Grid of the Future:
PJM’s Regional Planning Perspective

PJM Planning Division

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Contents

1. Executive Summary

Over the past decade, increasing focus by federal and state governments on climate change, energy independence and other policy areas continues to make clear the critical role of the transmission system. PJM is working to outline a vision and present a road map for the grid of the future by examining industry trends and drivers to assess the potential impacts on PJM's transmission planning process.

The grid of the future is not some far-distant idea but is here now. PJM, like other power grid operators across the U.S., has before it a robust, reliable transmission grid, but one upon which enhanced operational flexibility must continue to grow to ensure reliable power delivery 24/7 year-round.

Vision

PJM's Regional Transmission Expansion Plan (RTEP) process continues to evolve, bringing into clearer focus a future grid driven by decarbonization, renewables, public policy, resource mix and new technologies. Achieving this future means enhancing operational flexibility and ensuring that reliability and resilience remain paramount.

Road Map

This report outlines PJM's system planning road map to achieve its future grid vision by examining trends and drivers that are impacting the RTEP process. This initiative is part of a multi-year effort to implement PJM's corporate strategy as approved by the PJM Board to enable transition in a changing industry. The RTEP process component as discussed in this report builds on work completed as part of PJM's related renewable integration studies and papers emphasizing markets and operations.

PJM's road map encompasses four areas of focus as part of continuing efforts to enhance planning processes in preparation for the future grid.

1 | ***Transmission build-out scenario studies*** will be conducted in 2022 based on power-flow case alignment with PJM's renewable integration studies and by leveraging analytical work of the Offshore Wind Scenario Study Phase 1. This major planning effort considered not only offshore wind injection, but renewable resources to meet states' Renewable Portfolio Standard (RPS) objectives. As PJM continues its initiatives to enable a decarbonized grid, additional analysis will be undertaken beyond the offshore wind scenario studies to examine an accelerated renewable penetration case, including a more in-depth assessment of the impacts driven by greater building and transportation electrification.

2 | ***Targeted reliability studies*** will build on 2022 scenario study results to evaluate generation and transmission reliability attributes, such as reactive control, stability, system inertia and frequency control, and short-circuit impacts to ensure reliable operations.

3 | ***RTEP process enhancements*** will continue to evolve, including a number of key initiatives already underway: interconnection process reform, generator deliverability methodology improvement, Effective Load Carrying Capability methodology development, and implementation of probabilistic planning techniques.

4 | ***Regulatory policy impacts*** continue to inform new reliability criteria for extreme events, state electrification policies, interconnection process reform, state policy implementation, distributed energy resources (DER) expansion and FERC action on regional transmission planning per its recent ANOPR.[1] Going forward, PJM must continue to be engaged on policy discussions that will impact how it plans the transmission system through the ongoing changes.

The goal of this report is to ensure that PJM's future grid maintains the reliability and operational flexibility necessary to address key drivers that are changing the face of the industry. It builds on PJM's renewable integration study work and is informed by the work completed by other RTOs and other relevant industry entities.

Industry Trends and Drivers

Planning's approach for this report was to examine the key industry trends driving future grid expansion: generation development, evolving load characteristics, emerging transmission technologies and resilience.

Generation – Addresses growing renewable resource trends for wind, solar and storage. These resources are typically variable and of limited output duration. PJM's generation shift is also driven by deactivation of conventional generation resources powered by coal, natural gas and nuclear, given their "at-risk" vulnerability arising out of economics and decarbonization public policy.

Load – Discusses two key dimensions of future load trends: (1) DER, which explore unique challenges for integrating a growing amount of generation connected at the distribution level and may include retail and wholesale market participation; and (2) discussion of load trends driven by the impact of electrification of transportation and building heating.

Emerging Technologies – Explores the emerging technologies that may play a role in managing congestion and solving reliability criteria violations associated with integrating significant amounts of renewable resources. Such technologies may reduce the need for, or mitigate impacts of, new greenfield transmission lines and the attendant siting approval and permitting challenges.

Resilience – Considers criteria needed to address more extreme system events. These warrant greater attention for a transmission grid with: (1) higher penetration of variable and duration-limited resources reliant on sun and wind to operate; and (2) an end-use sector with growing reliance on electrification.

Generation Shift

While PJM state renewable goals differ in scope, timing, resource specificity, means of implementation, and mandatory versus voluntary, most state jurisdictions in the region PJM serves have some level of renewable resource or clean energy targets. Meeting these targets will include terrestrial wind, offshore wind and solar resource development as well as storage. In PJM's interconnection queue, renewables and storage account for over 90% of requests. Most of the recent queue requests for grid interconnection throughout the region PJM serves are from inverter-based solar generation resources. Previously, solar projects were smaller in size and limited to a handful of areas. Now, the size of individual projects can be on the order of hundreds of megawatts, driven by states' RPS goals, and are locating in every PJM transmission zone.

[1] On Oct. 12, 2021, PJM filed its initial comments in FERC's Advanced Notice of Proposed Rulemaking (ANOPR), Building for the Future Through Electric Regional Transmission Planning and Cost Allocation and Generator Interconnection, Docket No. RM21-17-000. Core aspects of this FERC initiative and PJM's initial comments speak to the decarbonized future that is at the heart of the grid of the future.

Onshore wind continues to interconnect to the grid, but current trends show it to be more concentrated in western areas of the PJM footprint. Offshore wind is also emerging as a major source of power, seeking to interconnect to the grid along PJM coastal states. Although offshore wind is on a longer planning horizon, the potential for development is substantial. PJM must solve the challenges that these locationally constrained resources present and address the interregional implications associated with offshore wind lease areas that can also serve regions north and south of PJM RTO borders for states along the eastern seaboard.

Offshore Wind Transmission Study

An initial assessment of the transmission needed to interconnect the anticipated growth in renewable generation was completed as part of the Offshore Wind Transmission Scenario Study Phase 1. The study consisted of multiple scenarios that integrated between 30,000 MW and 80,000 MW of renewable generation and identified the need for as much as $3 billion in transmission upgrades to integrate PJM coastal states' offshore wind targets, as well as RPS goals across the entire RTO footprint, in the next 10–15 years. The analysis provides a view as to the magnitude of transmission expansion that will be needed to integrate the growing number of renewable resources.

With a generation fleet fuel mix shift from conventional generation resources to variable and/or duration-limited, inverter-based resources, a number of key reliability attributes have been identified that will need increased focus to ensure reliable operation throughout the transition to a decarbonized grid. These reliability attributes include inertia and frequency control, ramping capability, short circuit, and voltage control as discussed in the white paper, PJM's Evolving Resource Mix and System Reliability.[2]

Future Impacts to Load Forecasts

Distributed Energy Resources

Currently, PJM Planning studies account for retail DER through the load forecast by netting load by the amount of forecast DER. This approach may be adequate at low levels of DER but is likely problematic with a substantial increase. With such an increase, PJM may not be accounting for the full load that must otherwise be served absent DER. Nonetheless, DER may provide benefits given their proximity to load and thereby reduce the burden on transmission if load were otherwise served by more distant sources.

Research shows an increasing trend toward customer installation of resources behind their electric meter. These resources can take the form of renewable resources stimulated by state programs, local generation installed for individual reliability needs, etc. Such resources clearly impact the operation of local distribution grids, but they can also impact bulk power system operations to the extent they impact net load to be served, transmission facility power flows, local voltage conditions, etc. The continued penetration of DER will require close and effective coordination between PJM and distribution operators in order to ensure reliability and efficient operations given the behavior of these resources.

The trend with DER interconnections – currently consisting primarily of rooftop solar, which has been steadily growing in recent years – may increase as a result of FERC Order 2222. The intent of the order is to reduce barriers to DER participation in wholesale markets by incorporating processes to permit the aggregation of smaller-sized resources.

[2] PJM's Evolving Resource Mix and System Reliability, March 30, 2017, Figure 6, page 16: https://www.pjm.com/-/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx

Electrification

More directly, the key elements driving future peak load levels and load shape are the electrification of transportation and building heating. A key finding of this report is that electrification of light-duty vehicles is likely to be the main trend for which PJM must prepare.

Although recent electric vehicle (EV) trends have been relatively modest, PJM's expectation is that policies at the federal and state level will incentivize a faster pace of EV adoption. Consumer EV charging behavior will impact the load demand curve shape. The impact is expected to be greater in the winter when the curve tends to be flatter, versus the summer when there is more opportunity to shift charging times. With appropriate policies to incentivize charging at off-peak hours, the bump in peak demand can be mitigated in part, even as overall energy consumption increases.

The impact of building heating electrification appears to be less certain given the economics of switching from oil or gas heating, especially in the colder geographic areas of the PJM footprint. Electrification of building heating appears to be on a much longer horizon with less certainty.

The Role of Emerging Technologies

Studies are already identifying the need for additional transmission capability to make the transition to a more decarbonized grid. For example, as mentioned above, PJM recently completed scenario studies to accommodate offshore wind and other renewables that identified the need for significant transmission upgrades. Similarly, PJM studies examining energy transition and its impact from a markets perspective have also identified the need for grid expansion.

The needs of the future grid in the PJM region will likely require a range of solutions. While new transmission lines on new rights-of-way continue to be an option for developers, the attendant siting and permitting, time to construct, and cost to build can be formidable challenges. For these and other reasons, PJM anticipates that innovative solutions that maximize the use of existing facilities and existing transmission corridors will play a role in meeting the future grid's needs. Among the technologies discussed in this paper are dynamic line ratings (DLRs), specialized conductor designs, compact tower construction, power-flow control devices and grid-forming Flexible AC Transmission System (FACTS) devices.

Resilience

A resilient grid must be able to withstand larger-scale system disturbances, to which it is difficult to attach probabilities and that can exceed conventional NERC planning N-1-1 and operations N-1 criteria. Generation and transmission low-probability, high-impact contingencies can significantly impact PJM's ability to serve load reliably. Heavy reliance on intermittent variable resource types raises resilience concerns, as the impact of the February 2021 arctic event impact on ERCOT, SPP and MISO demonstrated.

2. Generation Shift Drives Future Grid Expansion

Across the PJM service area, as in other areas of the country, the generation fleet fuel mix continues to shift. Driven by public policy (including RPS mandates and environmental regulations) and abundant shale natural gas in the PJM footprint, coal-fired generation is retiring and being replaced by renewable-powered and natural gas-fired generation. From 2012 through 2021, 41,211 MW of generation in the PJM footprint retired, including more than 31,833 MW from 154 coal-fired units, 135 of which were more than 40 years old. These deactivated units have been replaced by more than 43,000 MW of new resources, including over 3,000 MW of solar generation and 6,000 MW of wind generation. As this section discusses, another estimated 105,000 MW of renewables, coupled with age and public-policy-driven deactivations, will drive grid expansion.

2.1 Trends in Renewable Power

PJM's diverse installed capacity resource profile today includes generation powered by natural gas, coal, nuclear, wind and solar, coupled with demand response and storage. However, increasing public demand for cleaner sources of electricity, combined with public policy standards and goals, is driving unprecedented growth in renewable resources. As discussed below, PJM generation interconnection queue activity reflects a shift from interconnection requests by natural gas generation to solar, wind and storage.

2.1.1 Geography

PJM's footprint draws attention to the two locational dimensions of wind-powered generation:

1 | Onshore, mainly along the Appalachian Mountains' ridge and PJM's western subregion

2 | Offshore, along the coasts of New Jersey, Maryland, Delaware, Virginia and North Carolina

Only through careful scenario analyses will PJM be able to evaluate the holistic impact on the need for grid expansion. Notably, unlike other areas of the country, renewable-powered generation developers in the PJM footprint are not seeking interconnection far from load centers. This trend has significant implications for future grid planning, insofar as the need for major long-distance, possible multi-state, backbone transmission lines to deliver RPS-mandated power may not necessarily be the most efficient first-choice grid solution.

Table 1 and accompanying **0** show that of the 691 renewable generation projects currently in-service, 613 generation projects (88.7%) are geographically located 100 miles or less from load centers, 74 generation projects (10.7%) are geographically located between 101 miles to 200 miles from load centers, and only four generation projects (0.6%) are geographically located more than 200 miles from a load center.

Table 1. PJM Current In-Service Generation – Geographical Distance From Load Center

Distance From Load Center	In-Service Generating Facilities: Count					MW				
	Renewable	Fossil	Nuclear	Other	**Total**	Renewable	Fossil	Nuclear	Other	**Total**
0–100 miles	236	270	17	90	**613**	20,242	124,617	30,838	1,007	**176,704**
101–200 miles	47	20	1	6	**74**	7,014	11,778	1,819	59	**20,670**
201–300 miles	1	3	0	0	**4**	250	1,846	0	0	**2,096**

Renewable: Solar, Wind, Hydro | **Fossil:** Natural Gas, Coal, Oil | **Other:** Biomass, Landfill, Battery, Flywheel

Map 1. PJM Current In-Service Generation – Geographical Distance to Load Center

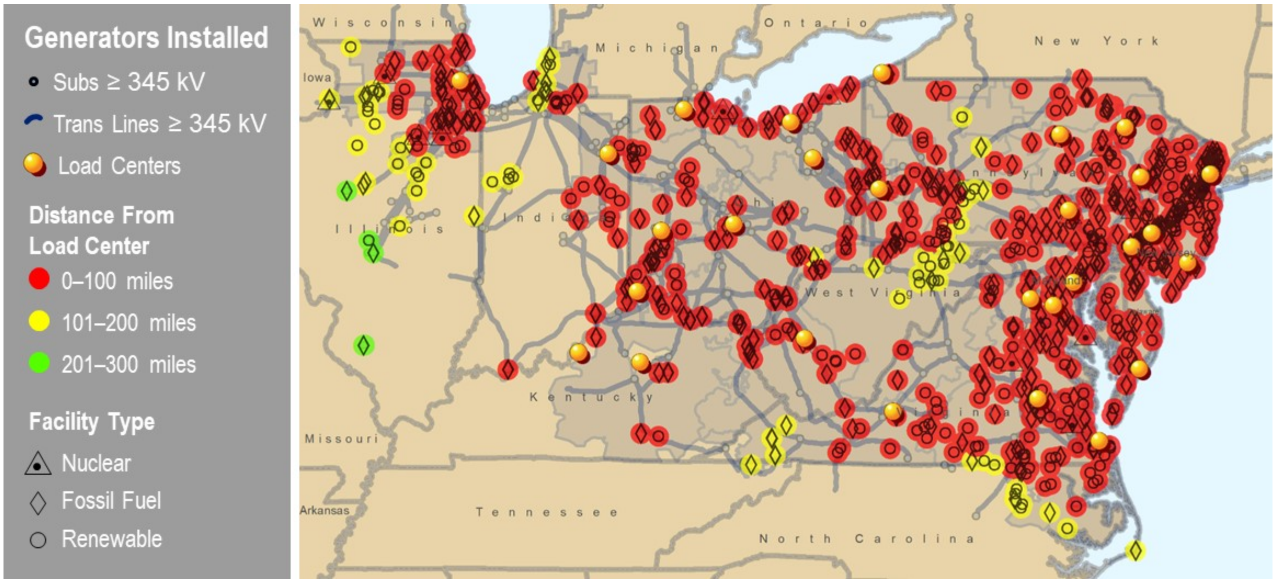


Table 2 and **Map 2** show that of the 1,826 planned generation projects currently in PJM's interconnection queue, 1,560 planned generation (85.4%) projects are geographically located 100 miles or less from load centers, 254 planned generation projects (13.9%) are geographically located between 101 miles to 200 miles from load centers, and only 12 planned generation projects (0.7%) are geographically located more than 200 miles from a load center. Thus, future interconnection queue generation will remain close to load centers within the PJM service area, with only a marginal reduction in relative proximity.

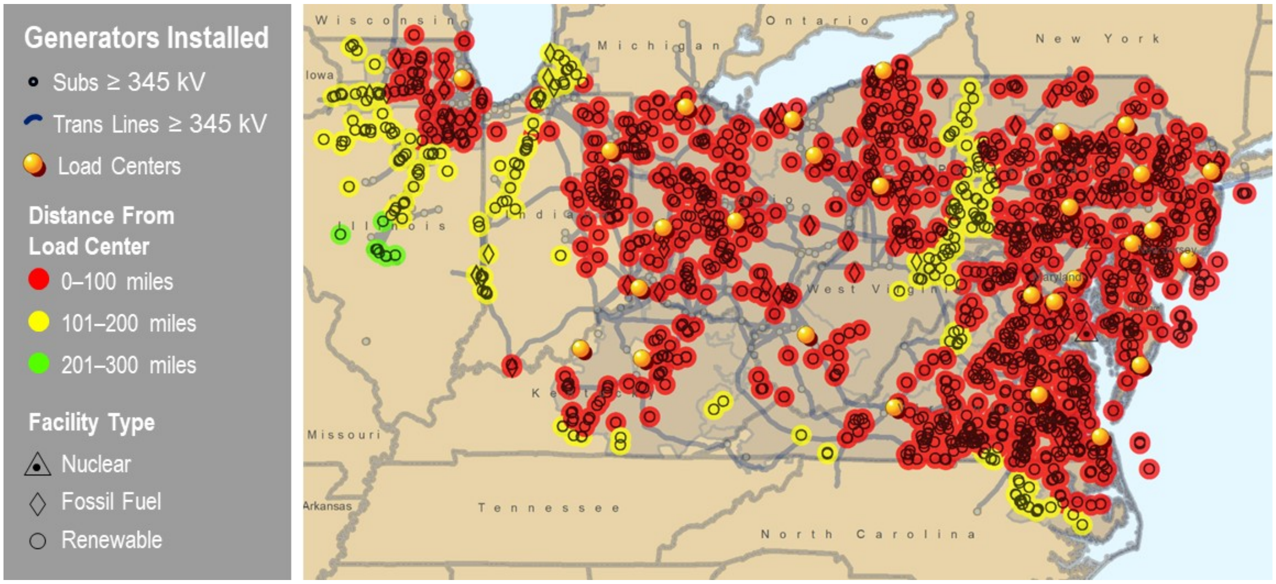
Table 2. PJM Interconnection Queue Projects – Geographical Distance From Load Center

Future Projects

Distance From Load Center	Count					MW				
	Renewable	Fossil	Nuclear	Other	**Total**	Renewable	Fossil	Nuclear	Other	**Total**
0–100 miles	1,212	98	6	244	**1,560**	108,435	17,552	190	19,055	**145,232**
101–200 miles	200	13	0	41	**254**	27,784	4,588	0	3,365	**35,737**
201–300 miles	8	0	0	4	**12**	1,008	0	0	186	**1,194**

Renewable: Solar, Wind, Hydro | **Fossil:** Natural Gas, Coal, Oil | **Other:** Biomass, Landfill, Battery, Flywheel

Map 2. PJM Interconnection Queue Projects – Geographical Distance From Load Center



2.1.2 State Renewable Portfolio Standards

PJM's grid of the future will enable customer access to renewable power at much greater levels than today, driven by states' RPS mandates. Ten states in the PJM footprint, plus the District of Columbia, have enacted them as shown in **Table 3** and **Map 3**, below.

These mandated state RPS targets require that a certain percentage of a state's load are served by qualified renewable energy resources. RPS policies have functioned as a significant driver of renewable resource development. Across the nation, and in PJM, many states have increased their RPS targets in recent years in pursuit of accelerated decarbonization objectives. Since 2018, Delaware, the District of Columbia, Illinois, Maryland, New Jersey and Virginia have all established new RPS targets.

State RPS policies also vary by eligible resource technology, in-state resource carve-out requirement, and required qualified resource location. Whether characterized as a goal or target, the majority of PJM states are moving toward a decarbonized grid over the course of the next 20–30 years. In addition, some in-state resource carve-outs are crafted as a percentage of energy, while others specify the minimum renewable capacity to be developed in-state. The variability in policies has not been a hindrance to building new renewable generation and, in fact, has provided developers both direction and flexibility in siting planned renewable generators. As a result, renewable generation is now the most prominent resource type in PJM's interconnection queue in each state, including those that have historically been more fossil fuel intensive.

Table 3. PJM State RPS Targets

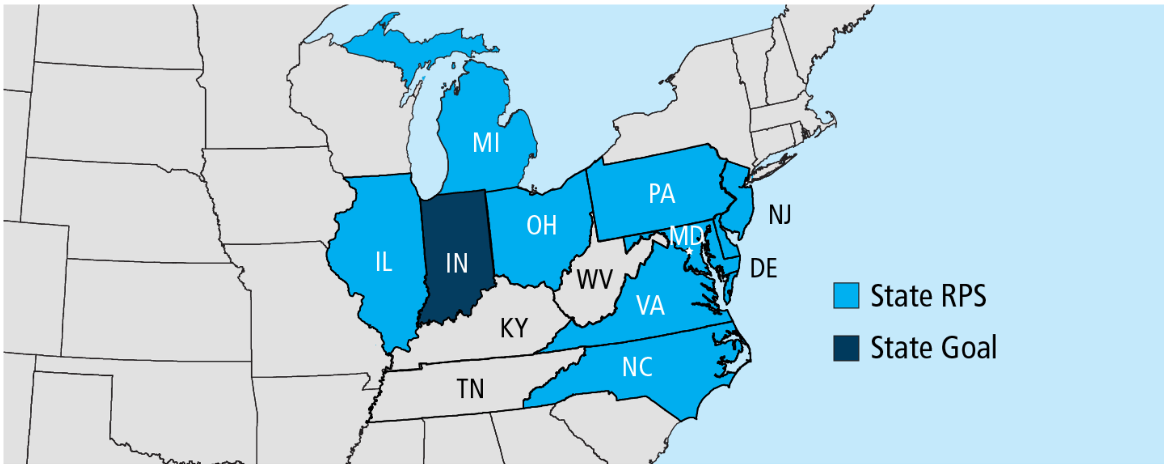
State RPS Targets*

☼	**NJ:** 50% by 2030**	☼	**PA:** 18% by 2021***		**OH:** 8.5% by 2026
☼	**MD:** 50% by 2030**	☼	**IL:** 50% by 2040		**MI:** 15% by 2021
☼	**DE:** 40% by 2035	☼	**VA:** 100% by 2045/2050 (IOUs)		**IN:** 10% by 2025***
☼	**DC:** 100% by 2032	☼	**NC:** 12.5% by 2021 (IOUs)		

☼ Minimum solar requirement

* Targets may change over time; these are recent representative snapshot values.
** Includes an additional 2.5% of Class II resources each year
*** Includes non-renewable "alternative" energy resources

Map 3. PJM State RPS Targets and Goals



2.1.3 120,000 MW by 2050 – Energy Transition Analysis Insights

As noted above, the public policies vary widely among the PJM states in terms of the types of resources targeted, how achievement is measured, and the time frame to achieve desired goals. Nonetheless, the estimated impact, based on PJM's energy transition analysis, is that wind and solar resources will grow between three and eight times (in installed capacity terms) over the course of the next 15 years, potentially adding another 105,000 MW to the existing level of roughly 15,000 MW of renewable wind, solar and storage resources.

The energy transition analysis culminated in a report, Energy Transition in PJM: Frameworks for Analysis[3] published on Dec. 15, 2021, and has informed the grid of the future road map discussed in this paper. The analysis studied three scenarios of varying levels of renewable penetration comprising offshore wind, onshore wind and solar power as shown in **Figure 1**:[4]

1 | Business-as-Usual Reference Case – The amount of renewable energy penetration levels is modeled after RTEP 2023 power-flow cases.

[3] Energy Transition in PJM: Frameworks for Analysis, Dec. 15, 2021.

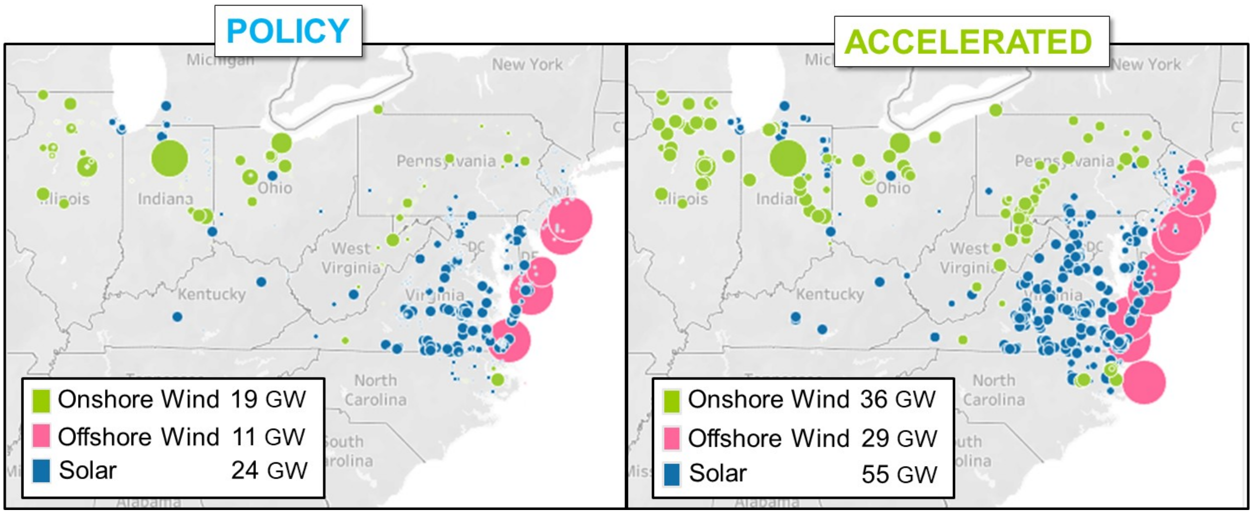
[4] Ibid. page 6.

2 | Policy Scenario Case – 22% of the RTO's energy comes from renewable generation based on analysis of state and utility corporate clean energy targets through 2035.

3 | Accelerated Scenario Case – 50% of the RTO's energy comes from renewable generation. This scenario referenced additional state and corporate clean energy targets extending to 2050.

PJM's fuel mix will drastically change due to the state and corporate clean energy policy targets, with solar and wind generation increasing and replacing coal and natural gas generation. With that in mind, the energy transition in PJM analysis evaluated hourly market PLEXOS simulations, with nodal model monitoring at 230 kV and higher, for each of the three renewable penetration scenarios above.

Figure 1. Renewable Generation Expansion in Policy and Accelerated Scenarios – PJM Energy Transition Analysis



The energy transition analysis results yielded a number of significant conclusions, including the following, with a more direct impact on PJM's future grid road map:

- 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 sunset.[5]
- No load-shedding events were observed in the energy market simulation.[6]
- Adding zero-marginal-cost renewable resources decreased the average locational marginal price (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%.[7]

[5] Ibid. page 1.
[6] Ibid. page 1.
[7] Ibid. page 2.

- The analysis 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.[8] As the power flow in the network changed, so did congestion patterns. Simulations showed an overall increase in congestion hours.[9]

- A significant amount of renewable curtailment was needed to manage transmission limitations and minimum generation events.[10]

2.1.4 RPS Impacts on Queue Activity

The impact of states' RPS policies can be seen in **Figure 2,** which shows interconnection request trends by queue – AB2 through AH1 – and fuel type over the past six years in terms of unit Maximum Facility Output (MFO). Trends show that requests for solar- and wind-powered interconnection, together with storage, continue to grow steadily, queue-over-queue, while requests for new natural gas plants have ebbed.

Figure 3 provides another perspective by showing the queue status as of Dec. 31, 2021, in terms of requested Capacity Interconnection Rights (CIRs). This look at PJM's queue activity demonstrates that renewable developers see the market opportunities enabled by RPS policies, given that generators must have CIRs to participate in PJM's capacity market.

Figure 4 shows a time-based view of forecast growth of onshore and offshore wind generation alone, indicating that future grid expansion planning must ensure that over 46,000 MW of wind power can interconnect reliably.

As PJM's generation mix shifts more toward renewables, PJM must evaluate how to maintain or even increase the level of NERC-defined essential reliability services to ensure system reliability. This is particularly critical in the face of the extreme weather events recently experienced across the United States against the backdrop of increasing renewables penetration, retirements of dispatchable generation, and growing reliance on interregional transfer capability.

[8] Ibid. page 3.

[9] Ibid. page 3.

[10] Ibid. page 12.

Figure 2. PJM Queued Generator Interconnection Requests[11] (Megawatts, MFO[12])

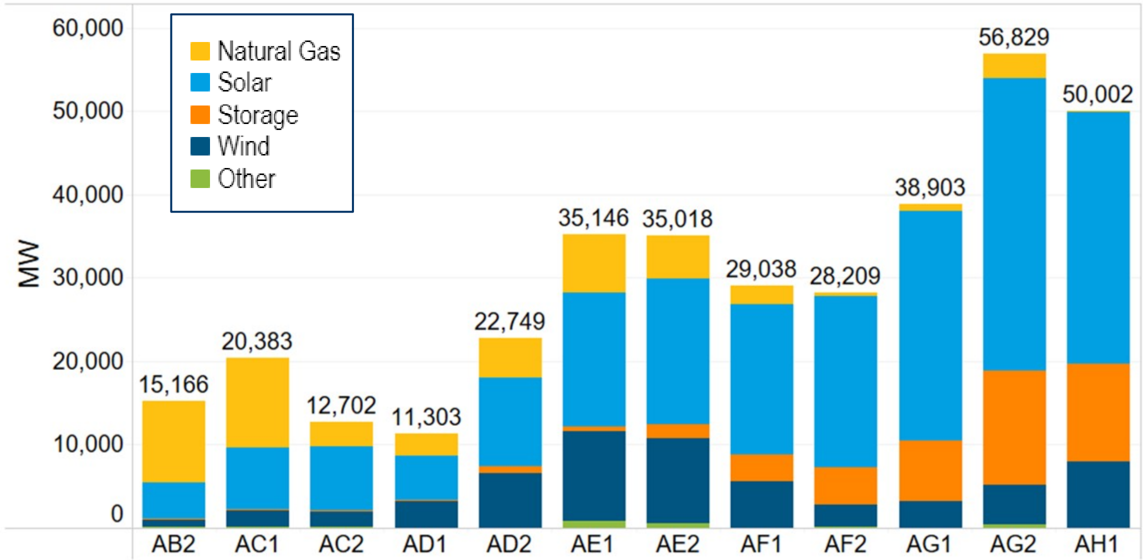
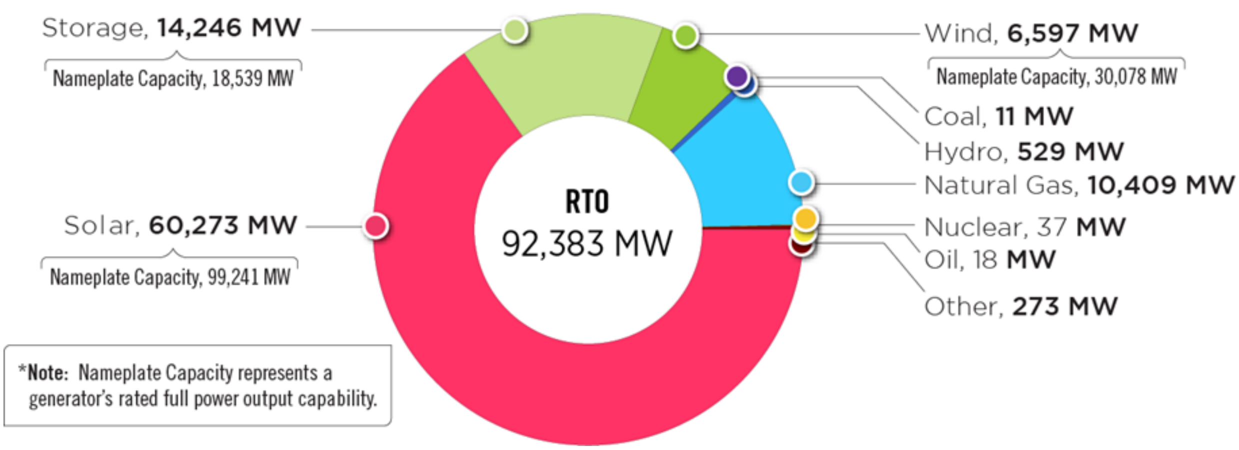


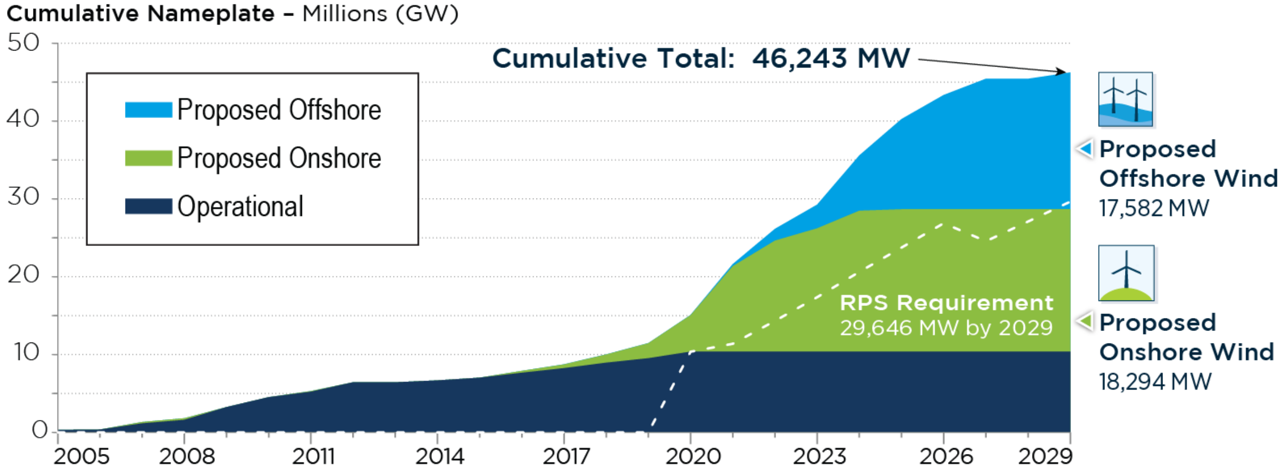
Figure 3. PJM Generator Interconnection Request Queue by Fuel Type (Requested Capacity Interconnection Rights, Close of Queue AH1, Sept. 30. 2021)



[11] Data for Queue AH1 is preliminary.

[12] MFO stands for Maximum Facility Output, which can also be called nameplate capacity, and is defined in PJM's Open Access Transmission Tariff: "…the maximum (not nominal) net electrical power output in megawatts, specified in the Interconnection Service Agreement, after supply of any parasitic or host facility loads, that a Generation Interconnection Customer's Customer Facility is expected to produce, provided that the specified Maximum Facility Output shall not exceed the output of the proposed Customer Facility that Transmission Provider utilized in the System Impact Study."

Figure 4. Wind Installed Capacity in PJM – Operational and Proposed



2.1.5 Onshore Wind Trends

Federal and state legislative and regulatory RPS and public policy initiatives continue to drive the development of onshore wind-powered generators across the RTO, bringing into clear focus the critical role of transmission in delivering power reliably. Wind-powered generating resources have played a growing role in meeting PJM customer load requirements since April 2002 when the first wind generator, located in Fayette County, Pennsylvania, was interconnected to the PJM transmission grid with total nameplate capacity of 15 MW. Since then, total wind nameplate[13] capacity has grown to 11,000 MW within PJM.

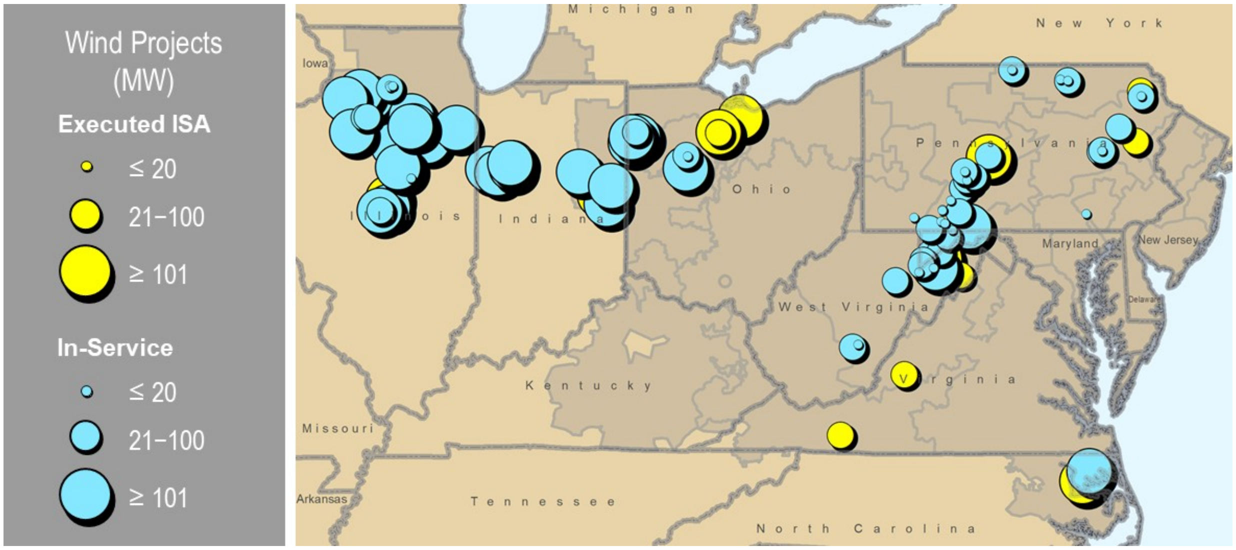
2.1.5.1 Queue Activity

Renewables growth is not emerging uniformly across PJM's footprint. Growth is occurring fastest in areas with favorable wind speed and sustained duration in order to achieve energy production levels that generate profit-making revenue streams. PJM continues to see developer interest in constructing wind-powered generating facilities throughout its footprint with clusters emerging in PJM's western subregion (including Illinois, Indiana and Ohio) and along the Allegheny Mountains in Pennsylvania and West Virginia. **Map 4** shows generator interconnection requests received by PJM through the close of Queue AG2 that are currently at the Interconnection Service Agreement execution phase or later.[14] These requests total 14,976 MW. **Map 4** shows interconnection requests for 15,338 MW of wind-powered generation (also through the close of Queue AG2) that are currently under active study (i.e., they have reached the feasibility, impact or facility study stage). The trend that **Map 4** shows earlier in the interconnection process demonstrates ongoing developer interest in PJM's western subregion.

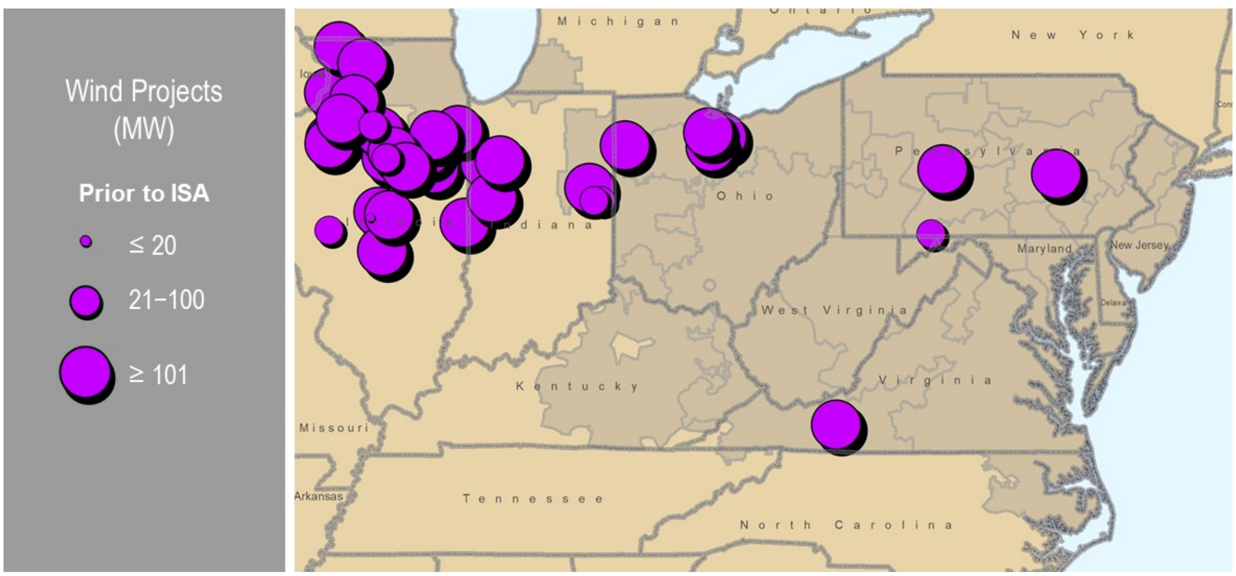
[13] Nameplate capacity represents a generator's rated full power output capability and is typically much greater than CIRs for wind- and solar-powered generators. This is because, while some resources can operate continuously like conventional fossil-fueled power plants, power output from renewable resources like wind and solar can be variable.

[14] PJM's generation interconnection process has three study phases: feasibility, system impact and facilities studies, to ensure that new resources interconnect without violating established NERC, PJM, transmission owner and regional reliability criteria. This culminates in the execution of an Interconnection Service Agreement. Each generator that completes the necessary transmission system enhancements becomes eligible to interconnect to the grid and to participate in PJM capacity and energy markets.

Map 4. Onshore Wind Generation Project Locations Through Queue AG2 Currently at ISA Phase or Later



Map 5. Onshore Wind Generation Project Locations, Through Queue AG2, Prior to ISA



2.1.6 Offshore Wind Trends

The area off the U.S. Atlantic coast encompasses a major wind-energy resource that could potentially yield thousands of megawatts of power. Efficiently harnessing that energy through the construction of offshore wind farms will require extending the existing transmission grid to deliver power ashore to users, particularly to load centers along the East Coast.

Offshore wind has been a source of power for decades in Europe and other parts of the world. In the United States, and in PJM more specifically, it remains a nascent technology. Through September 2021, only two operational offshore wind farms in the United States have reached commercial operation: the 30 MW Block Island Wind Farm off the coast of Rhode Island and the 12 MW Coastal Virginia Offshore Wind Pilot Project near Virginia Beach. Although current operational capacity totals are low, offshore wind is expected to be a major contributor to U.S. clean energy and decarbonization initiatives over the coming decades.

To date, the primary location for offshore wind development in the United States has been the Atlantic coast, primarily in New England and the mid-Atlantic states. However, the Pacific coast, Hawaii, the Gulf of Mexico and the Great Lakes are also being considered for offshore wind potential. **Table 4** provides an overview of every state's current offshore wind procurement targets.

Table 4. Current Offshore Wind Policy Targets

State	Offshore Wind Target (MW)	Target Date
Connecticut	2,300	2030
Maryland	2,022.5	2030
Massachusetts	5,600	2035
New Jersey	7,500	2035
New York	9,000	2035
North Carolina[15]	8,000	2040
Rhode Island	430	-
Virginia	5,200	2035
Total	**40,053**	

Within the PJM service area, Maryland, New Jersey and Virginia have all established offshore wind targets totaling 14,722.5 MW (36% of the Atlantic coast targets noted in **Table 4** with planned in-service dates by 2035). Also, North Carolina recently announced an 8,000 MW target by 2040 via a June 2021 executive order. Legislation is driving offshore wind objectives in Maryland and Virginia. New Jersey's goal is supported by a combination of legislation and an executive order.

Several projects that will be used to achieve the PJM states' offshore wind targets have already been selected. New Jersey has conducted two solicitations to date to award Offshore Wind Renewable Energy Certificates (ORECs) to three projects totaling 3,758 MW.[16] Maryland has awarded ORECs to four projects totaling 2,022.5 MW, with their most recent award coming in 2021.[17] Within Virginia, Dominion Energy has already proposed 2,640 MW of offshore wind capacity to be constructed by 2026 via three phases of 880 MW each. In addition to these announced projects, Avangrid Renewables is advancing a 2,500 MW merchant offshore wind project off the coast of North Carolina.

While offshore wind development in the United States has largely been led by individual state initiatives, the Biden administration introduced a federal offshore wind policy target in March 2021. Through a shared goal between the Department of the Interior, Department of Energy and Department of Commerce, the United States is now pursuing 30 GW of operational offshore wind by 2030. As part of its plan to reach this milestone, the Biden administration

[15] Target in North Carolina, per executive order

[16] New Jersey's first solicitation was awarded to Ørsted's 1,100 MW Ocean Wind I project. The second solicitation was awarded to Ørsted's 1,148 MW Ocean Wind II project and 1,509.6 MW Atlantic Shores project, which is a joint venture between EDF Renewables North America and Shell New Energies.

[17] Maryland's first two offshore wind solicitations were awarded to Ørsted's 120 MW Skipjack project and US Wind's 248 MW MarWin project. Maryland's third offshore wind solicitation awarded ORECs to Ørsted's 846 MW Skipjack 2.1 project and US Wind's 808.5 MW MarWin II project.

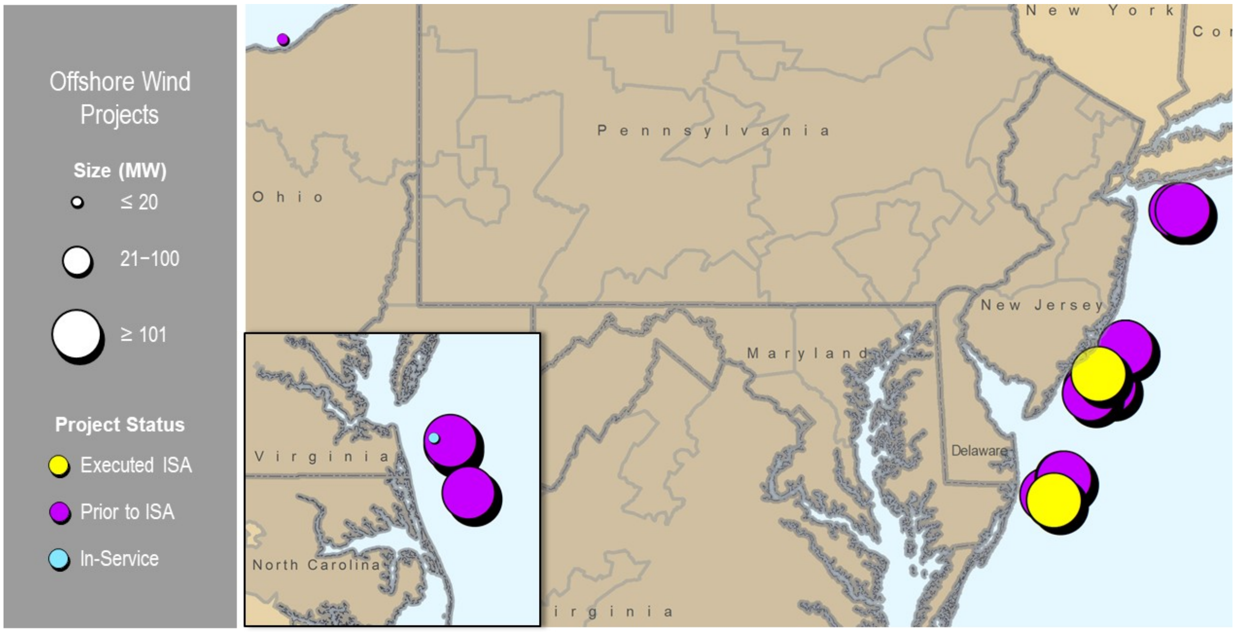
plans to support the Bureau of Ocean Energy Management (BOEM) in issuing new lease sales[18, 19] and reviewing at least 16 construction and operations plans by 2025.[20] The national 30 GW target is also believed to be a starting point for an eventual offshore wind goal of 110 GW by 2050.[21]

The injection of thousands of megawatts from offshore wind will fundamentally change how power flows over the transmission grid in the Northeast and mid-Atlantic. Generation will now be located closer to load centers along the I-95 corridor; this area of the grid was originally served mainly by west-to-east power flow from large mine-mouth coal generating stations in western Pennsylvania and beyond and, later, shale natural gas-fired plants in central Pennsylvania. This unfolding scenario will drive the need for new transmission assets and system configurations to maximize power delivery to onshore load.

2.1.6.1 Queue Activity

The capital costs involved with building offshore wind facilities and the supporting transmission upgrades present a major barrier to offshore wind entering a competitive market without financial support at the state or federal levels. Given the costs of developing offshore wind resources, these facilities will not likely enter the PJM queue absent: (1) the expectation of contributing to a state's offshore wind target; and (2) receiving public funding. As a result, the queued offshore wind resource activity illustrated in **Map 6** is likely to continue to follow existing and anticipated offshore wind policies to the extent that financial support is available.

Map 6. PJM Offshore Wind Generation Locations (Through Queue AG2)



[18] On Feb. 25, 2022, the Department of the Interior announced results of its competitive offshore energy lease sale for the New York Bight: https://www.doi.gov/pressreleases/biden-harris-administration-sets-offshore-energy-records-437-billion-winning-bids-wind

[19] Additional information about the New York Bight can be found online: https://www.boem.gov/renewable-energy/state-activities/new-york-bight

[20] Fact Sheet: Biden Administration Jumpstarts Offshore Wind Energy Projects to Create Jobs (March 29, 2021) – https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/29/fact-sheet-biden-administration-jumpstarts-offshore-wind-energy-projects-to-create-jobs/

[21] *Id.*

2.1.6.2 State Agreement Approach

The State Agreement Approach (SAA) is a PJM Operating Agreement provision that allows one or more states to pursue public policy requirements as part of PJM RTEP process study planning parameters. States, in collaboration with PJM, voluntarily agree to develop identified transmission solutions identified in RTEP process studies. States are subsequently responsible for 100% of the cost allocation of each such SAA-derived RTEP projects for which they elect to move forward.

The New Jersey Board of Public Utilities (NJBPU) initiated PJM's SAA in November 2020 by soliciting transmission proposals to accommodate full integration of 7,500 MW of planned offshore wind-powered generation by 2035. The parties filed an SAA agreement[22] with FERC on Jan. 27, 2022, outlining how New Jersey will put PJM's competitive planning process to work in pursuit of its offshore wind goals. The agreement details the contractual commitments and responsibilities of the NJBPU and PJM regarding the competitive selection of transmission solutions.

New Jersey's initiation of the SAA is the first time a state in the PJM region has elected to pursue achieving public policy requirements through PJM's competitive RTEP process. In this instance, doing so will enable the construction of large-scale, offshore wind-powered generation. This joint New Jersey-PJM SAA experience provides an effective planning blueprint going forward for states to pursue their own respective RPS and other public policy goals as part of effective, coordinated planning within PJM for the grid of the future.

2.1.6.3 PJM's Offshore Wind Transmission Study

Planning grid of the future road map efforts are already underway as part of PJM's Offshore Wind (OSW) Transmission Study,[23] mentioned earlier, and initiated in response to a request from the Organization of PJM States (OPSI)[24] to look at various future OSW scenarios. The study's first phase, completed in October 2021, examined onshore grid reinforcements needed by 2035 to deliver wind-powered generation located off the coasts of Maryland, New Jersey and Virginia, as part of achieving all RPS targets across all PJM states.

Multiple scenarios examined the integration of renewables at levels between 30,000 MW and 80,000 MW. The study identified the need for an estimated $3 billion of bulk electric system[25] transmission enhancements over the next 10 to 15 years to integrate PJM's coastal states' OSW targets and to meet RPS goals across the entire RTO footprint. The analysis provides a sense of the magnitude of grid expansion needed to integrate growing renewable resource penetration. As PJM continues to implement its road map to enable a decarbonized grid, additional OSW scenario study analysis will examine accelerated renewable penetration levels and will incorporate a more in-depth assessment of the impacts from higher levels of building heating and transportation electrification.

By synchronizing transmission planning across all its coastal states' offshore wind deployment, PJM is able to identify transmission solutions that offer a more efficient and economic means for states collectively to achieve their offshore wind policy objectives than if each pursued respective objectives independently. The OSW study does not commit any PJM state to any transmission grid enhancement. Rather, it serves as an opportunity to identify the potential scope of coordinated transmission solutions to help inform state policymakers as they advance their offshore wind policy objectives. States can incorporate study findings into future offshore wind solicitations and related SAA-derived

[22] FERC Docket No. ER22-902

[23] https://www.pjm.com/-/media/library/reports-notices/special-reports/2021/20211019-offshore-wind-transmission-study-phase-1-results.ashx

[24] https://www.pjm.com/-/media/about-pjm/who-we-are/public-disclosures/20191217-opsi-letter-re-october-board-to-board-discussion-follow-up.ashx

[25] Essentially, the bulk electric system comprises transmission facilities at 100 KV and higher.

transmission solutions. States ultimately reserve the right and ability to work together on transmission solutions for offshore wind and other clean energy objectives, or can defer to the existing PJM generation interconnection queue process in which generators are assigned cost responsibility for associated network transmission upgrades.

2.1.7 Solar Power Trends

Solar-powered generation is typically considered on the same terms as wind-powered generation as a key dimension in achieving RPS standards, as discussed earlier in **Section 2.1.2**. A key dimension of achieving those goals must necessarily account for industry experience, which has shown that as solar resources meet a larger share of the mid-day generation needs, non-solar resources are needed to ramp down in the morning and ramp up again in the evening to balance daily and seasonal solar unit output patterns. This system behavior will drive studies to examine the impact on power-flow patterns and potential for reliability criteria violations.

2.1.7.1 Queue Activity

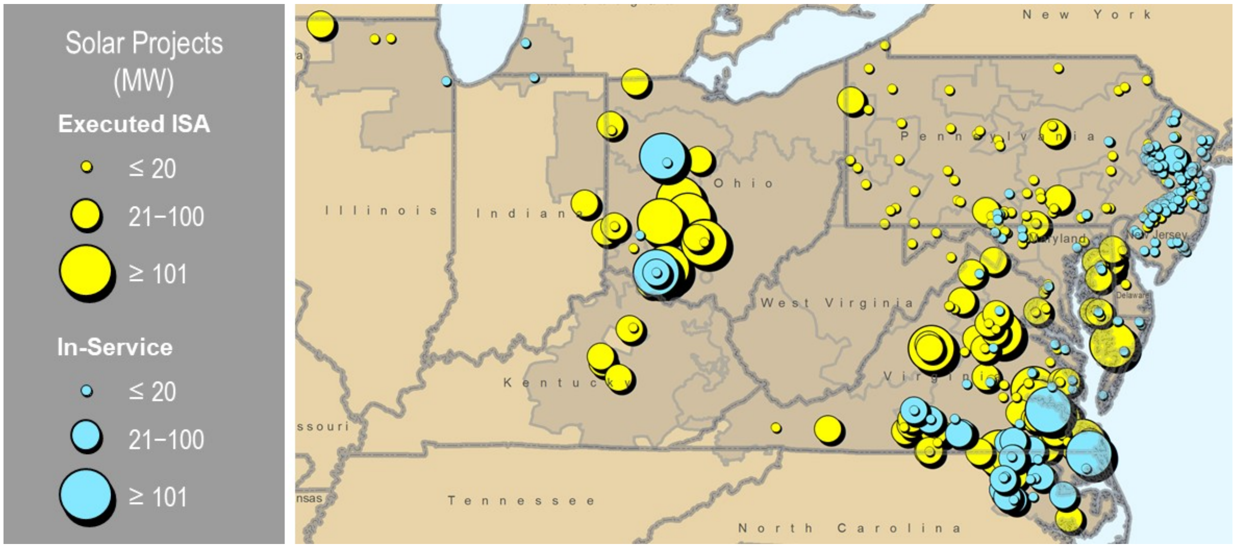
With approximately 175,000 MW of interconnection requests[26] in PJM's queue, nearly 100,000 MW, or 57%, of all submitted queue requests for CIRs have been for solar generation. In 2020, solar generation exceeded natural gas as the largest percentage of units, by fuel type, seeking CIRs. Solar interconnection requests more than doubled in 2020 over 2019, driven by federal and state public policy and broader fuel economics of other types of units.

The location of early utility-scale solar installations within PJM was driven by the financial incentives offered by specific states. To date, existing and planned solar generation with executed Impact Study Agreements (ISAs), totaling 13,453 MW, have been concentrated in these states, as shown on **Map 7**. However, queued solar projects seeking interconnection that have not yet reached ISA status – currently totaling approximately 140,000 MW – are shown on **Map 8** and indicate that the trend has shifted. These more recent additions to the interconnection queue demonstrate increasing geographic diversity across the PJM footprint, with growing numbers of new solar projects now in every state and transmission owner zone.

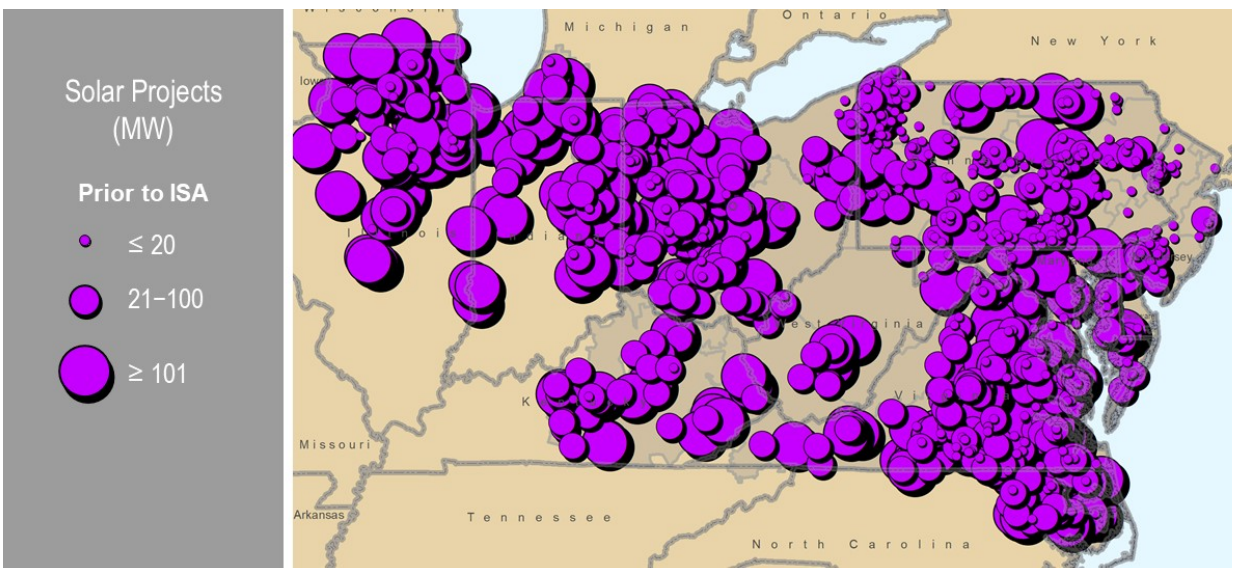
PJM recognizes that solar presents its own challenges, such as when low availability of solar power coincides with high power demand. To address this future grid risk, PJM studies must examine time-of-day and seasonal impact of solar on grid power-flow patterns. And, as with wind-powered generation, the inverter-based resource (IBR) power electronics associated with solar-powered generation also introduces concern with maintaining – or even increasing – the availability of sufficient levels of NERC-defined reliability attributes, an issue that PJM continues to examine.

[26] Through the close of Queue AG2 on March 31, 2021

Map 7. Utility-Scale Solar Installations in PJM: Currently In-Service Projects and Queued Projects Through Queue AG2, at Executed ISA Phase or Later



Map 8. Utility-Scale Solar Installation Interconnection Requests in PJM Through Queue AG2, Prior to ISA



2.1.7.2 State Solar Public Policy Drivers

States rely on solar power as one of the main resources to meet their RPS requirements. Eight of the 10 PJM states with mandatory RPS targets include solar-specific requirements, the details of which vary by state. Some include in-state solar carve-outs as a percentage of total state energy demand. Others permit their solar carve-outs to be met by solar resources located anywhere within the PJM footprint. Still others, particularly those located along PJM's seams, allow solar commitments from resources located outside the PJM footprint to meet RPS targets and goals.

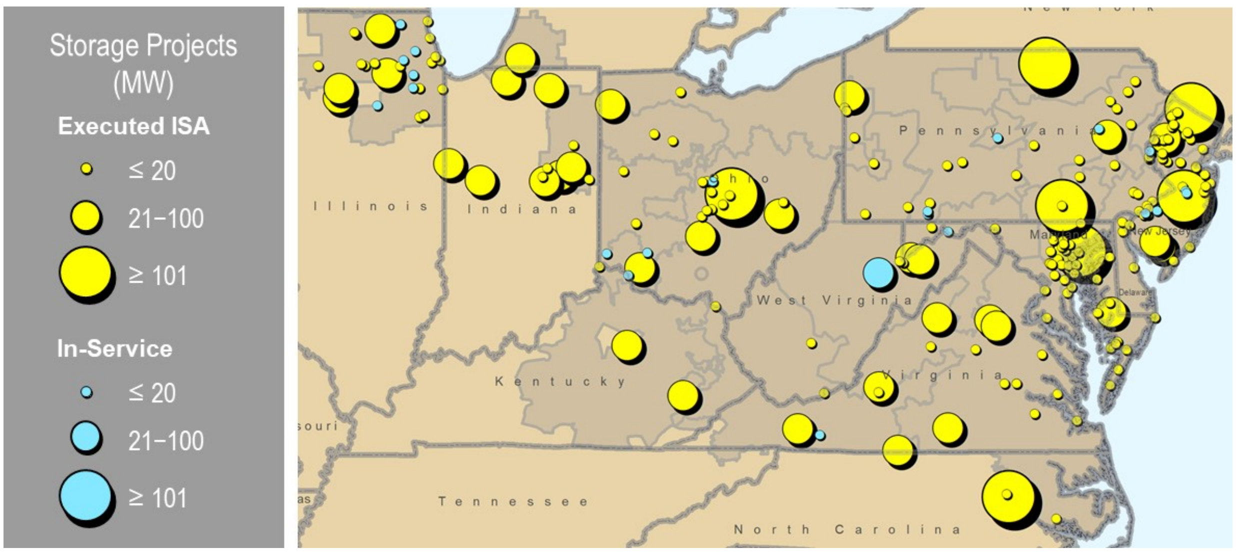
2.1.8 Storage and Renewable Plant Hybrids

Energy storage development continues to grow in PJM as in other RTOs. As solar generation increases across the PJM footprint, storage growth is expected to follow, particularly as part of co-located projects. Efficient grid operations in an era of rapid renewable energy resource growth will require increased electric system flexibility. Energy storage can help grid operators maintain stable power supply under varying wind and solar power output, driven by weather conditions and unit outages, and improve utilization levels of existing transmission facilities. PJM has worked with various companies and national laboratories to study storage use and to ensure that the PJM wholesale market can permit all forms of energy storage to participate. Storage as a transmission asset is discussed further in **Section 5.4.**

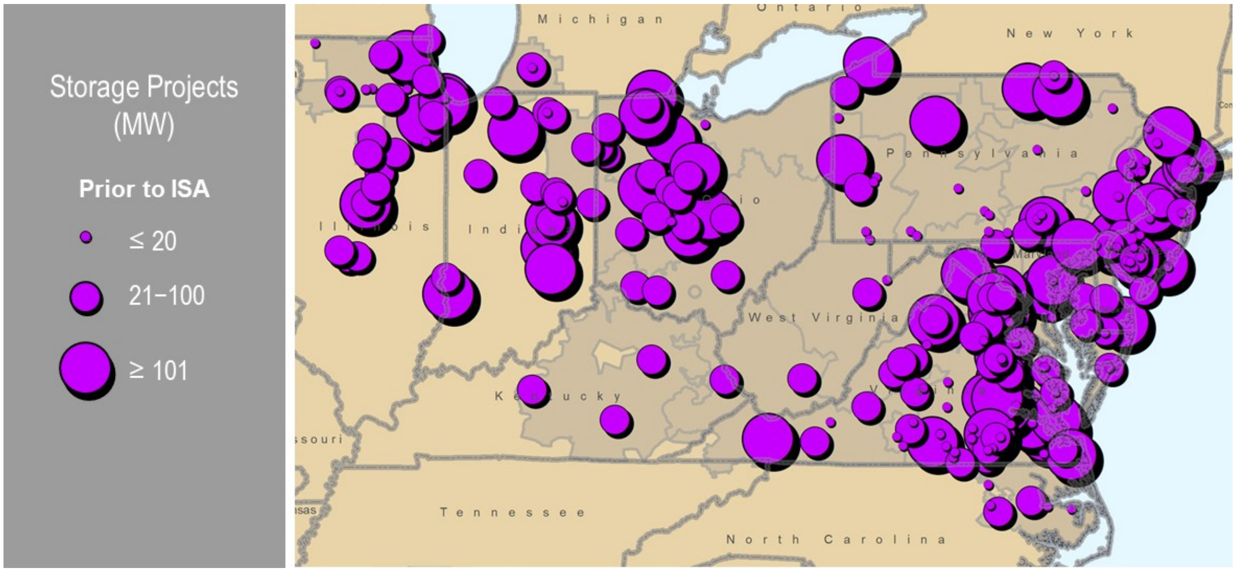
2.1.8.1 Queue Activity

Queued storage resources total over 11,800 MW of interconnection requests for CIRs (over 15,800 MW on a nameplate capacity basis), as shown in **Figure 3** in **Section 2.1.4** and on **Map 9** and **Map 10.** This is in addition to the storage resources today comprising pumped-storage hydro totaling 5,000 MW and battery and flywheel energy storage totaling 300 MW. Pumped storage can participate in the PJM capacity, Energy, Regulation and Reserve markets.

Map 9. Storage Installations in PJM: Currently In-Service Projects and Queued Projects, Through Queue AG2, at Executed ISA Phase or Later



Map 10. Storage Installation Interconnection Requests in PJM through Queue AG2, Prior to ISA



2.1.8.2 State Public Policy Drivers

Storage development is also being driven by both explicit and implicit state policy objectives. Explicit state targets include Virginia's 3,100 MW of storage by 2035 and New Jersey's 2,000 MW target by 2030, as outlined in its 2019 Energy Master Plan.[27] Maryland also has an energy storage pilot program that was implemented in 2019 to develop storage capacity within the state.[28] Implicitly, storage is being developed to complement the influx of renewable resources driven by state RPS targets.

2.1.8.3 Impacts of Storage on Future Grid

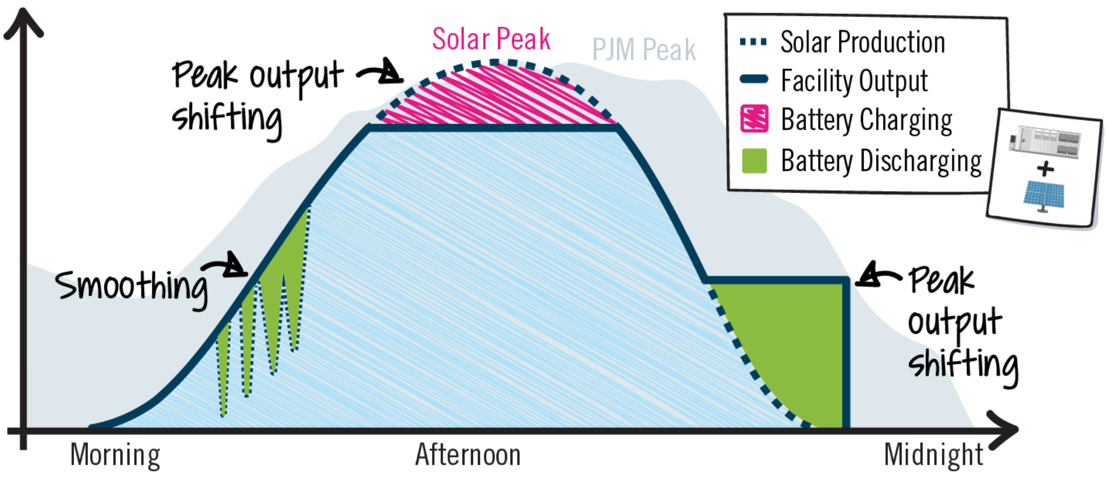
PJM recognizes that storage paired with renewables and transmission can optimize the delivery of power. To address the limited-duration issue, some developers are pairing storage with variable, renewable generation, such as solar or wind, to create opportunistic revenue streams. The pairing is either co-located (in which the storage facility and the generator facility are sited on the same parcel of land, but each has its own connection to the grid) or is hybrid (in which the storage facility and generator share a common connection to the grid).

Whether co-located or hybrid, the net result with respect to solar power, for example, smooths minute-by-minute load fluctuations, flattens peak load while storage devices are charging, and discharges power back into the grid at later hours, as shown in **Figure 5.** PJM and the industry continue to research such impacts on the future grid's load shape and reliability. Likewise, PJM and the industry are also exploring how storage can mitigate IBR reliability attribute risks like frequency and other aspects of system stability.

[27] 2019 New Jersey Master Plan: Pathway to 2050 – https://nj.gov/emp/docs/pdf/2020_NJBPU_EMP.pdf

[28] "Maryland passes energy storage pilot program to determine future regulatory framework" *Utility Dive* (2019) – https://www.utilitydive.com/news/maryland-passes-energy-storage-pilot-program-to-determine-future-regulatory/551769/

Figure 5. Impact of Storage on Peak Solar Production



2.2 Trends in Conventional Generation

From 2012 through 2021, 41,211 MW of generation have retired in PJM (as discussed later in this paper), including more than 31,833 MW from 154 coal-fired units, 135 of which were more than 40 years old. Retiring units are being replaced by new generation, which previously consisted of new natural gas plants, but increasingly are renewable energy resources, as shown in **Figure 3** in **Section 2.1.4**. This generation shift, expected to continue through at least 2035, will impact the magnitude of grid expansion through 2035 and beyond.

2.2.1 Natural Gas-Powered Plant Trends

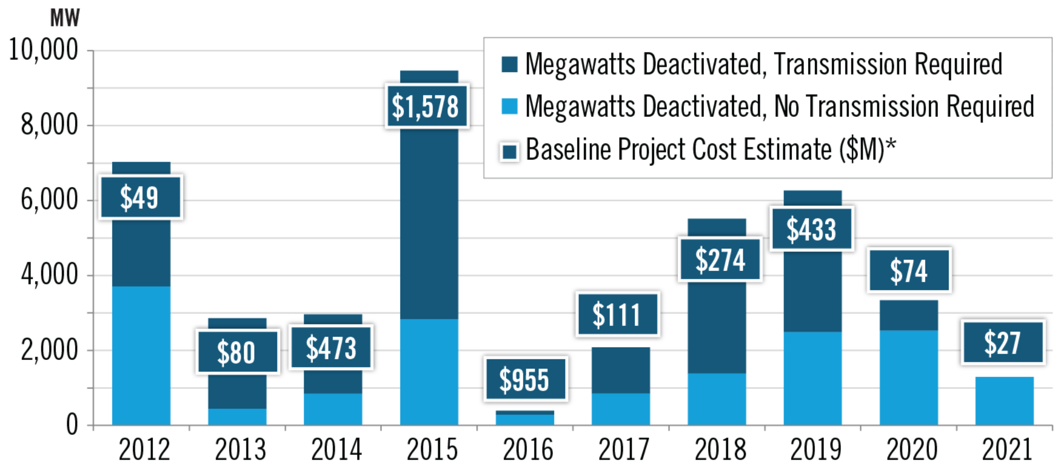
Currently, over 10,000 MW of new capacity powered by natural gas is seeking interconnection to the PJM grid, adding to more than 81,000 MW already in service. This capacity exceeded that powered by coal in 2016, marking an unprecedented shift in PJM's fuel mix and accounting for approximately 43% of PJM's installed capacity mix. Natural gas generation requests were a substantial percentage of the interconnection queue for several years, largely due to the availability of natural gas from the Marcellus and Utica shale gas deposits located in the middle of the PJM footprint. The shale gas development contributed significantly to the transition from coal between 2013 and 2018. Today, though, natural gas-powered units make up roughly 10% of interconnection queue requests on a CIR megawatt basis, as shown earlier in **Section 2.1.4**, **Figure 3.**

2.2.2 Generator Deactivations

Generator deactivations alter power flows that can cause transmission line overloads and, given the loss of reactive power control capability from large-scale coal-fired and nuclear-powered generators, can undermine voltage control. When PJM receives a formal generator deactivation request, it conducts thermal and reactive studies to ensure that remaining generation continues to be deliverable to load. If criteria violations are identified, PJM develops a solution in coordination with affected transmission owners.

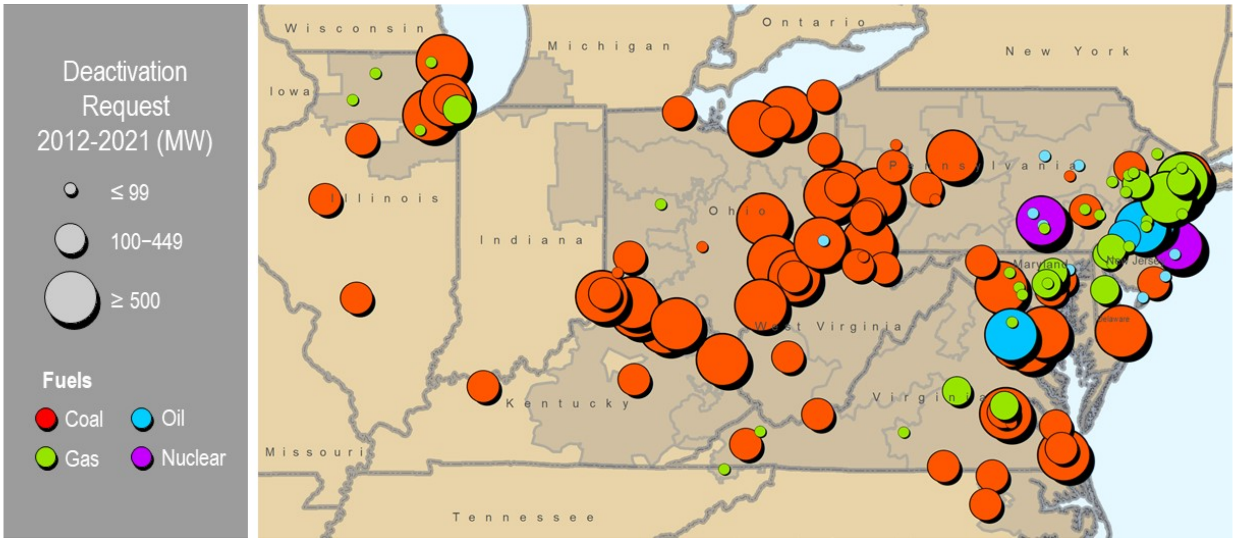
Figure 6 summarizes, and **Map 11** shows, the 41,209 MW of deactivation request notifications[29] across all fuel types that PJM received from 2012 through 2021. Notifications totaling 24,507 MW have accounted for $4.1 billion of baseline grid enhancements to solve reliability criteria violations. The remaining 16,702 MW of deactivating generation did not cause reliability criteria violations, and thus did not require baseline transmission enhancements.

Figure 6. PJM Generator Deactivation-Driven Baseline Transmission Investment



*Note: Cost estimate for baseline transmission enhancements required to allow generators to deactivate reliably

Map 11. PJM Deactivation Notification Requests, All Fuel Types, 2012–2021



Many factors can lead units to deactivate. Plant age and economic impacts of increasing operating costs are often key drivers. Other significant factors include environmental public policy, particularly with regard to carbon emissions.

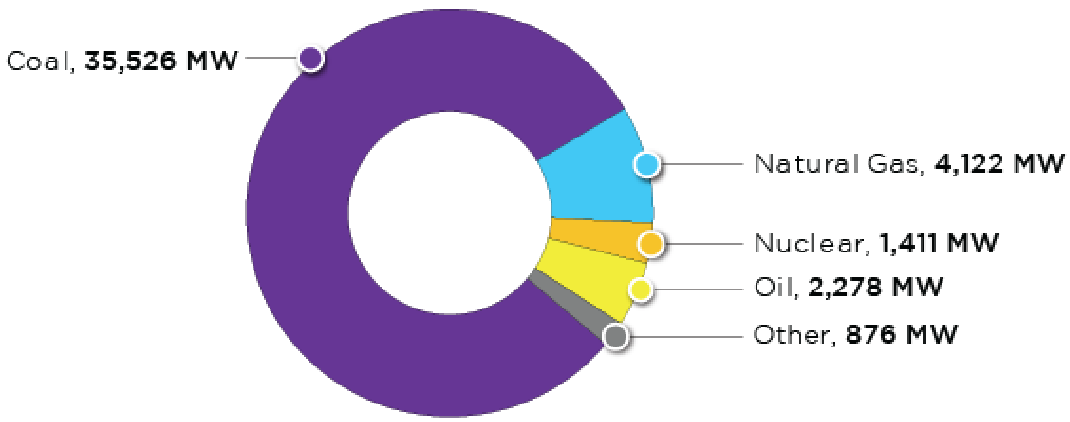
[29] The impact of generator deactivation requests that were subsequently withdrawn do not appear in **Map 11**, nor as part of megawatt values and baseline transmission dollar values.

Generator deactivations are both driven by and directly impact PJM capacity auction activity. For example, 10 coal-powered units did not clear the 2022/2023 Base Residual Auction conducted in May 2021. Nine of these units submitted notifications of deactivation in June 2021. The tenth unit that did not request deactivation exhibited strong energy and ancillary service revenue supported by expected strong operating periods. A major factor putting a generator at risk is its inability to clear a capacity auction given its costs compared to other resources offered into the auction:

- New entrants with more efficient performance, including those powered by Marcellus and Utica shale natural gas
- Wind- and solar-powered renewable energy resources with no marginal fuel cost
- Demand resources
- Energy efficiency programs

Such factors are driving the business decisions by owners to retire over 47,000 MW of generation between 2012 and 2021 as shown in **Figure 7.** Coal and nuclear deactivations account for 87% of the total.

Figure 7. Actual Generation Deactivation by Fuel Type, 2012–2021



2.2.2.1 Coal-Powered Plant Deactivation

As **Figure 7** shows, coal-fired power plants account for 81% (over 35,500 MW) of total deactivations between 2012 and 2021 driven by one or more factors. Some larger coal units were located on or near now-depleted coal mines in order to reduce fuel transportation costs. To remain in operation, these plants sought more cost-effective sources for coal, increasing the fuel transportation component of their unit operating costs. For many other coal plants, environmental regulations, including those to reduce NO_X, SO_2 and CO_2 emissions under the Mercury and Air Toxics Standard (MATS) of 2011 and the Clean Power Plan of 2015, have increased unit costs driven by the need to install new emission control equipment.

2.2.2.2 Nuclear-Powered Plant Deactivation

As **Figure 7** shows, nuclear power plants account for 3% (over 1,400 MW) of total generation retiring in PJM's footprint between 2012 and 2021. Original investment costs have put nuclear-powered units at risk in PJM's Reliability Pricing Model capacity auctions. Ongoing regulatory and engineering operating costs have put them at risk in energy markets compared to bids of units powered by other fuels. The potential for financial loss is amplified during operating conditions when they are directed to reduce their output below levels for which they were designed.

Unlike many older coal-fired generating plants, nuclear plants are carbon friendly. This aspect of their operation is drawing state-level attention with zero emission credits (ZECs). To that end, the financial benefit of ZECs have meant the withdrawal of deactivation notifications in 2019 and 2021 for seven nuclear plant deactivations totaling over 11,500 MW. ZECs are subject to periodic review and renewal and, like other public policy action, can have an impact on deactivation decisions.

Nuclear plants have rising operating costs but are kept in the market to ensure reliability and to satisfy decarbonization and other environmental public policy objectives. To the extent that nuclear plant operators can reap positive revenue streams, they will likely pursue relicensing. The Nuclear Regulatory Commission (NRC) staff has defined subsequent license renewal (SLR) to be an operating extension from 60 years to 80 years.[30] Nevertheless, PJM must face the reality that some or all of the nuclear plants within in its footprint could deactivate by 2050.

2.3 Impacts of Generation Shift

2.3.1 Loss of Generator Reliability Attributes

PJM issued a white paper[31] in March 2017 to quantify the generator reliability attributes that contribute to grid reliability. As part of that paper, PJM examined information and data it compiled from: (1) various NERC forums that defined Interconnected Operations Services and Essential Reliability Services; (2) PJM renewable integration (energy transition) studies, ancillary service markets, the Capacity Performance Initiative, and the Advanced Technology Pilot program; and (3) PJM staff, stakeholders and other industry experts. The result was the generator reliability attributes summarized below in **Figure 8,** based on PJM operational experience with generating units powered by coal, natural gas (steam and combustion turbine), oil (steam and combustion turbine), nuclear, solar, wind and hydro, and with battery/storage and demand response.

[30] https://www.nrc.gov/reactors/operating/licensing/renewal/subsequent-license-renewal.html

[31] PJM's Evolving Resource Mix and System Reliability. March 30, 2017. https://www.pjm.com/-/media/library/reports-notices/special-reports/20170330-pjms-evolving-resource-mix-and-system-reliability.ashx

Figure 8. Generator Reliability Attribute Matrix[32]

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

Resource Type/ Rank	Essential Reliability Services (Frequency, Voltage, Ramp Capability)					Sustainability		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	◓	◓	○	○	◓	○	○	●	●	●	○	◓	●

The ability of generators to provide various reliability attributes will likely be driven by advances in technology and overall fuel mix. If PJM's actual future dispatch-stack fuel mix should evolve such that adequate levels of generator reliability attributes fall below the levels needed to maintain reliable grid operations, then additional operating procedures, market incentives and regulatory structures may be needed to maintain adequate levels. **Section 7** discusses PJM's future grid road map to address this challenge.

2.3.2 Addressing Inverter-Based Generator Characteristics

If current trends continue, PJM will continue to see more IBR wind and solar generation, which is expected to increase to 22% of PJM's fuel mix by 2035. By contrast, fewer conventional synchronous generators – primarily driven by coal and nuclear deactivations – will be available to provide essential NERC-defined reliability functions. Non-synchronous inverter-based generation is connected to the grid via inverters that utilize power-electronic devices to integrate the variable resources to the grid. A proliferation of IBRs can significantly impact reactive control, stability, short-circuit current, inertia and frequency control – all critical dimensions of future grid planning. **Section 7** discusses PJM's road map to address these future grid impacts.

[32] Ibid. page 16.

Additionally, as the Energy Transition in PJM white paper discussed earlier in **Section 2.1.3** indicated, IBRs may not be able to provide the same level of other essential, operationally focused reliability attributes as well: ramping, balancing control, flexibility and black start. That report speaks to their impacts and potential solutions; they are not addressed, per se, in this report.

3. Distributed Energy Resources

Distributed energy resources (DER)[33] are not new to PJM, nor to regional grid planning. Since its New Services Queue process began in the late 1990s, PJM has integrated DER that have included hydro, natural gas, landfill gas (methane), diesel, oil, waste, wood byproducts, storage, wind, solar and hybrid facilities. But, while PJM has integrated DER into its wholesale market, DER can also operate outside it and PJM's New Services Queue process. Accounting for approximately two-thirds of all DER interconnection requests, these non-wholesale facilities typically fall under state regulations (i.e., outside the jurisdiction of PJM's FERC-approved Tariff) and include the following:

1 | **Behind-the-meter generation (load reducer) –** This DER output offset load under owner's control; any excess power is not injected past the meter onto the distribution system.

2 | **Electric vehicles (EVs) –** Vehicles with battery storage capability can inject into or withdraw power from the distribution system in a controlled manner.

3 | **Backup generation –** Such generation can operate in islanded mode to serve owner's load during a distribution system outage.

4 | **Retail generation –** A distribution company, municipality or cooperative may develop such generation to serve their system load but does not inject power onto the transmission system.

5 | **Net metering –** Generation in excess of load is netted against that purchased off local distribution system over some defined period of time.

6 | **Storage as distribution system tool –** Installed by a distribution company, municipality or cooperative, this storage can absorb power and inject it onto local distribution systems when called upon.

While EV penetration levels will impact transmission and distribution systems as load, the focus in this section is on EVs as a potential distribution voltage level generation resource. **Section 4.1.1** of this report discusses anticipated future grid EV impacts on load shape and timing.

[33] As defined by FERC in 2016: DER is "A source or sink of power that is located on the distribution system, any subsystem thereof, or behind a customer meter. These resources may include, but are not limited to, electric storage resources, distributed generation, thermal storage, and electric vehicles and their supply equipment."

3.1 DER Activity

DER interconnections have been growing steadily since 2009 and are expected to continue to grow over the next two decades. Currently, over 6,300 MW of distributed solar capacity is connected at the distribution level, as reported through PJM's Generation Attribute Tracking System (GATS). DER growth in PJM is due partly to state, local and federal policies but is also driven by environmental considerations, customer desire for self-supply, and declining costs for acquiring and implementing DER technologies.

PJM's Resource Adequacy Planning Department has published projections for further DER growth. By 2035, the current 2,300 MW of load reduction, due to non-wholesale DER, is projected to grow by more than three times to an estimated 8,000 MW. Some electric distribution companies have established public information vehicles that parties can use in developing DER on their systems.[34] Currently, FirstEnergy, Pepco and PSE&G have implemented web-based geographic information system map graphical displays of their respective DER development potential.[35]

3.1.1.1 Public Policy Drivers

Federal and state policies are driving rapid growth of DER in PJM, as evidenced by the interconnection queue. PJM states have also adopted EV growth policies and battery storage pilots, which could drive additional future DER growth. Moreover, the Biden administration has set even more aggressive goals than PJM states to achieve a "carbon-free power sector" by 2035.[36] In addition to the clean electricity standard, the administration has also established goals to expand the EV market from 2.5% of cars in 2021[37] to 50% by 2030 – a penetration level that could impact transmission planning and operations, especially in densely populated areas like the eastern subregion of PJM.

Existing and newly proposed financial incentives could accelerate this target-driven growth. The federal government offers tax credits for renewables and some EVs, with more proposals (including possible clean energy program payments) making their way through Congress. When combined with possible state and local incentives for EVs and renewables (including tax abatement, grants, net metering, Renewable Energy Certificates and even state tax credits), the market could surpass target-driven growth projections in certain locations, especially where project capital and unused space are available.

Taken together, these policy drivers are yielding a number of potential future grid DER penetration scenarios, ranging from 10% to 50%, by 2030.[38] While quantitative analysis for predicting DER penetration by location may still be somewhat primitive, anecdotal data could contribute to qualitative analysis of a high-penetration DER future.

3.1.1.2 Impact of FERC Order 2222

FERC Order 2222 enables DER, including non-wholesale DER, to participate in wholesale markets. Realizing the grid of the future will require PJM to implement changes in its planning process modeling and dispatch methods to consider future DER growth. Enhancements to the RTEP process will enable greater DER visibility and provide more

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[34] California Public Utility Commission, R.21-06-017, June 24, 2021; p. 18.

[35] FirstEnergy: https://firstenergycorp.maps.arcgis.com/apps/webappviewer/index.html?id=d43cf2482a344e469eae6ca569403c24
Pepco: https://www.pepco.com/SmartEnergy/MyGreenPowerConnection/Pages/HostingCapacityMap.aspx
PSE&G: https://nj.pseg.com/saveenergyandmoney/solarandrenewableenergy/solarpowersustainability

[36] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/

[37] https://insideevs.com/news/526699/us-electric-car-registrations-2021h1/

[38] https://www.pv-tech.org/renewable-energy-could-provide-33-50-of-us-electricity-by-2030-but-unlikely-to-hit-biden-80-target/

accurate alignment with operations and markets grid studies. The order allows aggregated non-wholesale DER to participate in wholesale markets. Overall, PJM will need to track three types: (1) wholesale DER; (2) non-wholesale DER still being netted; and (3) non-wholesale DER participating in wholesale aggregation. The need to explicitly model loads and DER generation will require careful tracking to avoid double counting.

PJM currently relies heavily on economic modeling of rooftop solar development and nets it out as part of the PJM load forecast. In reality, this essentially masks the actual total PJM load being served. While netting such solar DER against gross load may be adequate for now, this modeling approach may be inadequate to reliably plan the system under certain solar conditions as penetration levels grow. This issue is illustrated by a 2017 operational event in the North Carolina area of the Dominion Transmission Zone. A combination of facility switching and maintenance outages caused power on local 115 kV lines to exceed ratings when the setting sun reduced local DER solar output.

3.2 DER – Future Grid Impacts

PJM's grid of the future road map must determine and examine the point at which DER growth actually causes reliability criteria violations. Doing so must consider the reality that DER fall into three categories: controllable, non-controllable and semi-controllable. Renewable resource output is variable and cannot be assumed to operate continuously. Such output is inherently non-controllable. Resources like storage and EVs are semi-controllable because once fully charged, they can no longer draw power from the grid. Likewise, once depleted, such devices can no longer inject power back onto the system. With growing DER deployment, PJM must be increasingly able to account for these characteristics as part of grid planning and operations.

With that in mind, PJM's analysis will evaluate the impacts of DER (including that from EV charging and discharging) on line-loading conditions as part of time-of-day studies in addition to peak load periods. Fundamentally, energy costs will influence human power consumption behavior, altering transmission flow patterns from historical norms.

4. Electrification Impacts on Load

4.1 Electrification Trends

Electrification is the process of converting an end-use load that uses fossil fuels (or other non-electric energy sources) to electricity. This most commonly refers to vehicles, but can also refer to home and business uses for ambient heating, water heating, cooking and other activities. Transportation and heating could have the greatest impact on load forecast and load shape.

4.1.1 Transportation Electrification

Transportation electrification will be a significant contributor to future demand. Electric vehicle purchases have been growing at an exponential rate yet still amount to less than 1% of light-duty vehicles in the PJM service area. As with any emerging technology, a significant degree of adoption-rate uncertainty always exists. Forecasts for EV sales range widely from 4% of total vehicle sales by 2030 and 8% by 2040,[39] to the recent White House EV target to reach 50% by 2030.[40] Ultimately, the pace of EV sales will fundamentally be driven by battery prices and government incentives.

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[39] Outlook of the Energy Information Administration 2020 Annual Energy Outlook is the basis for the projections in the PJM 2021 Load Forecast.

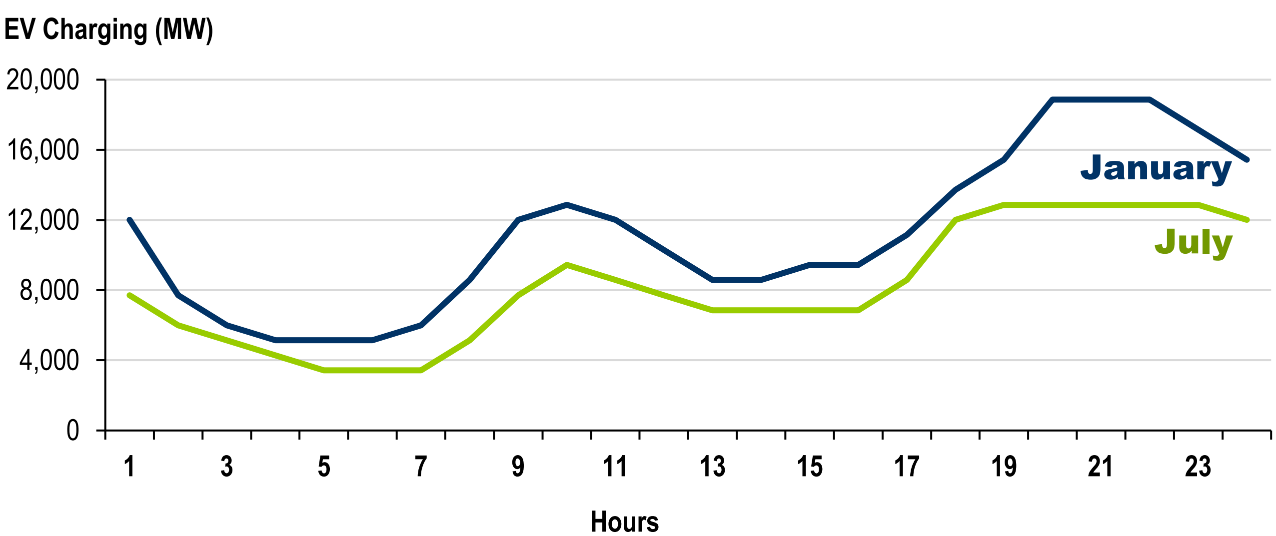
[40] https://www.whitehouse.gov/briefing-room/statements-releases/2021/08/05/fact-sheet-president-biden-announces-steps-to-drive-american-leadership-forward-on-clean-cars-and-trucks/

Industry research[41] currently shows a tendency for EV owners to charge the most at home during evening hours. An ISO New England (ISO-NE) study revealed weekday patterns feature two charging behavior ramps: first in the morning when drivers get to work, and then in the evening when drivers get home. The ISO-NE study also showed that charging needs are higher in winter months, which they attributed to the dual effects of automobile cabin heating and reduced battery performance at low temperatures.[42]

At current EV penetration levels in the PJM region, this is inconsequential, amounting to an estimated peak contribution of several hundred megawatts. However, if EVs represented one-third of light-duty vehicles, as they likely would if the White House target is met, then impacts to peak loads could be considerable. Winter peak impacts could amount to 19 GW, and summer peak impacts could amount to 13 GW, as shown in **Figure 9**. As EV penetration grows even further – to one-half or more of total vehicles – then the potential impacts would be magnified.

Research has shown that EV demand can be flexible if properly incentivized. Some utilities within the PJM region have already begun to implement time-of-use rates or peak/off-peak pricing. As EVs become more prevalent, these strategies and perhaps others, such as demand charges or load response programs, are very likely to become more commonplace. A successful strategy would shift charging into overnight and midday hours, significantly blunting peak load and, consequently, the resource adequacy impact of additional EV penetration.

Figure 9. Example Weekday Charging Under Vehicle Electrification Scenario Based on Current Behavior[43]



[41] NREL study on "Electric Vehicle Charging Implications for Utility Ratemaking in Colorado" (https://www.nrel.gov/docs/fy19osti/73303.pdf) and EV profiles in the "2021 Final Transportation Electrification Forecast" from ISO New England (https://www.iso-ne.com/static-assets/documents/2021/04/final_2021_transp_elec_forecast.pdf)

[42] https://www.iso-ne.com/static-assets/documents/2019/11/p2_transp_elect_fx_update.pdf

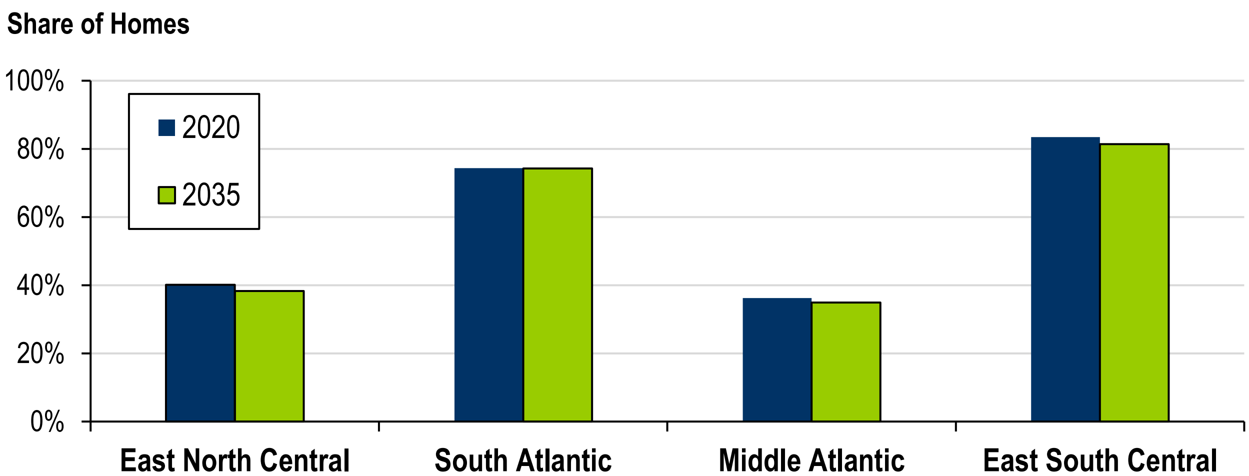
[43] State incentives would be expected to alter these curves to drive desired off-peak charging behavior.

4.1.2 Building Heating Electrification

The outlook for building heating is more uncertain than that for EVs. General consensus holds that future EV penetration levels will be significantly higher than today, but the uncertainty centers on quantifying the magnitude of that growth. This is not the case with electric heating.

In PJM's 2021 Load Forecast, which used input from the 2020 Energy Information Administration Annual Energy Outlook, electric heating does not gain traction. **Figure 10** shows the percent level of homes forecast to have electric heating in each PJM sub-region by 2035. Given current policy and costs, the direction tends to be more toward natural gas heating in much of the PJM service area. Some areas in PJM's southern subregion already rely on electricity to some degree for heating (e.g., Virginia). However, northern Midwest and mid-Atlantic areas of PJM predominately use non-electric fuels (mostly natural gas and some propane and fuel oil).

Figure 10. Residential Electric Heating* Share of Homes[44]



**Electric heating here is defined as electric furnaces, heat pumps (air-source and geothermal), and secondary heating elements.*

In New England, states are incentivizing greater adoption of electric air-source heat pumps to help meet decarbonization goals[45] by offering significant rebates to replace gas equipment with electric heat pumps.[46] This is in contrast to some states in the PJM service area, which still have incentives for purchasing new natural gas furnaces. A sea change on the public policy front would be needed to bring about large-scale increases in electric heating in the PJM footprint.

If such a policy change was to be implemented, the impacts to the load would be considerable. From a geographical perspective, the largest impacts would be to those regions that are not already pursuing electrification: primarily the mid-Atlantic and northern Midwest areas of PJM's service area.

[44] Data comes from Itron through analysis of data from the EIA Annual Energy Outlook. Geographic definitions correspond to U.S. Census Bureau defined divisions, which are East North Central (IN, IL, MI, OH, WI), South Atlantic (DE, DC, FL, GA, MD, NC, SC, VA, WV), Middle Atlantic (NJ, NY, PA), and East South Central (AL, KY, MS, TN).

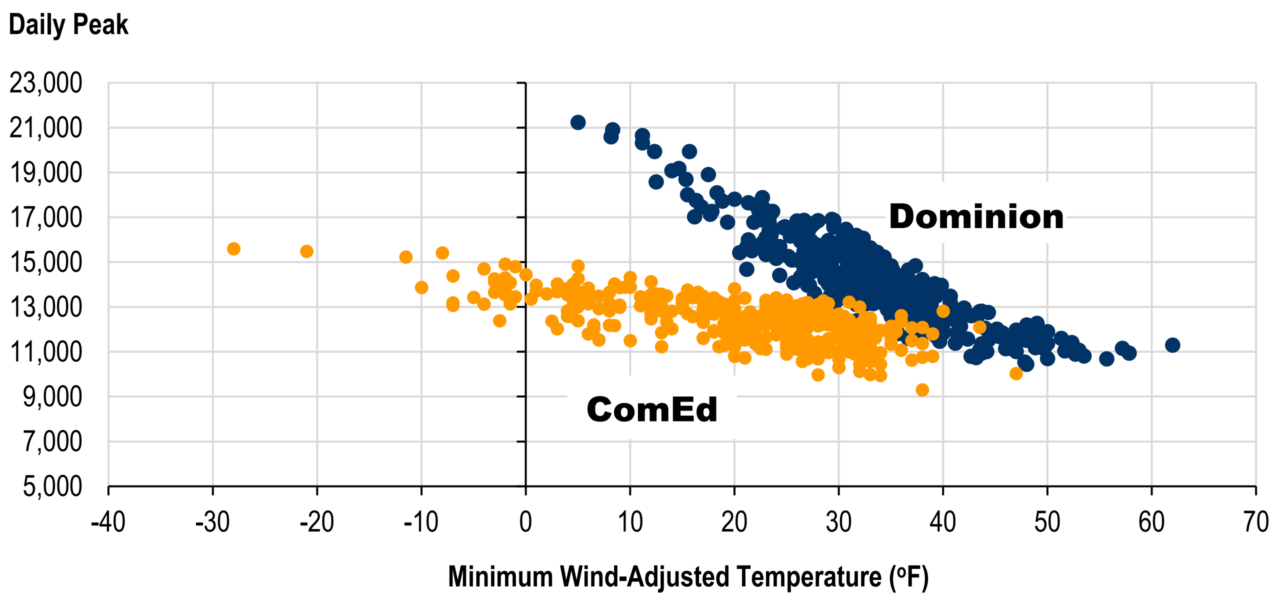
[45] ISO-NE "Final 2021 Heating Electrification Forecast" (https://www.iso-ne.com/static-assets/documents/2021/02/lfc2021_final_heating_elec.pdf).

[46] Massachusetts heat pump rebate program: https://www.masssave.com/en/saving/residential-rebates/heat-pump

For example, consider two similarly sized transmission zones: Commonwealth Edison (ComEd) and Dominion. The ComEd Transmission Zone is summer-peaking while the Dominion Transmission Zone is winter-peaking by a small margin (but in any given year could be summer- or winter-peaking), as shown in **Figure 11**. Customers in the ComEd Zone primarily use natural gas for heating, with little reliance on electricity; roughly 2% of homes use heat pumps. Customers in the Dominion Zone primarily use electricity for heating, with more than 50% of homes using heat pumps. The ComEd Zone sees minimum daily wind-adjusted temperatures that commonly dip below zero degrees, while the Dominion Zone only experiences temperatures below 20 degrees on a couple of days.

Based on this information, if the Dominion Zone was to experience typical ComEd weather, load levels at 25,000 MW or more could be experienced. This may be mitigated to some degree if homes have backup heating like gas furnaces, which is more likely in colder climates, adding another layer of uncertainty.

Figure 11. Dominion and ComEd Winter Daily Peak Loads Since December 2017



4.2 Electrification – Future Grid Impacts

In the event that the White House EV target of 50% of light-duty vehicle sales by 2030 is met, accelerated sales could lead to EV charging that would account for approximately 10% of total RTO energy in the next 15 years and then grow further. Demand impacts could be similar given current charging behavior, if public policy remains unaltered. However, given the growing availability of time-of-use rates, the impact could likely be mitigated to some extent. Reaching that target is also likely to have a higher impact on winter peaks than on summer peaks for two reasons: (1) additional EV charging needs in winter vs. summer; and (2) a flatter winter load shape.

If EV charging is done optimally, it can fill in daily load-shape valleys. During the summer, this primarily means overnight and some midday hours to take advantage of both behind-the-meter and front-of-the-meter solar installations. In the winter, load valleys are shallower, but EV charging also impacts peak load levels.

As described earlier, heating electrification is not considered in PJM's current baseline load forecast. To consider the potential impacts, a plausible scenario must be developed using baseline projections from the EIA that are modified to represent a move of new heating equipment purchasing toward electric heat pumps rather than natural gas furnaces.[47] As a result, because of the current combination of high proportions of natural gas furnaces and low proportions of heat pumps in the Middle Atlantic and East North Central census areas within PJM, this scenario will have a higher impact there than in the South Atlantic and East South Central census areas within PJM where the reverse is true.

For perspective, **Figure 12** shows current PJM summer- and winter-peak load profiles. **Figure 13** shows examples of net-load peak shapes for summer and winter, respectively, under a heating electrification scenario before taking into account EVs. Depending on the degree to which the level of electric heating increases, the gap between winter and summer peaks would narrow with PJM potentially becoming a winter-peaking system. Winter peaks are made even more likely in this scenario once EV charging needs are layered on top.

Figure 12. PJM Current Summer and Winter Peak Profiles, Per-Unit Basis (Peak = 1.0)

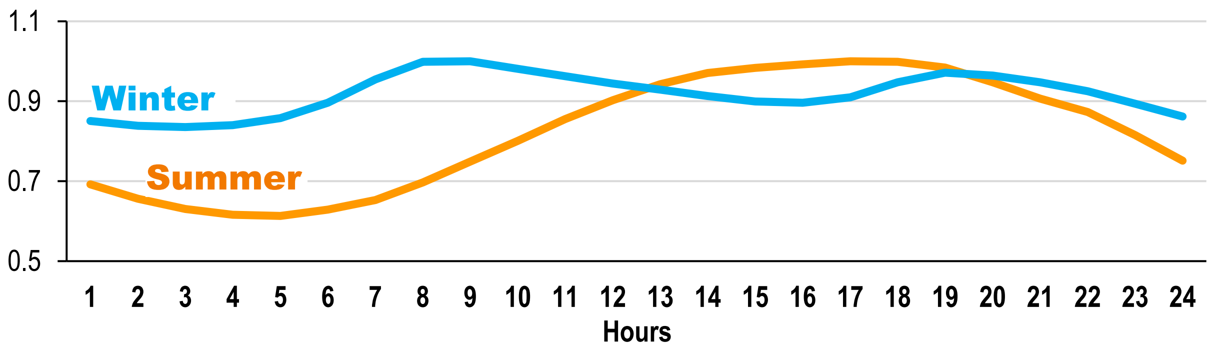
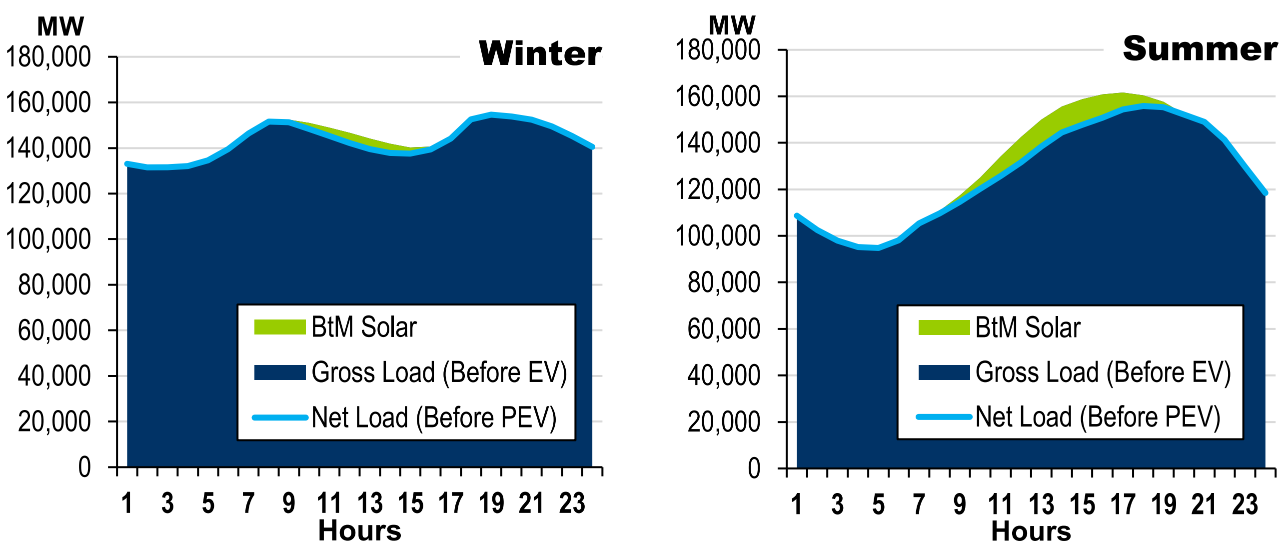


Figure 13. Potential Future Winter/Summer Peak Day Under Scenario Before EV Charging



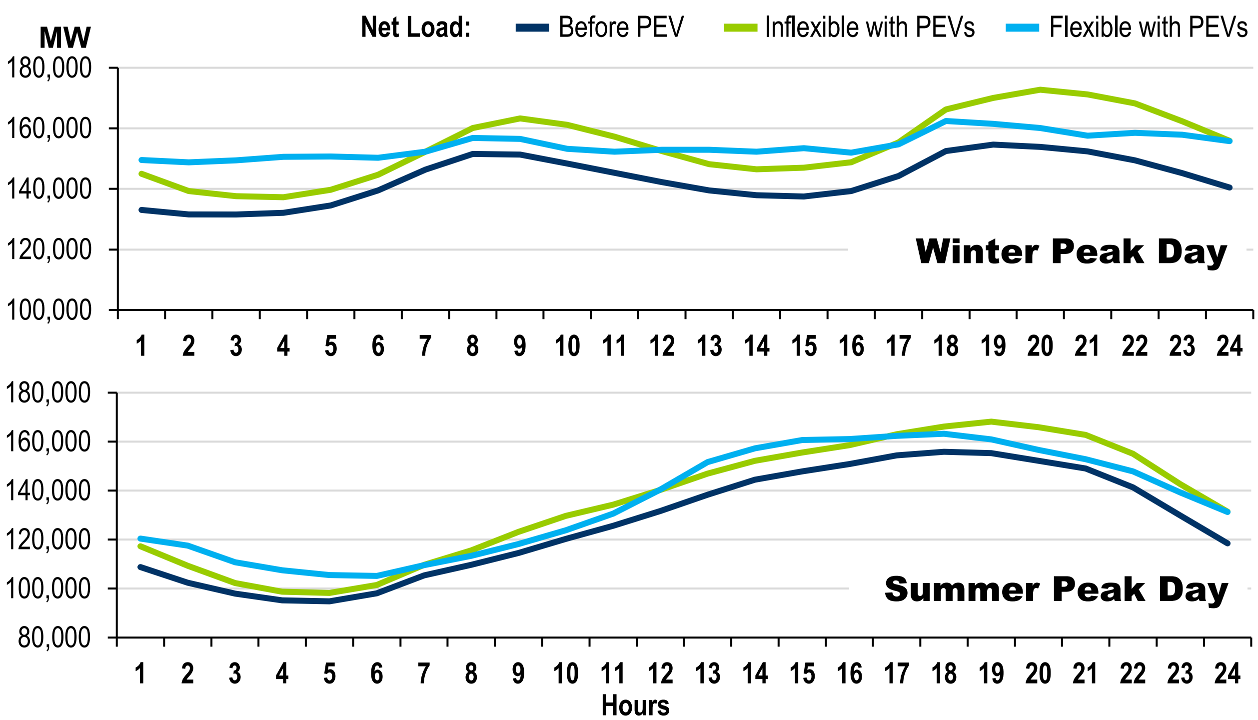
In **Figure 14**, EV charging is added to the net load shapes for summer and winter peaks. Two EV charging scenarios are shown:

[47] New heating units are a function of: (1) aggregate increases in total heating; and (2) replacement of obsolescent heating. Assuming an average lifetime of 17.5 years for a natural gas furnace, these two factors amount to approximately 4% of households obtaining new furnaces per year in the mid-Atlantic and east-north-central areas of PJM and a little less than 2% of households in the south Atlantic and east-south-central areas of PJM. PJM assumes that 10% of these new units will be electric heat pumps rather than natural gas furnaces.

Inflexible – charging behavior observed today that is also expected in the future	**Flexible –** charging behavior modified such that it shifts somewhat to off-peak load

This would mean that under a scenario that incorporates winter EV charging flexibility, peak-saving benefits do reach a limit. Once a certain amount of EV load on the system is reached, additional EV load has fewer places along a daily load curve on which to move, becoming increasingly difficult to avoid adding to a daily peak. In the summer, given the relatively deeper overnight valley, considerable room still exists to add EVs without necessarily impacting peak load significantly.

Figure 14. Potential Future PJM Winter and Summer Peak Day Under PEV[48] Scenario



5. Emerging Transmission Grid Technologies

5.1 Increasing Transmission Capability

Applying emerging technologies in new ways will play a growing role in realizing PJM's grid of the future. The generation shift discussed in **Section 2** will alter how power flows across the region PJM serves as the interconnection of substantial levels of renewables at many locations will replace the deactivation of large-scale, centralized coal-fired and nuclear-powered generation at different, existing locations. This will drive future grid expansion to ensure reliable power delivery to load centers. Indeed, within the PJM footprint, as noted earlier in **Section 2.1.3**, an estimated 105,000 MW of new renewable resources will interconnect to the PJM grid by 2035, much of which will be less than 100 miles from the load centers being served, as discussed in **Section 2.1.1.**

The grid expansion technology needed to deliver power will not be limited to conventional greenfield (and often multi-state) transmission lines, which are increasingly more difficult to site and permit. Emerging technologies that will

[48] PEV is an acronym for plug-in electric vehicle and is used synonymously with "EV."

continue to play a growing role include dynamic line ratings, special conductors, tower configurations and other technologies, and are summarized below and described in more detail in PJM's 2021 Regional Transmission Expansion Plan, Section 1.3.5., and in the white paper Reliability in PJM: Today and Tomorrow.

1 | **Dynamic line rating (DLR) technology** can identify additional capacity on transmission lines, potentially relieving congestion and creating economic efficiencies. Such technology can also enhance system resilience by providing enhanced real-time monitoring of transmission assets.

2 | **Advanced conductor designs** can provide a means of achieving a higher ampacity transmission line capability on existing corridors, mitigating the need for new lines or significant rebuild. Developers that build new transmission lines, or rebuild existing ones, often encounter siting and permitting challenges that can cause lengthy delays or even prevent project construction altogether. Other advanced conductor design incorporates the use of special conductor coatings that have a higher emissivity and lower absorptivity, which leads to cooler conductors and, thus, higher ampacity ratings.

3 | **Advanced transmission tower configuration technology** can provide a means to enhance the utilization of existing and new transmission line corridors as part of future grid expansion. Such designs, coupled with low-impedance bundled conductors, reduce line losses and significantly increase power delivery capability while avoiding the complexities and costs of series compensation.

4 | **Flexible alternating current transmission systems** (FACTS) are power system devices that take more conventional power system components – capacitors and reactors – and integrate them in various configurations with intelligent power electronics, high-speed thyristor valve technology and voltage-sourced converter (VSC) technology. FACTS devices can directly support additional transmission line power flow with reactive power injections at their point of interconnection and can indirectly control power flow by modulating transmission line impedances. The most common FACTS devices include static VAR compensators (SVCs) and static synchronous compensators (STATCOMs).

5 | **SVC hybrids** are a new type of FACTS device that combines the reactive support of a traditional STATCOM with the real power support of energy storage. The purpose of an SVC hybrid is to level-out power fluctuations from variable generating resources, such as wind and solar, by employing the SVC hybrid's grid-forming inverter enabled by the active power control of its energy storage. A grid-forming inverter functions to "go first, not follow" existing grid conditions to try to establish desired power levels and quality.

PJM remains neutral with respect to grid-enhancing technologies that are part of proposals submitted in RTEP windows or as part of transmission owner supplemental projects. To the extent submitted as part of a competitive RTEP window, PJM evaluates qualifying grid-enhancing technology proposals in a manner that is not materially different than the way it evaluates other project proposals. PJM examines the impact of a technology's characteristics on solving identified reliability and market efficiency needs efficiently or cost-effectively. Further, PJM evaluates whether a proposal that includes the deployment of a grid-enhancing technology requires any changes to telemetry, modeling and other operating tools or protocols to support and accommodate integration from a PJM markets and operations standpoint.

5.2 Electric Vehicles

PJM continues to pay close attention to U.S. transportation sector electrification and, in particular, the impact of EVs on transmission system needs. The Edison Electric Institute estimates that EVs will grow from 1 million today to 7 million across the country by 2025.[49] The report goes on to cite the Northeast as one of the regions of the country "with higher concentrations of first adopters of electric vehicles and more immediate, more ambitious policy targets."[50]

From a future grid perspective, PJM load forecasting processes must ensure that EVs are accounted for in charging mode, and transmission planning studies must account for the bus loads associated with charging stations. EVs may also be in a position to provide grid reliability services like regulation vis-à-vis their on-board battery storage capability if public policy economic incentives can drive desired customer behaviors.

5.3 Microgrids

Microgrid control technology, coupled with distributed energy assets, has the real potential to improve grid resilience, security, reliability and efficiency. Microgrids are small clusters of energy assets and loads that are controlled to achieve a variety of benefits for the owner/operator. One of the primary benefits of building a microgrid is the ability to provide reliable electric power during significant electric grid disturbances, such as storm outages. PJM continues to work with industry partners, universities and states to better understand how microgrids can impact the grid in a positive way and how they can derive value from the PJM wholesale markets.

5.4 Storage as a Transmission Asset

Energy storage development continues to grow in PJM and other RTOs. As solar generation increases in PJM, growth of storage is expected to follow. Storage devices are frequently co-located with solar projects. Efficient grid operations in an era of rapid renewable energy resource growth will require greater system flexibility. To that end, PJM continues to pursue process improvements to permit storage as a transmission asset (SATA).

5.4.1 SATA Applications

Energy storage can offer grid operators another tool to maintain stable power supply under varying wind and solar power output driven by weather conditions or unit outages. Storage can also improve grid efficiency by increasing utilization of existing transmission lines. PJM continues to work with members, DOE national laboratories, and other industry entities to advance the use of energy storage and, in particular, enable its participation in PJM markets.

Queued storage resources currently total over 34,000 MW of interconnection requests for CIRs. These resources are anticipated to provide significant grid benefits given their ability to "firm-up" otherwise variable resources by charging and discharging to serve load at any given point in time. In addition to storage projects that interconnect as a resource seeking participation in PJM markets, storage may also serve as a transmission solution to address identified planning needs. Nonetheless, PJM's planning process must account for limited duration of each SATA installation, which could deplete itself and become unable to mitigate the violation, for which it was designed, when called upon to do so. To that end, and given that PJM is the regional transmission planner as designated by FERC,

[49] "The Coming Electrification of the North American Economy: Why We Need a Robust Transmission Grid": https://wiresgroup.com/new/wp-content/uploads/2019/03/Electrification_BrattleReport_WIRES_FINAL_03062019.pdf.

[50] Ibid.

PJM will not deploy SATA to mitigate violations identified for baseline reliability and market efficiency unless compliance with standards, manuals and governing documents are strictly met.

5.4.2 State Public Policy Drivers

Storage development is also being driven both explicitly and implicitly by state policy objectives. Explicit state targets include Virginia's 3,100 MW of storage by 2035 and New Jersey's 2,000 MW target by 2030, as outlined in its 2019 Energy Master Plan. Maryland also has an energy storage pilot program that was implemented in 2019 to develop storage capacity within the state. Implicitly, storage is being developed as a complement to the influx of renewable resources driven by state RPS targets.

6. Resilience

6.1 Enhanced Reliability for Tomorrow's Grid

A resilient grid must be able to withstand large-scale system disturbances, to which it is difficult to attach probabilities and that can exceed conventional NERC planning N-1-1 and N-1 planning criteria. High-impact, low-frequency contingencies – encompassing generation, transmission or both – can significantly impact PJM's ability to serve load reliably and maintain overall system integrity. Growing reliance on greater levels of variable resources raises resilience concerns, as the winter weather impacts of February 2021 on ERCOT, SPP and MISO demonstrated.

A number of emerging system conditions already present challenges to reliable system operations:

1 | Extreme weather

2 | Cyber and physical attacks

3 | Generation fleet shift driven by natural gas and increased deployment of renewable resources

Such challenges will continue to stress future grid resilience, which enhanced reliability criteria must address. For decades, planning criteria have been developed and applied to power systems across the country (and around the world) to ascertain the need for grid enhancement, so that system operators can meet the operating conditions they encounter on any given day. Planners test the system under simulated stressed conditions, such as extreme weather, to understand where reinforcements may be warranted to make the grid reliable.

6.2 Reliability and Resilience

While resilience and reliability both define what it means for PJM to keep the lights on under a broad range of conditions, the concepts are not identical. PJM already complies with established NERC, regional and transmission owner reliability standards. To that end, PJM conducts its planning studies under critical, stressed conditions, so that system dispatchers can manage the actual system conditions on any given day in real time. Resilience takes this to another level, addressing challenges and emerging risks that existing reliability standards do not fully capture, such as:

1. Maintaining reliability in the face of significant events beyond typical planning criteria
2. Evaluating threats as part of the transmission planning process
3. Slowing disruptive events, mitigating their impacts and quickly recovering essential functions
4. Protecting essential systems based on assessed risks and hazards
5. Improving grid flexibility and control to adapt efficiently and quickly to post-event conditions
6. Addressing heavy reliance on one resource type

Planning for the grid of the future must consider all of these dimensions of resilience.

6.3 Beyond NERC Transmission Standards

Existing NERC planning criteria are structured around likely events, requiring that the bulk power system be tested for such contingencies as the loss of a transmission line (a high-probability, low-impact event) under the assumption that all other transmission facilities are in service. Yet in reality, dozens of facilities are out of service on any given day. PJM also simulates more severe, lower-probability "N-1-1" events like the loss of two circuits on a common tower line or a fault on a circuit followed by a breaker failure.

NERC standards address resilience to a degree. Existing planning standards require examination of the impact of extreme events such as the loss of an entire substation or the loss of an entire right-of-way – caused by a landslide, tornado, hurricane or fire, for example – that would take out multiple transmission lines at one time. Although an assessment of the impact of these events is required, reinforcement for these high-impact, low frequency events is not required under current NERC criteria. Planners must now also assess whether the transmission system is sufficiently reinforced to address extreme events like these as well those caused by physical and cyberattacks.

6.4 Reliability Criteria for Extreme Events

PJM's ongoing efforts are taking a forward-looking, holistic and proactive approach to plan for future transmission needs with respect to extreme events, which may become a more significant grid expansion driver under higher levels of renewable penetration. The scope of planning studies will support efforts to assess how extreme events can be analytically evaluated and how consequential impacts to system reliability are identified. This may lead to new reliability criteria and planning tests. To that end, PJM continues to work with stakeholders to consider planning process policy changes that may be needed to enable it to identify and plan needed transmission to address extreme events. PJM, in its ANOPR comments (noted earlier in the Executive Summary), has urged FERC to adopt a common definition of resilience and a specific resilience planning driver for grid enhancements, applicable to all planning entities.

6.5 Fuel Assurance

Resilience also encompasses fuel assurance – the ability of PJM to withstand disruptions to power output caused by the availability of fuel, ranging from natural gas pipeline delivery to weather-based restrictions on renewable resources. The 2014 Polar Vortex event demonstrated the exposure of gas-fired generation to pipeline delivery constraints as did the impacts of the February 2021 arctic event on ERCOT, SPP and MISO.

Solar and wind generator availability is characterized as variable insofar as output is impacted by both weather and time of day. Wind generation may be forced to shut down during periods of high winds to protect equipment. Such generators are designed with cut-out speeds of approximately 55 mph. The opposite conditions also present fuel-assurance concerns, including loss of wind-powered generation under severe, windless heat spells.

6.6 Loss of Transmission

Extreme weather, such as hurricanes and derechos, can force out significant portions of the transmission system, and the generation connected to it, for days. This could also happen under a geomagnetic disturbance, which is a space-weather phenomenon during which the grid can be exposed to quasi-DC-induced currents. These currents cause grid elements like transformers to overheat, necessitating their preemptive removal from service.

Additionally, NERC's CIP-014 standard requires transmission owner assessments to identify critical facilities that, if rendered inoperable, would cause instability, uncontrolled separation or cascading outages. Concerns across the industry about grid security and resilience under the outage of such facilities continues to grow. PJM's future planning must include efforts to eliminate current vulnerabilities for CIP-014 critical infrastructure, while also working to develop RTEP process criteria to avoid and mitigate the same risk for future critical infrastructure.

7. PJM Grid of the Future Road Map

7.1 Four Areas of Focus

Each of the preceding sections for this report discussed grid of the future impacts for PJM RTEP process drivers. Those impacts are the impetus behind the road map presented here, comprising four focus areas:

1. Transmission build-out scenario studies	**2.** Targeted reliability studies	**3.** RTEP process enhancements	**4.** Regulatory policy outcomes

PJM discusses each focus area below in terms of current status and road map to meet future grid challenges.

7.2 Transmission Build-Out Scenario Studies

Transmission build-out scenario studies will be conducted in 2022 based on power-flow case alignment with PJM's Energy Transition in PJM white paper and additional renewable integration studies, and leveraging analysis work of the OSW Scenario Study Phase 1. This OSW study phase considered multiple offshore wind injection scenarios as well as the renewable resources needed to meet state RPS onshore wind objectives. As PJM continues its initiatives to enable a decarbonized grid, additional analysis beyond the OSW scenario studies will examine an accelerated renewable penetration case, including a more in-depth assessment of the impacts from higher levels of building and transportation electrification.

The heart of RTEP grid of the future scenario studies to be conducted in 2022 will focus on identifying reliability impacts in terms of both transmission planning and resource adequacy. These scenario studies are not starting from scratch. To the contrary, as discussed above, they are building on foundational studies that have preceded them, including the energy transition analysis and OSW study efforts discussed earlier.

Scenario studies will examine the need for additional grid expansion driven by the location of retiring capacity (primarily coal and nuclear) relative to capacity replacement (natural gas and renewables), and the load centers they serve. These studies will employ generator deliverability methodologies to identify NERC and regional reliability criteria violations under test conditions that include summer peak, winter peak and light-load system conditions, as well as time-of-day conditions given the intermittency of renewables. The studies will focus on impacts to the bulk electric system where the impacts might lead to the rebuild of existing, or construction of new, grid infrastructure.

7.2.1 Renewables Penetration – Case Alignment With Ongoing Studies

PJM is adopting the approach used by the ongoing energy transition analysis and OSW study, discussed earlier in **Section 2.1.3** and **Section 2.1.6,** respectively. The energy transition studies are modeling installed capacity by resource type for each case based on RPS, state and corporate policy goal assumptions. Policy and Accelerated cases are employing a profitability assessment to identify candidate units for retirement, primarily coal-fired plants.

7.2.2 Modeling Generator Deactivations

As discussed in **Section 2.2.2**, conventional generation retirements are expected to continue, driven by the economics of unit age and environmental public policy. Deactivation studies typically examine how generator deactivations alter power flows that can cause transmission line thermal overloads and, given reductions in system reactive support from those generators, can undermine voltage control. In order to ensure alignment with renewable integration studies, grid of the future planning studies will employ the same methods to determine the generation to be modeled out-of-service in power-flow simulations. In summary, PJM planners will adopt the three deactivation categories developed as part of PJM's energy transition analysis:

1 | Formal deactivation notices – these retirements were included in all markets scenarios.

2 | State or utility policies or agreements that include shutdown of coal and oil generation, in addition to units that have formally submitted deactivation notices to PJM – these retirements were also included in all scenarios.

3 | Unit-specific retirements for capacity replacement – these retirements were included only in the Policy and Accelerated cases in order to offset the additional capacity being added by the renewable build-out.

To generate the list of candidate units to retire, each was ranked from most to least likely to retire based on an algorithm that looked at: (1) simulated profit and loss using production cost simulation; and (2) fixed-cost assumptions for coal- and nuclear-powered units. Resources were retired from this profit-loss list based on an amount equivalent to the renewables added. For the incremental amount of renewable resources added in each scenario, the value of these resources was determined through ELCC in unforced capacity (UCAP) terms. This capacity value was used as a target for total megawatt value of retirements in the power-flow case of each scenario.

7.2.3 Identifying Need for Grid Expansion

The heart of RTEP future grid scenario studies to be conducted in 2022 will focus on identifying reliability impacts in terms of both transmission planning and resource adequacy. These scenario studies are not starting from scratch. To the contrary, as discussed above, they are building on foundational studies that have preceded them, including Energy Transition analysis and OSW study efforts.

Scenario studies will examine the need for additional grid expansion driven by the location of retiring capacity (primarily coal and nuclear) relative to capacity replacement (natural gas and renewables), and the load centers they serve. These studies will employ generator deliverability methodologies to identify NERC and regional reliability criteria violations under test conditions that include summer peak, winter peak and light-load system conditions, as well as time-of-day conditions given the intermittency of renewables. The studies will focus on impacts to the bulk electric system where the impacts might lead to the rebuild of existing, or construction of new, grid infrastructure.

7.3 Targeted Reliability Studies

Targeted reliability studies will build on 2022 scenario study results in order to evaluate generation and transmission reliability attributes, such as reactive control, stability, system inertia and frequency control, and short-circuit impacts, to ensure grid reliability.

The scenario studies described above make up just one area of future grid reliability evaluation. PJM's generation shift from large coal and nuclear plants to utility-scale renewables at new locations, more numerous than those of the generators they replace, will necessarily drive grid development. The ability of new, natural gas-fired generating units to replace reliability attributes (inertia, voltage support, frequency response, short-circuit current, etc.) lost by coal and nuclear unit deactivations will depend significantly on their location. Operability issues can arise in areas where sufficient levels of those attributes are not readily accessible. As a result, targeted reliability studies that examine them are also a necessary component of PJM's grid of the future road map.

Operability issues can arise in areas where sufficient levels of those attributes are not readily accessible. As a result, targeted reliability studies that examine them are also a necessary component of PJM's grid of the future road map, as discussed below. Detailed planning will be required to reduce the risk of operability issues and ensure resilience under extreme events:

1 | **Reactive Control** – As discussed earlier, voltage that is too low or too high can become a serious reliability issue and is dependent on the availability of resources – both generation and transmission – to produce or absorb reactive power. To the extent that PJM's generation resource mix does not provide the necessary minimum and maximum reactive capability to maintain adequate steady-state system bus voltages, then reliance on other reactive control devices will be required.

2 | **Voltage Instability** – This type of post-disturbance system response is defined as the point in power system operation beyond which no amount of reactive power injection will raise system voltages to pre-disturbance steady-state levels. Such voltage instability can cause power system voltage collapse if the post-disturbance equilibrium voltage is below acceptable limits. Under such conditions, system voltage can only be adjusted by reactive power injections until sustainable system voltage levels are restored. Voltage stability studies will guide the determination of system conditions and locations where such injections will be critical to maintaining grid reliability.

3 | **Dynamic Stability and Subsynchronous Resonance** (SSR) – System stability risk severity can increase as conventional generation deactivates (e.g., coal- and nuclear-powered units) in one area and is replaced with renewable IBR generation clustered in another area, particularly if those units are not near load centers. Such circumstances are aggravated by the fact that IBRs are non-synchronously connected to the grid via inverters and associated power electronics, often in geographical areas characterized by less tightly networked system topologies. PJM's grid of the future road map must encompass sophisticated and more granular studies and study techniques to identify potential unstable system conditions so that grid enhancements are developed to: (1) dampen potential instability that could otherwise cause cascading blackouts; and (2) mitigate SSR conditions that could cause turbine torsional stress and damage to conventional synchronous machines.

4 | **Inertia and Frequency Control** – This can be a concern in a grid with a high penetration of renewables, as it may 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. Because non-synchronous generators like wind and solar are connected to the grid via inverters, they do not inherently provide natural inertial response for grid frequency control. NERC requires PJM, as a planning coordinator, to conduct an under-frequency load-shedding study. In the future, PJM will need to consider how to incentivize inertial frequency response that may become necessary to ensure an adequate supply on the system at all times and appropriately compensate those resources.

5 | **Leverage EIPC Frequency Response Task Force (FRTF) Results –** The Eastern Interconnection Planning Collaborative (EIPC) FRTF conducts a frequency response study every two years to evaluate the five-year-out future Eastern Interconnection. PJM must continue its participation in EIPC's frequency study project that is focusing on developing sound, near-term frequency study cases and developing a detailed plan for a long-term frequency study.

6 | **Short-Circuit Current Studies** – Specific studies will be required that evaluate reliability issues when insufficient short-circuit current exists under the proliferation of IBRs. These units produce less short-circuit current to trigger protective device response. Conventional protection systems are designed for large fault currents from synchronous and induction machines. Reduced short-circuit current could mean that circuit breakers may not clear faults in sufficient time, if at all, to prevent equipment loss and system instability.

7 | **Interregional Coordination** – Future planning must also address the need for greater interregional transmission expansion to address extreme events under a high penetration of renewables, the loss of which could impose the need for greater transfer capability to import power to serve load.

8 | **CIP-014 Analysis** – Planning must include efforts to eliminate existing CIP-014 vulnerabilities and incorporate criteria to mitigate CIP-014 risk in future infrastructure, as described in **Section 6.6**.

9 | **Natural Gas Availability** – PJM must continue to ensure the ability of the grid to withstand the loss of natural gas-fired generation output caused by natural gas pipeline delivery disruption. Previous cold weather events have amplified the importance of addressing exposure of gas-fired generation to pipeline delivery constraints. As PJM continues to rely on natural gas generation, pipeline contingency analysis will continue to play an important role in planning for resilience.

10 | **Renewable Resource Availability** – Planning will use the Effective Load Carrying Capability (ELCC) methodology to account for the typical variability of weather-dependent wind and solar resources and continue to explore enhancements to increase confidence in study findings.

11 | **Loss of Transmission** – Planning and Operations must consider extreme events, such as hurricanes, derechos and geomagnetic disturbances in planning studies and assess potential measures to mitigate impacts and respond to such events, as outlined in **Section 6.6.**

7.4 RTEP Process Enhancements

PJM's RTEP process continues to evolve as the scope of system enhancement drivers continues to shift. These efforts, including the ones enumerated below, will continue to bring the grid of the future into clearer focus:

1. Interconnection Process Reform	**2.** Generator Deliverability Methodology	**3.** Effective Load Carrying Capability	**4.** Probabilistic Planning Techniques

These are summarized below.

7.4.1 Interconnection Process Reform

PJM's existing interconnection process is designed to provide nondiscriminatory treatment for all interconnection customers, regardless of generator fuel type. The process has been key to helping states achieve renewable targets. PJM recognizes, though, that changes are warranted, driven by sustained, record-setting levels of interconnection requests received each year, directly impacting PJM's study process volume and timing. In 2021, for example, PJM received 1,351 new service requests, more than triple the 470 new service requests received just three years prior and the highest number since implementation of the interconnection queue 25 years ago in 1997.

PJM's interconnection process is a critical step in integrating renewable generation into the grid as part of federal and state policy goals. To that end, PJM and stakeholders continue to improve process efficiency and reduce study backlogs.

7.4.2 Generator Deliverability Process

In 2021, PJM initiated discussions with stakeholders to improve variable resource modeling. PJM is pursuing modifications to the RTEP process generator deliverability methodology to more accurately reflect emerging resource mix under light load and winter operating conditions. The existing generator deliverability procedure is overly complex and has remained relatively unchanged for many years. PJM's discussions with the Planning Committee will continue in 2022.

7.4.3 Effective Load Carrying Capability

PJM continues to witness extraordinary growth in energy storage and intermittent generating resources, such as wind, solar and other renewables. As a result, the manner in which PJM evaluates the contribution of such resources toward resource capacity value has also evolved. Prior to 2021, PJM calculated the resource capacity value of an intermittent resource, and that which historically has been labeled as "limited duration," by a methodology independent of changes to the overall resource mix. This meant that a resource's capacity capability and its contribution toward meeting PJM's resource adequacy requirements would not have been impacted by the amount of renewables and energy storage within the RTO as a whole.

This began to draw PJM attention and concern in 2018, given that increasing amounts of intermittent and limited-duration resources impact hourly loss-of-load probability (LOLP) risk profile. Without recognizing this dynamic, PJM could otherwise be overvaluing or undervaluing intermittent and limited-duration resource contribution to resource adequacy over time. The PJM Capacity Capability Senior Task Force (CCSTF) – created by the Markets and Reliability Committee in March 2020 – developed an ELCC methodology suitable to PJM to determine the capacity capability of renewables and storage. The results of the studies that were the outcome of that effort became effective in the second half of 2021. PJM's 2021 Region Transmission Expansion Plan report Section 2.3.2 discusses this in more detail. In addition, the PJM Planning Committee also initiated a separate stakeholder process in 2021 to review and modify existing CIR request and retention policies, with an emphasis on ELCC resources, including the application of CIRs to the ELCC methodology and UCAP valuation.

7.4.4 Probabilistic Transmission Planning

Since the implementation of the RTEP process in 1999, PJM has continued to add reliability planning criteria. These now include winter peak conditions, low-load system conditions, and natural gas pipeline contingencies in addition to summer peak load planning conditions. While existing transmission planning relies on a set of models, assumptions and scenarios using deterministic analytical tools, more powerful techniques can be used for longer-range scenario development to better understand the full range of grid of the future system conditions. This is particularly true given the added complexity associated with renewable generation variable output profiles.

7.4.4.1 Evaluating Resilience

As indicated in **Section 1,** PJM currently incorporates probabilistic methods into its planning process to analyze high-impact, low-frequency events and to identify areas of risk and potential resilience enhancements to the grid. Since the attacks of 9/11, the power industry has taken a closer look at system contingencies not only driven by naturally occurring events but additional man-made threats as well, including: (1) cyberattacks, (2) loss of interdependent systems, (3) earthquakes, (4) physical attacks, (5) severe terrestrial weather, (6) geomagnetic disturbances, and (7) electromagnetic pulses.

PJM uses cascading tree analysis to assess the probability and consequence of cascading outages in electric systems. PJM is currently developing a metric of resilience to complement and enhance a planning process that traditionally has been focused on reliability and market efficiency. The cascading trees methodology could be used in decision-making and as a driver for new projects. For example, transmission corridors that appear frequently across multiple cascading paths are good candidates for system reinforcements significantly lowering the probability of a severe cascading outage.

7.4.4.2 Grid of the Future Scenario Analysis

A larger shift to stochastic models could become an effective transmission planning tool. One application could involve renewable generation output profiles. These techniques may require a shift away from a deterministic elimination of violations to the identification of an optimal hedge against probable scenarios. These models, however, raise a number of complex issues that will require further thought and resolution:

1 | How to assign a proper probability to a scenario

2 | Resolving disagreement over assigned probabilities

3 | What constitutes an optimal hedge in all scenarios (e.g., eliminate or minimize violations for 99% of cases)

4 | Compatibility with other analytical tools (e.g., AC power flow, transient stability, electromagnetic transient, etc.)

PJM believes that probabilistic methods can be a valuable planning tool and will continue to study the application and effectiveness of probabilistic approaches.

7.5 Regulatory Action

PJM engagement with federal and state policymakers is critical to successful grid planning initiatives focused on renewable integration coupled with impacts of current trends in generation, transmission and load. Indeed, grid of the future trends associated with decarbonization are significantly driven by public policy, including FERC's July 15, 2021, Advance Notice of Proposed Rulemaking (ANOPR), entitled, Building for the Future Through Electric Regional Transmission Planning and Cost Allocation and Generator Interconnection. Discussion of PJM's Initial Comments and Reply Comments can be found in PJM's 2021 Regional Transmission Expansion Plan report, Section 1.4.10.

7.5.1 Reliability Criteria for Extreme Events

As stated in its ANOPR response, PJM's ongoing efforts are taking a forward-looking, holistic and proactive approach to plan grid of the future transmission needs with respect to extreme events, which may become a more significant grid expansion driver under higher levels of renewable penetration. The scope of planning studies will support efforts to assess how extreme events can be analytically evaluated and how consequential impacts to system reliability are identified. This may lead to new reliability criteria and planning tests. To that end, Planning will continue to work with stakeholders to consider planning process policy changes that may be needed to enable PJM to identify and plan needed transmission to address extreme events.

7.5.2 Interconnection Pricing Policies and Cost Allocation

Recognizing ongoing grid evolution, and in parallel with the Interconnection Process Reform Task Force discussed above, PJM undertook a series of Interconnection Policy Workshops beginning in May 2021 to encourage stakeholder discussions regarding cost-allocation methodologies and whether any changes or enhancements to the current participant funding approach are warranted.

Through the workshops, PJM and its stakeholders have discussed six potential alternative interconnection cost responsibility options.[51] Implementing one of the six could replace the present "cost causer pays" rule out of FERC Order 2003 and provide a more efficient and fairer way to allocate interconnection-related costs. Each option offers an approach that can address more than a single queue project, in anticipation of greater penetration of renewables and attendant volume of grid interconnection requests.

7.5.3 State Electrification Policies

As discussed above, state policies on electrification can be an important factor in the behavior of end users when opting to convert to electric transportation – including the charging behavior of EVs – and building heating. PJM continues to monitor these policies as they evolve, provide education where appropriate and update planning studies to reflect current polices.

7.5.4 Potential DER Reliability Issues

Growing levels of DER can, if not addressed adequately, create reliability challenges. FERC must ensure that DER is held to reliability, performance and cybersecurity standards that ensure grid reliability. State policies also impact customer DER facility performance characteristics. Importantly, PJM must continue to encourage state policies that also ensure reliability, enable PJM to cost-effectively plan grid expansion and facilitate data sharing.

7.5.5 Continued Development of Grid-Forming Inverter Technology

The challenges created by a rapidly shifting generation fleet must be addressed by NERC in its standard-setting initiatives and enforcement activities, as well as by policymakers at state and federal levels. Defining essential reliability services is necessary in the face of the increasing frequency of extreme weather events and growing levels of IBR-based, variable renewables.

8. Summary

As discussed in this report, many drivers are influencing PJM's generation mix, including state and federal policies as well as economic factors. The overall impact is that during the next 15 years, PJM anticipates that it will integrate more than 100,000 MW of onshore wind, offshore wind, solar and storage resources in addition to the 15,000 MW already in service. In order to interconnect these resources, future grid enhancements alone are estimated to be on the order of more than $3 billion, based on the first phase of PJM's OSW Transmission Study for OPSI. In order to plan for this shift in the generation portfolio mix, the study was a first step in considering the transmission needs to move toward a decarbonized grid.

This report marks a major step forward in the multi-year effort to implement PJM's grid of the future corporate strategy, as reviewed and approved by the PJM Board. A collaborative internal team made up of subject matter experts from throughout PJM continues to implement the road map discussed above in **Section 7**. Planning has also

[51] Interconnection Policy Workshop: Session 3 Presentation of Six Options at https://www.pjm.com/-/media/committees-groups/committees/pc/2021/20210722-workshop-3/20210722-item-03-interconnection-policyreforms-overview-presentation.ashx.

researched and reviewed external future grid initiatives by other ISOs/RTOs, states themselves, and industry studies and white papers. That collective research has informed the degree to which key drivers – generation shift to renewables, electrification-driven load impacts, emerging technologies and extreme event resilience – are governing the development of the grid of the future road map described in this report.

Over the past decade, increasing focus by federal and state governments on climate change, energy independence and other policy areas continues to make clear the critical role of the transmission system. And, while the existence of violations of NERC Reliability Standards is the basis for PJM's determination of need, construction of new transmission infrastructure will enable federal and state governments to promote public policy goals. An important element of these policies is greater use of renewable resources, primarily wind and solar, the integration of which presents a unique set of challenges to planning. PJM's future grid will encompass the operational flexibility to address key drivers that will be significantly different with increased penetration of variable, renewable resources.

The grid of the future is not some far-distant idea but is here now. PJM, like other RTOs across the U.S., has before it a robust, reliable transmission grid, but one upon which enhanced operational flexibility must continue to grow to ensure uninterrupted power delivery 24/7 year-round.