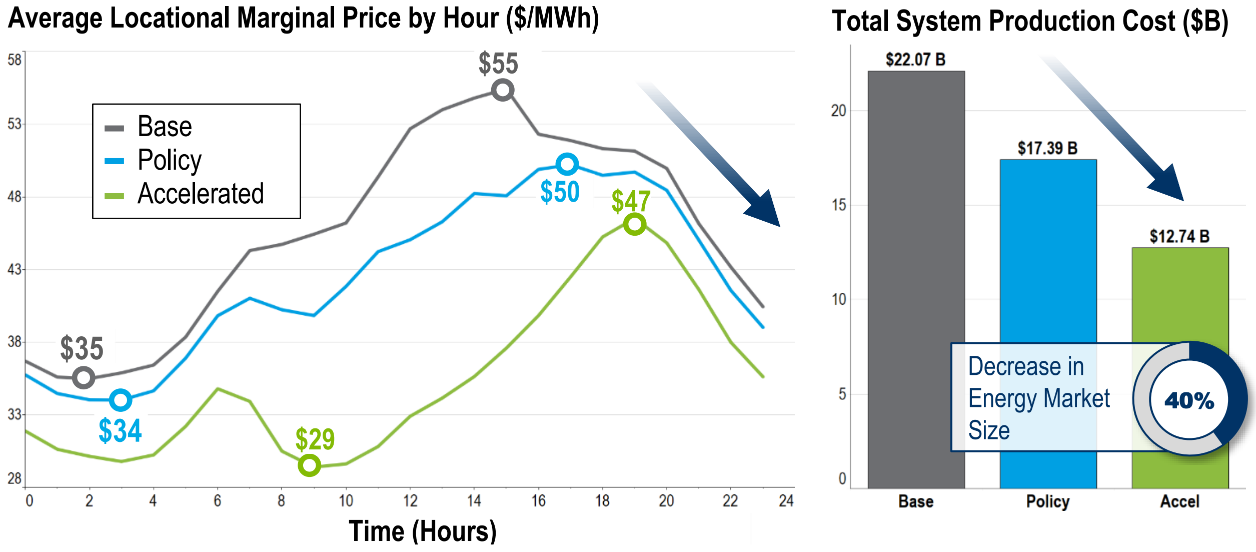
[9] PJM used Energy Exemplar's PLEXOS® Integrated Energy Model (PLEXOS), a production cost model that performs both a security-constrained unit commitment and dispatch over a given time horizon.

[10] Shortage pricing of reserves was modeled with a single $850/MW step. Thermal and hydroelectric resources were modeled to provide reserves where eligible, given ramping and startup participation constraints.

Figure 4. Energy Market Indicators



Generation Dispatch

Annual generation by fuel type for each scenario is shown in Figure 5. In the Accelerated scenario, 70% of the generator dispatched is carbon-free (renewables + nuclear). Total tons of carbon dioxide emissions were reduced by 40% when compared to the Base scenario.

The study revealed a substantial amount of renewable generation curtailments. As shown in Figure 6, such curtailments were particularly exacerbated during periods of time in which high renewable generation coincided with low periods of electricity demand.

Figure 5. Annual Energy Generation by Fuel Type (GWh)

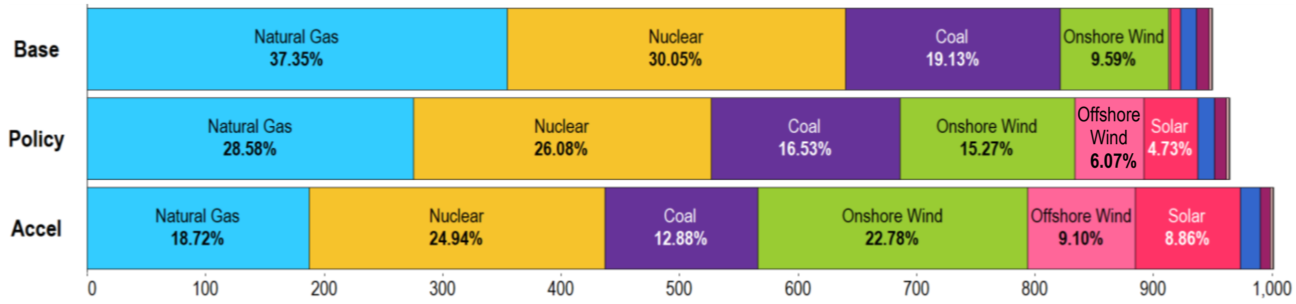
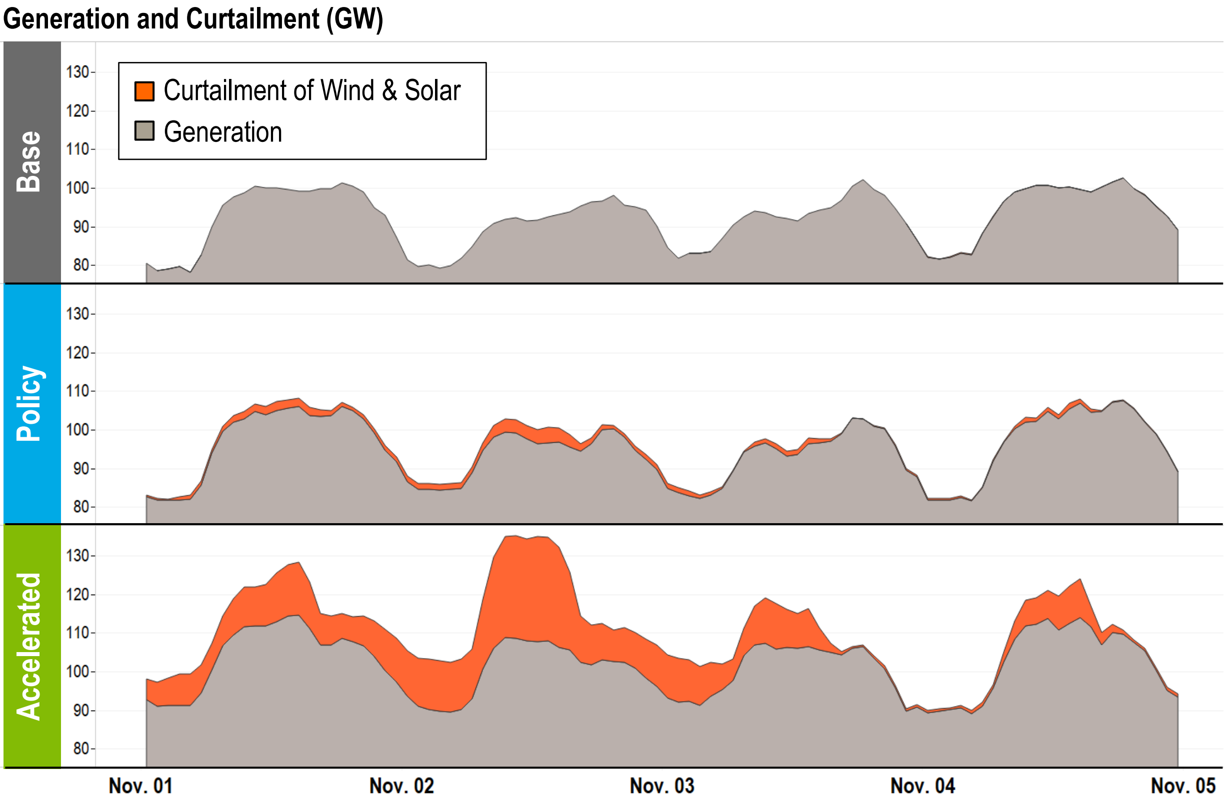


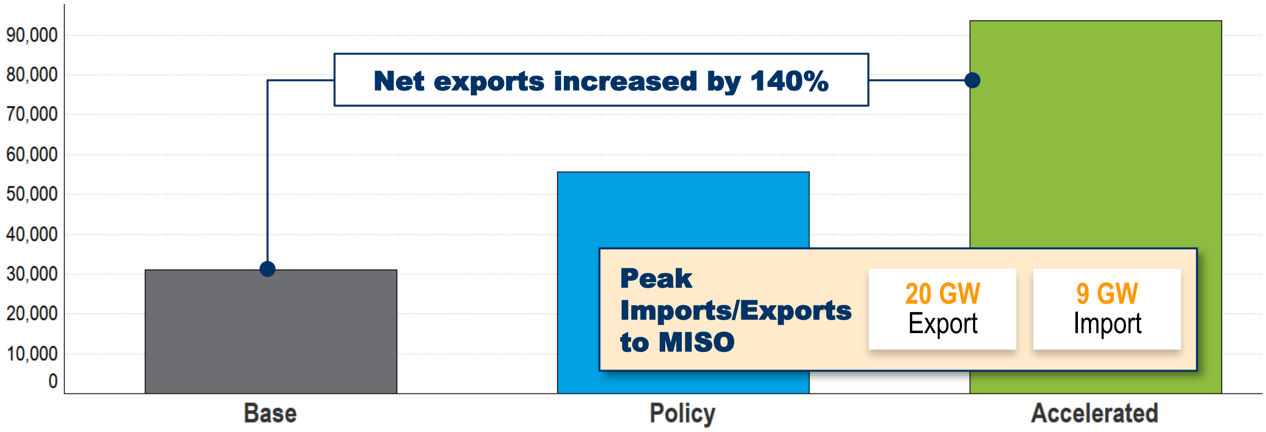
Figure 6. Renewable Generation Curtailments



Interchange and Congestion

Total net exports for the simulated year in each scenario are shown in Figure 7.

Figure 7. Total Annual Net Exports and Peak Export/Imports with MISO (MW)



Net exports increased by 140%

Peak Imports/Exports to MISO

20 GW Export

9 GW Import

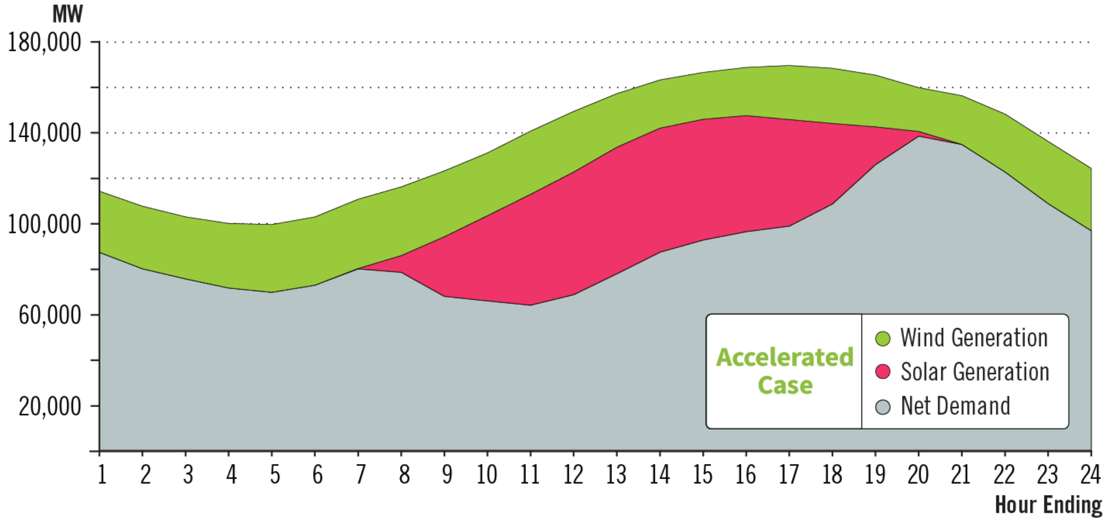
PJM exports increased by 140%, and interchange with MISO peaked at more than 20 GW of power flow. Congestion patterns across the PJM grid changed significantly. In the Accelerated scenario, the total hours of transmission line congestion increased by about 50%, and a significant amount of renewable curtailment was needed to manage transmission limitations and minimum generation events.

Together these initial results speak to the importance of efficient and nimble transmission planning as a tool for integrating renewables in a reliable manner and highlight the need for enhanced forecasting techniques for managing uncertainty (as detailed in the Operational Reliability section).

Flexibility To Address Uncertainty

Simulation results indicated an increased need for operational flexibility, with steeper ramps, frequent dispatch of generators to their economic minimum and lower capacity factors for natural gas and coal resources. Figure 8 shows the ramping requirements for the average summer load curve under the Accelerated scenario. The maximum load ramps were approximately 11 GW/hour in all scenarios. However, the net-load ramping (load minus renewable generation) varied drastically among scenarios. In the Base scenario, the net-load ramping was 12 GW/hour. In the Accelerated scenario, the net-load ramping requirement climbed up to 19 GW/hour.

Figure 8. Ramping Requirements for Summer Load Curve (Accelerated Scenario)



Operational Reliability Assessment

Reliability attributes are essential for maintaining system balance and supporting the reliable operation of the grid.[11] This section focuses on assessing the reliability impacts of proposed clean-energy programs and state initiatives. It is also intended to support the development of a PJM action plan to prepare for and manage the impacts of increasing levels of renewables on the regional high-voltage electric system.

PJM conducted extensive industry research and outreach, which was integral to inform the overall operations analysis. PJM also performed a qualitative assessment of NERC and power-industry-defined generator reliability attributes. This assessment was based on industry research, historical PJM system performance and the three future resource portfolios (Base, Policy and Accelerated) described previously in the Scenario Development section.

Key generator reliability attributes analyzed include the following:

- Inertial and Primary Frequency Response (PFR)
- Reactive Capability
- Ramping
- Regulation
- Flexibility
- Fuel Assurance
- Black Start
- System Stability

Reliability Attributes

Primary Frequency Response

Primary frequency response (PFR) is essential for grid reliability within the PJM footprint. It is the first line of defense to maintain frequency, it is critical for system restoration and it is necessary for accurate modeling and regulatory compliance. PFR is the inherent response of resources and load to detect and arrest local changes in frequency. It is an automatic, locally detected response by resources that is not driven by any centralized system and begins within seconds after a frequency excursion. It is essential to stopping a decline in frequency and preventing the activation of automatic under-frequency load shedding (UFLS). The fast, inherent response is a larger differentiator between PFR and regulation, the latter of which follows a centralized dispatch signal from PJM.

In February 2018, FERC Order 842 revised the regulations of provision for PFR by requiring new generating facilities to install, maintain and operate a functioning governor or equivalent controls as a precondition of interconnection (for both large and small generator interconnection agreements). These requirements were documented in PJM Interconnection Service Agreements as of Oct. 1, 2018.

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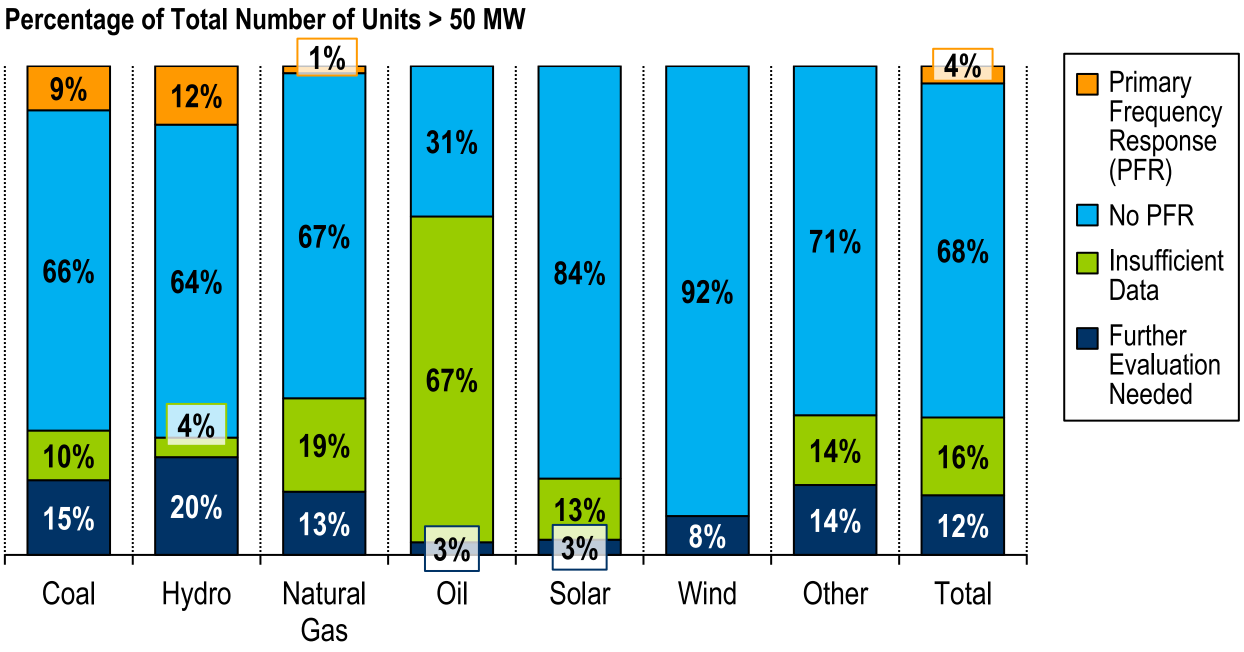
[11] These reliability attributes were previously analyzed and discussed in the 2017 white paper “PJM’s Evolving Resource Mix and System Reliability” and in the March 2021 white paper “Reliability in PJM: Today and Tomorrow.”

While FERC Order 842 requires PFR capability, it does not require resources to operate with headroom; therefore, PFR to under-frequency events is generally minimal for those resources operating at full output. Current event evaluations indicate renewable resources tend to operate at full output, and future renewable integration, along with a change of online resources, continues to be studied to best determine potential future needs for sufficient PFR.

PJM currently does not have requirements for either frequency-responsive generation or PFR reserves. Based on preliminary analysis, in the short term, PJM does not see a reliability concern with the amount of PFR on the system. However, PJM does see that PFR, maintaining adequate headroom, or PFR Reserve, are areas that will require ongoing monitoring and a possible reactivation of the Primary Frequency Response Senior Task Force.

In addition to the NERC BAL-003-2 Frequency Response and Frequency Bias Setting[12] Reliability Standard, PJM performs additional frequency response analysis, as documented in PJM Manual 12. This additional analysis is performed to evaluate generator PFR performance in the PJM footprint. Section 3.6 of PJM Manual 12: Balancing Operations (M-12) includes the criteria for evaluating the PFR performance of generating resources following an event and takes into account the droop, deadband and operating requirements in PJM Manual 14D: Generator Operational Requirements. This analysis evaluates units that are at least 50 MW and above and units that are FERC Order 842 compliant. Figure 9 shows the M-12 event evaluations shared at the June 10, 2021, Operating Committee meeting.

Figure 9. M-12 Primary Frequency Response Review as of June 10, 2021



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[12] NERC Standard BAL-003-2 Frequency Response and Frequency Bias Setting

The inertial frequency response of the system drops as large synchronous generators are retired and replaced with inverter-based resources such as wind, solar and storage. This can be a concern in a grid with high penetration of renewables, as it can result in a faster and larger frequency decline following a system disturbance because of a reduced level of reliance on generators with large rotating masses. In the future, consideration of how to secure inertial frequency response may become necessary to ensure an adequate supply on the system at all times and appropriately value those resources providing the service.

Reactive Capability

In 2016, FERC issued Order 827. This new order set reactive capability requirements for all nonsynchronous machines. Nonsynchronous generators now must have the capability of providing dynamic reactive power support and maintain a 0.95 power factor lagging and leading for the full range of active power output.

Since reactive power for inverter-based resources is controlled by power electronics, inverter-based resources can theoretically provide 1.0 pu apparent power at a power factor of zero lagging or leading, with 100% of inverter capability dedicated to providing or absorbing reactive power. This is very rare, though. Renewable facilities are not incentivized to operate at such a low power factor, and other design issues must be considered.

Instead, analysis reveals that inverter-based resources typically report “V-curves,” triangle-shaped reactive capability that is dependent upon, and proportional to, the real power output. These are not representative of the full theoretical reactive capability of inverter-based resources but instead appear artificially limited only to meet FERC Order 827 requirements. A review of PJM requirements for reporting, testing and providing reactive capability is suggested to ensure that PJM is sufficiently documenting and using the full reactive capability of the inverter-based resource fleet.

The DC link capacitor in inverters uses similar technology to that of a static synchronous compensator (STATCOM). With an additional initial investment, inverter-based resources can be designed to provide or consume reactive power at near-zero real power outputs. The additional design allows an inverter to consume a small amount of AC active power from the grid, instead of DC power from the plant, to power the link capacitor and associated power electronics in STATCOM mode. When this feature is built into the inverter, the capability is always there for future use at little operational cost.

However, this additional functionality comes with additional costs to the generation owner. On top of the higher initial investment and paying for increased active power consumption in standby mode, the generation owner also suffers additional costs related to increased maintenance and decreased power electronics lifespans.

The capability of inverter-based resources to regulate voltage without active power output could be useful in many scenarios, including solar farm reactive support after sunset, solar farms helping stabilize voltage during winter morning peak, voltage support from solar and wind farms at night during lighter loads and wind farm voltages support in remote areas during no-wind conditions. Enabling reactive capability in inverter-based resources would also potentially limit or avoid the need to install additional transmission devices for voltage control, such as SVCs, capacitors and reactors.

Ramping

Ramping is upward or downward control by resources over a period of time needed to maintain load-generation balance. This is most needed at times of major load shifts, especially during the winter evening ramps, when increases in load coincide with decreases in solar output, and are potentially amplified by wind output changes.

PJM performed a ramping capability analysis accounting for an increase in renewable resources. This analysis factored in maximum expected ramping capability and load forecasts. Requirements will remain unchanged for the near future because of a significant amount of ramping-capable generation on the system. Further analysis is needed to make sure PJM can stay ahead of any ramping capability deficiencies and identify any areas where renewable resources will closely synchronize their ramping behaviors.

A large amount of hybrid generation pairing solar with energy storage is in PJM's interconnection queue. These resources could provide great ramping capability depending on the size of the storage component.

Regulation

Ramping, regulation and reserves can be seen as a generator's ability to follow load, and all three are structured by NERC BAL (Resource and Demand Balancing) standards.

Regulation is the fastest of the three, requiring generators to control Area Control Error (ACE) and frequency deviations in a matter of seconds to a few minutes. Ramping capability and reserves are the generator's ability to follow the load shape over a matter of several minutes to an hour, or even days for more forward-looking reserves.

PJM assessed its regulation capability with higher renewable penetrations by examining current participation in regulation in PJM and how other ISOs/RTOs are incorporating higher renewable penetrations.

Currently, solar and wind units do not participate in PJM's Regulation Market, but there is significant participation from energy storage resources (ESRs). Therefore, hybrids that consist of renewables paired with ESRs may be an option for renewable resources to participate in the Regulation Market. PJM and stakeholders are currently examining hybrid resources in the PJM DER & Inverter-Based Resources Subcommittee (DIRS).

Other RTOs/ISOs have already seen a larger amount of renewable integration. Significant amounts of wind generation are installed in the Southwest Power Pool (SPP), Electric Reliability Council of Texas (ERCOT) and MISO systems. California ISO (CAISO) has a large amount of both wind and solar generation installed. PJM will need to review different market structures in order to plan for the best way to use renewable resources for regulation purposes. Next steps include analyzing how renewables and hybrid resources can participate and perform as regulation resources.

Flexibility

Flexibility is a reliability attribute that measures the ability of a unit to turn on and off quickly and frequently in a single operating day. Three characteristics that commonly determine a resource's flexibility are cycling capability, quick-start time and low minimum run times.

Units with the ability to start or stop quickly allow operators to balance load and generation during periods when load and/or generation are changing quickly, or when there is significant uncertainty in the load forecast. Renewable energy resources can be dispatched down but cannot be guaranteed to return to previous output levels or be dispatched up. An evaluation of existing requirements, regulations and rules should be completed to ensure all resources are incented and capable of providing flexibility.

PJM will review different market approaches to best incentivize renewable energy resources to be their most flexible. As renewable resource penetration increases, upward flexibility continues to decline, and downward flexibility continues to improve. A future analysis should observe the flexibility of each hour of dispatch in both the current system and future cases. The objective would be to see how much unused flexibility remains on the system after dispatch in each case.

Fuel and Energy Assurance

Fuel assurance considers the ability of a balancing authority to withstand disruptions to fuel supply chains and delivery mechanisms that hinder generator performance. The extreme cold weather of early 2014 challenged the long-standing paradigm that fuel would always be available to generators when needed and brought the concept of fuel assurance to the industry forefront.

PJM's Evolving Resource Mix and System Reliability paper in 2017, which evaluated several reliability attributes, defined fuel assurance 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." The results of this study led PJM to explore a subset of these reliability attributes more deeply, resulting in the 2018 Fuel Security Analysis Report and continued work with stakeholders through the Fuel Security Senior Task Force (FSSTF).

By definition, solar and wind resources do not rely on traditional on-site fuels, and therefore the concept of fuel assurance does not apply. However, due to the inherent intermittent nature of their sources for energy, this does introduce the concept of managing energy assurance to account for variability in solar irradiance and wind speed, though geographic diversity of installations and a highly networked transmission grid can help to reduce the impacts of local weather conditions on overall grid reliability. Therefore, as renewable penetration increases, risks associated with fuel and energy assurance will also rise, especially as operators increasingly depend on nonrenewable generators – particularly flexible combined-cycle gas turbines, which also lack fuel assurance except in cases of firm delivery contracts or dual fuel capability – to produce power when sunlight and wind are limited.

These fuel and energy assurance concerns highlight the need to implement market design reforms to better align incentives with the operational needs of a system with high renewable penetration. Capacity market reform discussions are currently underway in the PJM stakeholder process in order to address these concerns.

In addition to market design changes, the deployment of ESRs can help mitigate intermittency issues that prevent solar and wind generation from having fuel assurance. Storage resources such as batteries can provide balancing across hourly timescales, as either stand-alone resources or in tandem with renewables as hybrid generators.

Because deployment of ESRs is still in a nascent stage, PJM cannot presently count on it to substantially mitigate the fuel assurance concerns associated with high penetrations of renewables. PJM will continue to monitor the development of storage technologies and continually assess their ability to provide support in this area.

Fuel Requirements for Black Start Resources

PJM initiated the Fuel Requirements for Black Start Resources (FRBSR) stakeholder group in 2019 to review the need to add fuel assurance requirements for some or all PJM black start resources to mitigate the impacts of non-fuel assured black start resources being unavailable during a system-wide blackout. The FRBSR initiative is currently on hiatus while PJM performs additional analysis to support initially proposed packages or to develop new packages. PJM will continue to evaluate impacts to system restoration as inverter-based resource penetration increases.

Black Start

Black start capability is necessary to restore the PJM transmission system following a system-wide blackout. PJM black start resources are able to self-start and close to a de-energized bus within three hours without electrical assistance from the grid or stay online and operate at reduced levels when automatically disconnected from the grid.

PJM black start resources must be able to control frequency and voltage, as they are the first resources online following a system-wide blackout. Black start resources provide power to pick up loads, energize transmission equipment and power PJM Critical Loads defined as units with a hot start time four hours or less, nuclear safe shutdown loads or electric-only gas compressors.

Inverter-based resources are not precluded from providing black start service as long as they can meet PJM’s black start requirements. Currently, inverter-based resources are not classified as Critical Load.

Evaluating the impact of inverter-based resources and incorporating them into system restoration will become more important as state policies drive the transition away from traditional thermal resources.

System Stability

System stability is assessed from several perspectives:

1 | Transient (angular) stability

2 | Small signal stability, which is a degree of damping performance

3 | Voltage stability, which looks at dynamic voltage recovery performance

Inverter-based resources are asynchronously connected to the system, and their characteristics are quite different from traditional synchronous machines. Most fundamentally, stability for inverter-based resources is primarily judged by voltage performance. This is in contrast to rotor angle performance (δ), which is the typical quantity of interest in synchronous machines (rotor angle is not important because inverter-based resources are not truly synchronized with the grid).

Inverter-based renewable energy resources have several distinctive characteristics from a stability perspective:

- Since inverter-based resources are asynchronously connected to the system through power electronics interfaces, their inertia is normally small, which means less contribution to frequency stability. As their penetration level increases, the system is more prone to sharper frequency decline and a lower frequency nadir point given the same amount of generation loss.
- Unlike synchronous machines, inverter-based resources' low short-circuit contribution makes the system weaker from a voltage stability perspective.
- Inverter-based resources provide less reactive power support, which could make voltage recovery unhealthy after fault clearing.
- Distribution system-connected inverter-based resources are normally subject to less strict voltage/frequency ride-through requirements. When the amount of DER is substantial, the dynamics of DER along with load dynamics may need to be modeled in the simulation.

A weak transmission system exacerbates many of these issues. The typical measure of a point-of-interconnection strength is the short-circuit ratio (SCR). But measuring system strength with high power electronics penetrations may be more nuanced than simply using SCR. In the future, PJM may consider alternate weighted SCR methodologies to accurately gauge the strength of the system to determine where voltage stability issues are likely to occur.

When performing traditional stability studies, engineers use software that models the dynamic and transient interactions of generators. However, these models are inadequate for the types of voltage stability issues that arise with inverter-based resources. Thus, as renewable penetration increases, PJM may consider using Electromagnetic Transient modeling to ensure stability issues are properly identified.

Renewable Forecasting and Reliability Analysis

During PJM's industry research and outreach phase, predicting future renewable generation was found to be critical to near-term reliability analysis. Traditional reliability analysis focused on predicting, as accurately as possible, the expected system demand profile, or load curve, for a given day. Determining the load curve is highly complex and driven by both environmental factors as well as social behavior.

When performing reliability analysis, once this load curve is determined, generation is then dispatched via the economic stack. Known transmission and generation outages are analyzed, and operating plans are developed to ensure that all transmission facilities will be operated within their respective limits.

This past practice, however, requires the ability to actively schedule the generation in the economic stack. This is not the case for renewable resources for which fuel is not able to be actively scheduled, but rather is passively available based on ambient conditions (solar irradiance, wind speed, river levels). This introduces a new uncertainty that must be accounted for and adds a new dimension of complexity to PJM's reliability analysis, as well as generation and transmission outage coordination.

PJM has already started investigating enhancements to its operational assessments to account for the uncertainty in renewable output and the impacts on scheduled generation and transmission maintenance. Looking ahead to outage planning with renewables, PJM will need to be able to analyze planned and unplanned work with the most accurate forecasted data. This will help PJM operations personnel stay ahead of possible transmission constraints or capacity deficiencies.

In PJM's industry research, renewable forecasting came to the forefront as a crucial piece to maintaining reliability not just in outage planning, but also in analyzing most if not all of the reliability attributes discussed in this paper. Without an accurate forecast, reserve and regulation procurement will be much more difficult with the uncertainty of the intermittent resources. Accurate renewables forecasting will also be necessary for meeting capacity needs in the day ahead and for analyzing generation and transmission outages.

Other RTOs/ISOs use visual aids to help their operators gain situational awareness of their expected forecast. PJM plans to enhance its current visualization or situational awareness tools or add new tools that will be key to integrating renewables. PJM operators and engineers will need visual forecasting tools on solar and wind resources for real-time control. Integrating forecast data into existing reserve monitoring processes will be needed to help real-time generation dispatch and constraint control. Near-term studies will need to incorporate forecast data to prevent capacity deficiencies and transmission constraints.

Transmission Expansion

The Energy and Ancillary Services Market simulations performed did not include any transmission expansion that may be needed for reliability, but the results highlight the critical role of the interconnection in facilitating a reliable integration of renewables.

Additional scenarios would be necessary to incorporate impacts with future transmission upgrades that are likely needed to integrate the future renewable generation.

Separately, PJM has completed Phase 1 of an Offshore Transmission Study to identify transmission solutions across the PJM region to accommodate the PJM coastal states' offshore wind goals and PJM states' renewable portfolio standard (RPS) requirements. By synchronizing the planning of its coastal states' offshore wind deployment, PJM is able to identify transmission solutions that could present a more efficient and economic path for states to achieve their offshore wind policy objectives than if each state decided to independently integrate their offshore wind generation.

The Phase 1 component of this study analyzed five scenarios that were developed in collaboration with coastal state agencies within the PJM footprint. These five scenarios provide a high-level reliability assessment and cost estimate of how anticipated offshore wind generation and achieving current state RPS targets will impact the onshore PJM transmission system. It focused solely on identifying violations and upgrades to the current transmission system. The consideration of greenfield transmission solutions and offshore transmission facilities can be incorporated in later study phases.

The results presented in this study are to be considered advisory only and are meant to help inform policymakers as they advance their current and any future offshore wind policy endeavors. These results are also meant to serve as a starting point for any future scenarios that could be modeled in later study phases. In addition, while this study does identify the locations and costs of transmission upgrades, the results are not indicative of cost allocation to any ratepayer.

Moving Forward

PJM serves a region made up of diverse states with complex policies impacting the bulk electric power grid. These policies take many shapes, such as RPS, zero-emission credits, carbon cap-and-invest programs, energy efficiency incentives, electrification goals and offshore wind auctions. Cumulatively, these policies are driving the next energy transition in PJM, marked by an increase in renewable generation and energy storage, along with retirements of traditional thermal generation.

As we embark on this transition, it is important to recall that the grid has successfully endured multiple energy transitions. PJM and its members have reliably and effectively weathered these transitions due in large part to the value that comes with being a member of a Regional Transmission Organization with a robust planning process, efficient capacity market design, access to fuel diverse and geographically diverse generating resources, and a highly resilient network of transmission facilities that ensure the ability to deliver power to our customers.

PJM is proactively taking multiple steps to facilitate a reliable and cost-effective energy transition, focusing on improving the interconnection process, exploring potential enhancements to the capacity market and performing reliability studies to determine reinforcements needed to reliably deliver offshore wind in the PJM region.

This “living study” represents another tangible effort toward identifying gaps and opportunities in the current market construct and offering insights into the future of market design, transmission planning and system operations. The initial findings in this paper should not be regarded as expected outcomes but as bookends that will be refined as the study progresses. With that in mind, the following assumptions will be refined in the next phase of this multiyear effort:

Additional Sensitivities

- Electrification
- Generation retirement
- Energy storage and hybrid resources
- Interchange

Essential Reliability Services

Quantitative analysis of ERS

Transmission Expansion

Transmission upgrades for system reliability and efficiency

Market Design

- Downward sloping ORDC
- Updated ELCC rules