Research Report

Renewables for the Data Center Era: Meeting AI-Driven Demand Growth in the PJM Interconnection

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1. Introduction & Problem Statement

The rapid expansion of artificial intelligence (AI) has triggered an unprecedented surge in global compute demand, driving what many experts describe as a new industrial-scale energy challenge. According to McKinsey & Company, global data center capacity could nearly triple by 2030, with roughly 70 percent of this growth driven by AI workloads [1]. Meeting this increase could require as much as 5.2 trillion dollars in capital investment for AI-related capacity alone, and between 6.7 and 7 trillion dollars across all computing infrastructure by the end of the decade [1]. McKinsey further estimates that approximately 156 gigawatts of AI-related data center capacity will be needed by 2030, representing an additional 125 gigawatts between 2025 and 2030 [1]. Even as improvements in efficiency, cooling, and system design continue, new AI applications and experimental models are expected to offset these gains, driving total electricity consumption steadily upward. The accelerating growth in power demand, particularly around dense urban and industrial clusters where large data centers are concentrated, presents a critical challenge for power system operators. They must find ways to expand capacity and enhance flexibility while simultaneously maintaining reliability and advancing regional decarbonization goals.

PJM Interconnection holds a uniquely important position in the North American energy landscape. As the largest competitive wholesale electricity market in the continent, PJM coordinates electricity delivery for more than 65 million people across 13 states and the District of Columbia, spanning over 369,000 square miles [2]. Its service territory contains a diverse mix of resources, including natural gas, coal, nuclear, renewables, and growing distributed energy sources. The region has also emerged as one of the world's leading data center hubs, with PJM reporting that peak load is projected to grow by 32 gigawatts between 2024 and 2030, 30 gigawatts of which will come directly from data centers [3]. This scale of demand growth presents both significant opportunities and serious challenges for grid reliability and planning. While PJM has cleared more than 140 gigawatts of queued generation projects in recent years, many are delayed by permitting issues, supply chain constraints, and interconnection bottlenecks [4]. As one of the most mature and complex grid operators in the world, PJM now serves as both a model and a test case for how a large interconnected system can evolve to balance accelerating load growth from energy-intensive industries with its decarbonization commitments.

However, recent developments have raised concerns about whether the current system design can sustain reliability under rising load conditions. The 2025–2026 PJM capacity auction cleared at the market's administrative ceiling, reflecting deepening concerns about tightening supply margins and growing stress on the system [5]. These record-high clearing prices suggest that the region may be approaching a shortfall in dispatchable capacity. Analysts have also pointed to fundamental challenges in aligning PJM's market structure with state-level clean energy policies, noting that the system has struggled to integrate renewable resources quickly enough to replace retiring fossil fuel assets [6].

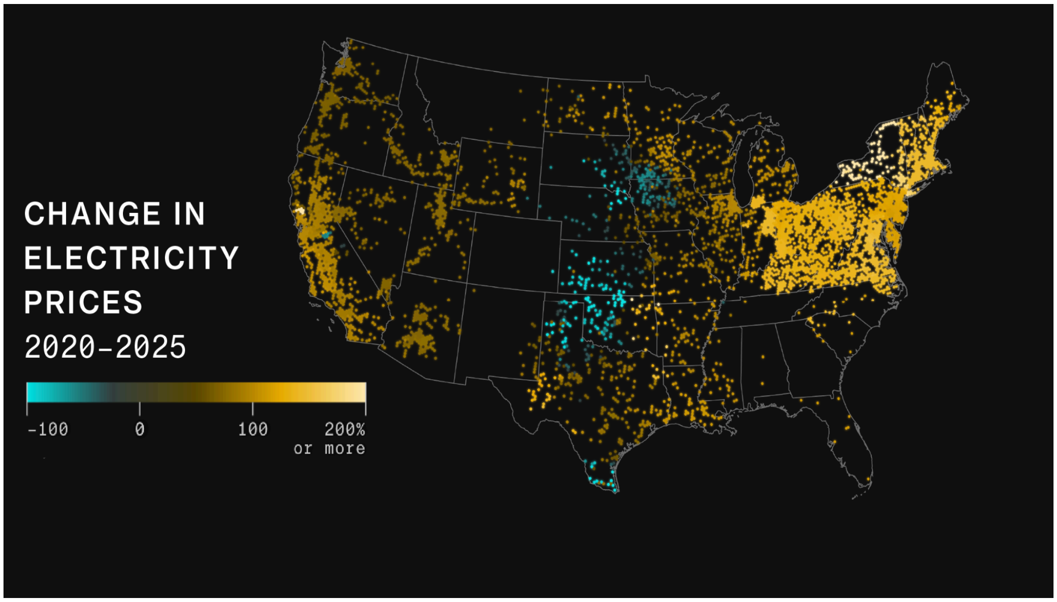

Figure 1: Regional Shifts in Electricity Prices Across the United States from 2020 to 2025 [7]

In response to the near-term reliability gap, PJM has approved 51 new generation projects, many of which are natural gas-fired, to accommodate projected load growth from data centers and other industrial users [8]. This response underscores the immediate pressures facing the system but also raises critical questions about long-term planning. Although renewable resources such as solar and wind have already proven to be increasingly cost-effective and capable of delivering resilient power when implemented with robust system design, their success depends heavily on how and where they are deployed. The challenge is therefore not the capability of renewable technologies themselves but the absence of coordinated strategies to integrate them efficiently at the scale required to serve large, continuous data center loads. Developing these strategies will require innovative approaches to system planning, market design, and dispatch optimization, ensuring that renewables and storage can operate as reliable, round-the-clock contributors to the grid.

This paper explores whether renewable energy systems can reliably meet data centers' demanding power requirements within PJM's existing operational and market framework. By examining the technical feasibility, economic competitiveness, and policy mechanisms necessary for large-scale renewable integration, this research seeks to identify effective strategies for the deployment and dispatch of renewables to meet AI-driven demand growth while maintaining system reliability and advancing decarbonization objectives.

Figure 2: Geographic Distribution of U.S. Data Centers by Operational Status and Capacity [9]

2. Background Information

2.1 Data Centers and Grid Reliability

Data Centers are a Continuous Inflexible Load

Data centers present uniquely challenging loads for power system operators because they operate continuously, 24 hours a day, seven days a week, with consistently high power demand. Unlike typical industrial or residential consumers, data centers cannot tolerate extended interruptions in electricity supply, as even brief outages can lead to significant operational and financial consequences. High uptime, typically targeted at 99.9 percent or higher, is critical, and the cost of downtime can reach thousands of dollars per minute for large organizations [10]. Maintaining stable voltage and frequency is essential because power quality issues can propagate quickly and disrupt sensitive computing infrastructure [11].

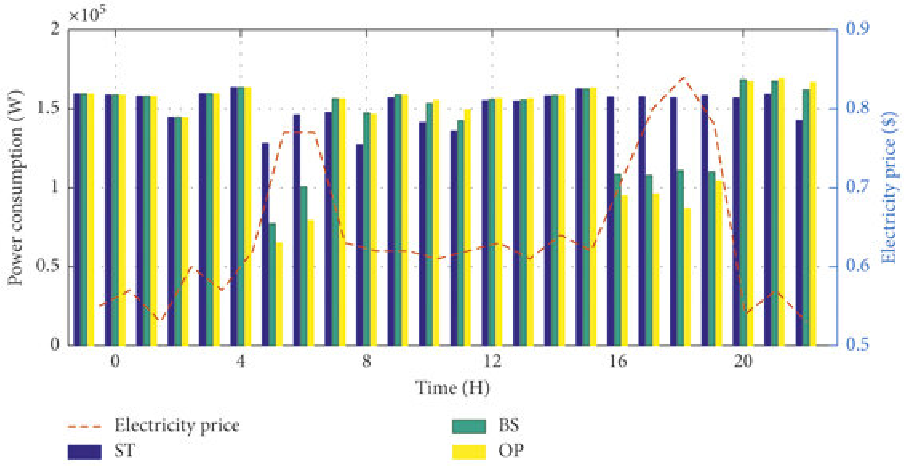

Figure 3: Typical Data Center Power Consumption Remains Nearly Constant Throughout the Day [12]

Modern Data Center Complexity

Modern data centers are more complex than traditional facilities. They rely on virtualized networks that connect multiple physical servers, storage systems, and application delivery controllers across both on-premises facilities and multicloud environments [13]. Data exists across multiple sites, including private and public clouds, and applications hosted in the cloud use resources from these distributed data centers. They are critical to supporting enterprise functions such as email and file sharing, productivity software, customer relationship management, enterprise resource planning, big data analytics, artificial intelligence, machine learning, virtual desktops, and communications services. Each of these functions depends on reliable, low-latency, and high-capacity power delivery. To achieve this, data centers incorporate redundant power supplies, uninterruptible power systems, backup generators, cooling and ventilation systems, fire suppression, and robust network and security appliances to maintain both operational integrity and cybersecurity [13].

Redundant and Fault-Tolerant Infrastructure

The core infrastructure of a data center includes network components, storage systems, and computing resources that collectively provide connectivity, data storage, and processing power. To ensure continuous operation, these systems are often built to Tier 3 or Tier 4 standards under the ANSI/TIA-942 framework, providing redundant paths and fault-tolerant design that allow maintenance or equipment failures without disrupting service. Tier 4 facilities, for example, are fault-tolerant and can withstand component failures without downtime, which is critical for organizations with high transaction volumes, AI workloads, or mission-critical operations where even minutes of disruption can have significant economic or operational impact [13].

2.3 Background: PJM

Rising Power Demand in PJM

Within the PJM Interconnection region, which serves 13 U.S. states and the District of Columbia, grid reliability is being increasingly tested by rising power demand from data centers and electrification. PJM’s 2025 Long-Term Load Forecast projects that total summer peak demand could reach nearly 220,000 megawatts by 2040, representing an increase of about 70,000 megawatts over the next 15 years (PJM Inside Lines, 2025). Much of this near-term growth is concentrated between 2024 and 2030, when peak load is expected to rise by approximately 32,000 megawatts, of which 30,000 megawatts are attributed to data centers [14].

PJM’s Continued Reliance on Fossil Fuels

The bulk of this expansion is occurring in states such as Virginia, Ohio, and Pennsylvania, where strong transmission networks, proximity to population centers, and favorable tax policies have attracted large-scale data center construction. Unlike other forms of electricity demand that peak intermittently, data centers require constant, high-volume power 24 hours a day, resulting in a sustained and inflexible load profile. According to analysts, this type of flat, continuous demand introduces more hours of operational risk and limits grid flexibility, making it more difficult to balance renewable generation that depends on variable weather conditions [15]. At the same time, PJM is facing persistent delays in bringing new generation and transmission resources online due to permitting, interconnection backlogs, and supply chain constraints [16]. To maintain short-term reliability, the organization has approved 51 new generation projects, many of which are natural gas-fired, to support the anticipated increase in load from data centers and other industrial users [17]. While this provides an immediate buffer against shortages, it also reinforces reliance on fossil fuels, a strategy that could heighten exposure to market volatility and carbon costs in the long run.

Adapting Grid Planning and Operations

The pace of data center expansion is forcing PJM to confront deeper structural and operational questions about how the regional grid is planned and managed. Unlike previous periods of load growth, the surge in digital infrastructure demand is emerging faster than the traditional project approval and interconnection processes can accommodate. Transmission corridors in high-growth areas such as Northern Virginia are already nearing capacity, and congestion management has become a growing operational concern [2]. These constraints highlight the need for more adaptive system planning that can anticipate clustered load growth and coordinate generation and transmission development accordingly. PJM has begun exploring solutions such as localized grid reinforcement, accelerated interconnection reviews, and flexible capacity products to better align generation with around-the-clock data center operations [16]. However, these efforts also raise broader policy and market questions about how costs are allocated and how long-term reliability can be maintained without compromising decarbonization objectives. As PJM works to modernize its planning framework, its experience is likely to influence how other large regional transmission organizations across North America respond to the combined pressures of digitalization, electrification, and climate policy.

3. The Solar-Plus-Storage Solution

3.1 Solar

Addressing PJM's Energy and Reliability Needs

A solution that supplements PJM's energy supply issues and the need to integrate affordable and reliable renewable energy resources is solar energy paired with battery energy storage systems (BESS). This combination directly addresses PJM's dual need to expand generation rapidly and integrate affordable, reliable renewable energy sources. Solar-plus-storage offers a technically feasible, economically competitive, and dependable pathway to large-scale decarbonization, aligning closely with both system reliability goals and state-level clean energy mandates.

Rapid Deployment to Meet Near-Term Load Growth

One of PJM's immediate priorities is bringing "shovel-ready" projects online to meet near-term load growth from data centers and electrification. Solar projects offer a clear advantage because they can be planned, permitted, and constructed much faster than most conventional plants. While natural gas facilities require complex siting, regulatory review, and multi-year construction timelines, utility-scale solar installations can be deployed within months once interconnection and financing are secured [18]. This rapid deployability is critical as PJM faces compounding reliability pressures from aging infrastructure and retiring fossil fuel capacity.

Affordability and Market Competitiveness

Over the past decade, solar technology has evolved into one of the world's most cost-effective sources of electricity. The International Energy Agency identifies solar photovoltaics as "the cheapest source of electricity in history," with global costs declining by more than 85% since 2010 [19]. These reductions result from lower module prices, improvements in balance-of-system efficiency, and financing mechanisms such as power purchase agreements (PPAs). In wholesale markets like PJM's capacity and energy auctions, solar now competes directly with conventional generation while offering long-term price stability that shields consumers from fuel price volatility. For energy-intensive users such as data centers, this stability makes solar an attractive foundation for meeting future load growth.

Unlocking PJM's Solar Potential

The PJM region possesses substantial solar resources, yet deployment remains far below potential. Solar currently represents only about 2–3% of PJM's total generation mix, despite abundant sunlight and a dense transmission network [4]. The underrepresentation of solar and dependence on fossil fuels in this region is not due to resource scarcity, but rather to interconnection bottlenecks and policy misalignment. Recent analysis by PV Magazine USA (2025) found that PJM could "fast-track up to 102 gigawatts (GW) of solar and 24 GW of energy storage" by utilizing existing but underused points of interconnection on the transmission network [20]. Transmission investment is one of the most costly aspects of implementing new energy infrastructure, and this represents low-cost, high-impact opportunities to add renewable capacity without major new transmission investment. The available grid hosting capacity exists from preexisting substations and feeder lines that were originally designed for retiring coal and gas plants. By connecting large-scale solar projects this infrastructure that is already providing grid hosting capacity represents a valuable opportunity to fast-track solar projects and phase out fossil fuels. Leveraging such infrastructure allows for faster permitting and construction timelines, which is a critical advantage in meeting near-term decarbonization goals and ensuring reliability amid increasing load demand.

Supporting State Clean Energy Mandates

Solar expansion also supports the policy frameworks of the states within PJM's footprint. Every PJM state has established either a Renewable Portfolio Standard (RPS) or a clean energy target, with most mandating 50–100% clean electricity by 2040–2050 [21]. Lawmakers have increasingly urged PJM to reform its interconnection process and market design to ensure renewable projects can be built in time to meet these mandates [22]. The regulatory direction of the market emphasizes solar energy as a critical component for regional utilities and developers to meet the goals they are comitted to achieving. By aligning project development with these mandates, solar investments benefit from stable policy support, access to state-level incentives, and eligibility for IRA provisions such as the Investment Tax Credit (ITC) if projects move quickly enough through the interconnection queue before they expire. Combined, solar energy's modularity, rapid build-out potential, and alignment with both market trends and regulatory structures, make it the most advantageous foundation for expanding PJM's renewable capacity.

3.2 Battery

The Role of Battery Storage

A significant concern propagated by widespread disinformation is that solar power is not a reliable technology. However, the intermittency of solar when there is limited sunlight can be addressed by BESS to ensure reliability and grid stability. The integration of solar and storage not only addresses variability concerns but also transforms renewable projects into firm, dispatchable resources capable of delivering grid services traditionally supplied by fossil fuels and peaker plants.

Managing Solar Intermittency and Enhancing Reliability

The challenge of solar power lies in its diurnal and weather-dependent generation profile. Battery storage solves this problem by capturing excess energy generated during solar hours and discharging it when production drops or demand spikes. In regions like PJM, where demand is heavily concentrated in evening hours and cloud cover can vary, energy shifting through storage is key to ensuring system adequacy and reducing curtailment of renewable generation. In addition to balancing load and generation, storage enhances resilience. During outage scenarios or extreme weather events, BESS installations can provide localized backup power and black-start capability for grid restoration, which is becoming increasingly important as the frequency of extreme weather events increases.

Providing Grid Services and Stability

Beyond addressing the intermittent nature of renewable energy sources, BESS units play a growing role in maintaining grid stability. Modern grid systems require continuous balancing of supply and demand to maintain frequency within ± 0.1 Hz of the nominal 60 Hz, and batteries are much more effective in responding to these fluctuations [23]. According to a 2023 study in Applied Energy, battery systems are already being deployed to deliver "frequency regulation, voltage control, reactive power support, and system congestion relief" across U.S. grids [24]. In PJM, frequency regulation is already a primary revenue stream for early battery projects, demonstrating the market trend in this region toward BESS participation in ancillary services markets. As both the technical feasibility and market viability of storage duration improves, its role is expanding from short-term stabilization toward multi-hour capacity and even seasonal balancing applications.

Technology Maturation and Cost Declines

Similar to solar, the production cost of BESS has rapidly declined over the past decades. The U.S. Department of Energy's NREL 2024 Annual Technology Baseline (ATB) reports that capital costs for utility-scale lithium-ion batteries have dropped by approximately 75% since 2015 and are projected to decline another 40% by 2035 as supply chains mature and manufacturing scales globally [25]. These improvements have led to significant market expansion for batteries that cover daily load cycles and optimize energy arbitrage for 4-8-hour windows [25].

In addition to cost reductions, technological performance has continued to improve as manufacturers enhance battery chemistry, energy density, cycle life, and thermal stability. Advances in lithium iron phosphate (LFP) and high-nickel chemistries have extended battery lifetimes and reduced degradation rates, making multi-hour storage more economically competitive for both utility-scale and behind-the-meter applications. Improvements in battery management systems and power electronics have also increased system efficiency and broadened the range of grid services that storage can reliably provide. These technical gains support the growing trend toward longer-duration storage systems that are capable of addressing evening peak demand, mitigating renewable curtailment, and providing higher-value ancillary services within wholesale energy markets.

Furthermore, economies of scale from global electric vehicle production continue to lower costs and diversify supply chains, while domestic manufacturing incentives in the United States have encouraged the development of new battery gigafactories. As these trends converge, storage technology is becoming more standardized, more reliable, and easier to deploy, which strengthens its role as a cornerstone resource for clean energy integration in regions such as PJM.

Implications for PJM's Energy Transition

The combination of solar energy and battery storage represents a critical pathway for PJM to meet its rapidly growing electricity demand while advancing regional decarbonization goals. Solar provides a scalable and rapidly deployable source of low-cost, renewable energy, which can be brought online faster than conventional fossil-fueled plants to address near-term capacity needs from data centers and electrification. When paired with battery energy storage systems, solar can overcome intermittency challenges, deliver firm and dispatchable power, and provide essential grid services such as frequency regulation, voltage support, and congestion relief. This synergy not only enhances system reliability but also allows PJM to replace retiring coal and gas plants with renewable resources while maintaining operational stability. Furthermore, leveraging underutilized transmission infrastructure and aligning project development with state-level clean energy mandates creates opportunities for cost-effective deployment of large-scale renewables. Together, these technologies provide PJM with the technical and economic foundation to accelerate the region's clean energy transition, reduce reliance on fossil fuels, and better position the grid to meet both near-term reliability requirements and long-term policy objectives.

4. Literature Review & Research Gap

4.1 Current Research on Solar Plus Storage Systems

General Grid Integration Studies

A large body of research examines how high penetrations of variable renewable energy, especially solar and wind, can be integrated into bulk power systems while maintaining reliability. Studies conducted by national laboratories and system operators consistently find that grids can reliably accommodate renewable shares ranging from 30 percent to 100 percent of total generation, provided that planning, operations, and market structures adapt to higher variability and uncertainty in supply [26]. These adaptations typically include increased system flexibility, expanded transmission capacity, improved forecasting, and greater use of demand response and storage. For example, a 2024 National Renewable Energy Laboratory (NREL) synthesis of high-renewable scenarios across multiple regions concludes that reliability can be preserved if operators make deliberate changes in how systems are planned and operated, such as enhancing ramping capability, broadening balancing areas, and deploying storage and grid enhancing technologies [25]. Similarly, PJM's own "Renewable Energy Transition Study" and related planning analyses describe how regional markets, geographic diversity, and robust transmission networks can facilitate a reliable and cost effective transition to higher renewable shares, although they also highlight risks such as increased congestion and curtailment without targeted investments in transmission and flexibility resources [27].

More recent work focuses specifically on the role of flexibility under high renewable penetration. PJM's report Energy Transition in PJM: Flexibility for the Future stresses that increasing amounts of wind, solar, and storage will fundamentally change system operations and that new products and planning tools will be needed to harness flexibility from storage, demand response, and hybrid plants [4]. Across this literature, solar is viewed as a central contributor to decarbonization, but its successful integration is contingent on complementary resources and new planning and market practices rather than on technology capability alone.

Utility Scale Storage Performance

Parallel to the grid integration literature, there is a growing set of studies that focus on utility scale battery energy storage systems (BESS). NREL's Annual Technology Baseline (ATB) and its dedicated reports on utility scale storage provide detailed cost and performance projections for lithium ion battery systems across a range of durations, typically 2 to 10 hours [28]. These analyses document rapid cost declines since the mid 2010s and anticipate further reductions driven by manufacturing scale, learning by doing, and spillovers from the electric vehicle sector. They also highlight how different storage durations align with different use cases, such as frequency regulation, energy arbitrage, resource adequacy, and transmission deferral.

Policy and market focused work, such as the Resources for the Future report Charging Up: The State of Utility-Scale Electricity Storage in the United States, examines how economic incentives, market rules, and regulatory frameworks have shaped storage deployment to date [29]. These studies find that storage has primarily been deployed to capture a limited set of revenue streams, especially frequency regulation and short duration arbitrage, rather than to fully support long duration reliability or large scale renewable integration. At the same time, modeling research from institutions such as Lawrence Berkeley National Laboratory explores the “modeling frontiers” of storage representation in power system planning and market clearing tools, emphasizing that existing models often understate the system value of storage because they treat it as a simple load or generator rather than a dynamic, multi service resource [30].

There are also practical case studies of solar plus storage projects that demonstrate the operational benefits of co-located systems. For instance, commercial and utility scale case studies show that pairing solar with storage can reduce peak demand charges, increase on site consumption of solar generation, and provide firm capacity to the grid [31]. NREL’s utility scale PV plus battery ATB further illustrates how joint cost trajectories for solar and storage make hybrid plants increasingly attractive for both merchant and contracted projects in wholesale markets [32]. The storage literature shows that the technology is technically capable of supporting grid reliability and renewable integration and that costs are declining quickly. However, deployment and utilization are still heavily influenced by market design and planning assumptions, which often lag behind the technical potential of storage.

4.2 Research on Data Center Power Requirements

A separate stream of research focuses on the electricity demand of data centers and, more recently, the specific impact of AI workloads. The International Energy Agency (IEA) projects that global data center electricity demand will more than double by 2030, reaching around 945 TWh, with AI identified as the primary driver of this increase [33]. In 2024, data centers accounted for an estimated 1.5 percent of global electricity consumption, and this share is expected to grow significantly as AI models become more computationally intensive and are deployed at scale [34].

Industry and policy analyses further highlight that AI oriented data centers tend to be larger, more power dense, and more continuously utilized than traditional enterprise facilities. Recent work by BloombergNEF, summarized in media reports, estimates that U.S. data center power demand could reach 106 gigawatts by 2035, with regions such as PJM and Texas already nearing capacity constraints as a result of large scale projects that frequently exceed 500 megawatts each [35]. McKinsey's analysis of U.S. data center growth suggests that data centers could account for up to 12 percent of U.S. electricity consumption by 2030, underscoring the national scale of the challenge [36].

Academic and technical literature also examines the characteristics of data center loads. Studies emphasize that hyperscale and AI optimized facilities operate with high load factors, often near continuous full utilization, and require extremely stringent reliability and power quality standards [36]. These facilities rely on redundant power feeds, uninterruptible power supplies, and backup generation, but their interaction with the grid is typically as a large, inflexible, and relatively opaque load rather than as a flexible or controllable resource. The combination of constant high demand and limited flexibility makes it more difficult for system operators to balance supply and demand, especially in regions attempting to integrate high shares of variable renewable energy. In PJM specifically, planning reports and stakeholder analyses have begun to acknowledge the impact of data center clusters, particularly in Northern Virginia and parts of Pennsylvania. These analyses note that the speed and scale of data center development exceed the timelines of traditional transmission planning and interconnection processes, which amplifies reliability risks if new generation and grid upgrades do not keep pace [4].

4.3 The Remaining Research Gap

Although there is substantial literature on high renewable grid integration and on the performance and cost of utility scale storage, as well as a growing body of work on data center power demand, these fields rarely intersect in a way that directly addresses the specific problem faced by PJM. Most grid integration studies analyze broad scenarios with high renewable penetrations but do not explicitly model large, clustered, and nearly constant data center loads within a real market and regulatory context such as PJM's.

Conversely, research on data center electricity use often treats the grid as an exogenous system and focuses on aggregate demand projections, efficiency improvements, or carbon accounting, rather than on the operational details of how renewables and storage can be dispatched to reliably serve these loads at scale. Many studies also examine on site solutions, such as direct procurement of renewable energy or co-located backup generation, but do not fully explore system level strategies for integrating large data center clusters into regional resource planning and dispatch decisions. The most significant gap lies at the intersection of these literatures: there is limited work that evaluates how large quantities of solar and storage can be optimally deployed and dispatched within PJM to meet rapid, data center driven demand growth, under realistic assumptions about interconnection constraints, transmission bottlenecks, and existing market rules. In particular, there is a lack of case specific analysis for sub regions such as the PECO service territory, where projected load increases are on the order of 1.2 gigawatts in the near term and where both renewable potential and grid constraints are highly location dependent [37].

4.4 How This Research Addresses the Gap

This research contributes to the literature by focusing explicitly on the question of whether renewable energy systems can reliably meet large, data center driven load growth in PJM, and by doing so in a way that is grounded in a specific regional case. The study centers on the PECO service area within PJM, which is projected to experience approximately 1.2 gigawatts of new demand from data centers over a short time horizon. By focusing on this concrete context, the analysis moves beyond abstract scenarios and examines realistic deployment and dispatch strategies that could be implemented within current or near term policy constraints.

The research synthesizes insights from solar plus storage cost and performance literature with PJM specific planning and renewable integration studies. This allows the study to construct techno economic scenarios that reflect both the rapidly improving economics of solar and storage and the institutional barriers within PJM's interconnection, transmission planning, and market design frameworks. The analysis evaluates different renewable configurations, such as solar only and solar plus storage systems, under varying incentive environments. By examining levelized cost of energy, revenue potential in PJM markets, and the ability to match the temporal profile of data center demand, the study provides a more detailed view of which configurations are both technically viable and financially realistic in the near term. The research links technical results to policy design. Rather than stopping at feasibility, the study identifies the specific regulatory and market reforms that would be necessary to scale solar plus storage solutions fast enough to meet emerging data center loads. This includes interconnection reform, a shift toward “connect and manage” transmission planning, and market rule changes that properly value storage and flexibility resources. In doing so, the paper helps bridge the gap between high level renewable integration studies and sector specific analyses of data center growth. It offers a regionally grounded, technology informed, and policy relevant perspective on how PJM can meet the dual challenge of rising AI driven electricity demand and ambitious decarbonization objectives.

5. Research Methodology

5.1 Methodology Overview: Techno-Economic Evaluation of Renewable Energy Integration for PJM

This study relied on detailed computer simulations to understand whether PJM can reliably integrate an additional 1.2 GW of renewable energy capacity, primarily solar, wind, and battery storage, to support the growing electricity needs of a large data center in the PECO region of Pennsylvania [38]. The analysis was carried out using the System Advisor Model (SAM), a widely used tool for evaluating renewable-energy projects. The goal of the methodology was to build scenarios that reflect what PJM is currently experiencing: rapid load growth, especially from data centers, and a strong push toward integrating more renewable resources across its system.

To make the study relevant to PJM's real-world conditions, we began by reviewing PJM's latest long-term energy-transition reports. These reports describe how PJM expects its generation mix, transmission flows, and reliability needs to evolve as more solar, wind, and storage come online. They highlight concerns about thermal power-plant retirements, the need for more flexible resources, and the increasing strain created by fast-growing electricity demand. Using these insights, we aligned our modeling assumptions with PJM's own expectations for 2030–2035, especially the region's strategic goals of increasing renewable penetration by 30% by 2030 and 50% by 2050, and the reality that large energy users like data centers are becoming some of the fastest-rising contributors to load growth.

The resource and weather conditions used in the simulations were obtained from NASA Power, which provides detailed information on sunlight, temperature, and wind patterns for Pennsylvania [39]. These weather conditions are important because they determine how much solar and wind energy can realistically be produced throughout the year. The NASA data also helped us optimize the placement of solar panels by providing information such as sunlight intensity, tilt angles, and seasonal cloud patterns.

We then designed four scenarios in SAM that reflect different combinations of solar power, wind power, and battery storage. These scenarios also take into account the financial conditions that renewable-energy developers face today, such as federal tax credits, state incentives, and land-lease costs. The first scenario modeled a solar-only system that takes advantage of federal incentives. The second scenario repeated that design but removed federal incentives to study what would happen if national policies are scaled back. The third scenario added both wind power and battery storage to the solar project to reflect PJM's view that hybrid resources will play a key role in future reliability. The fourth scenario paired solar with battery storage only, to examine how storage can help stabilize energy supply during cloudy periods, evenings, and times when the data center's electricity demand is highest.

Each scenario used the same overall system size: a solar farm of 1.5 GW, which produces 1.153 GW of usable AC power, consistent with typical system losses. The battery system, where included, was sized at 100 MW and designed to support PJM during rapid changes in renewable output. Which PJM has identified as one of its biggest operational challenges as more intermittent resources come online. Once the models were built, SAM ran year-long simulations to estimate how much energy each scenario would produce, how well that energy would match the data center's needs, and how much surplus energy could be sold back to the grid. Because PJM allows renewable generators to sell excess energy at market rates, the study also calculated how each scenario could generate revenue for the grid, particularly during seasons when renewable energy output is high.

We also included key assumptions about land costs, taxes, and system degradation over time to ensure that the financial results would be realistic. For example, the model accounted for a $700-per-acre land lease and a gradual 0.5% annual decline in solar output. We considered both federal and state tax incentives, but we also modeled the possibility that federal incentives may decline under future policy changes. These considerations are important because the economics of renewable projects can shift significantly when incentives change.

A major part of the methodology involved connecting our SAM simulations to PJM's broader system behavior. PJM's recent studies show that as renewable energy becomes a larger share of the generation mix, the grid will need more flexible resources especially storage and fast-responding generation to handle sudden changes in wind and solar output. By including scenarios with batteries and hybrid systems, our analysis directly responds to these findings. We also assumed that the energy from the renewable system would operate as part of PJM's existing renewable fleet, which currently includes about 7.2 GW of solar and wind capacity. This allowed us to assess how adding a new 1.5 GW project would reduce stress on the grid during peak hours, and whether such a project could realistically be built and integrated within a two-year timeline.

Finally, each scenario was evaluated across three categories: technical performance, economic viability, and contribution to system reliability. The simulations helped us estimate the annual energy production, the stability of supply during peak load hours, the project's cost-effectiveness, and how well each system design would support PJM's reliability needs today and in the future. By comparing the four scenarios, we were able to identify which combinations of technologies offer the strongest balance of cost, performance, and reliability while aligning with PJM's ongoing transition toward a more renewable-focused grid.

Table 1. Summary of the Four Simulated Scenarios

Scenario	**Technology Mix**	**Capacity Installed**	**Incentives Applied**	**Purpose of Scenario**
1. PV Only (With Incentives)	Utility-scale Solar PV	1.5 GW DC → 1.153 GW AC	30% Federal ITC, 10% State Credit, 5% Sales Tax	Evaluate solar performance under full incentive availability and assess cost-effectiveness during policy-supportive years.
2. PV Only (Without Federal Incentives)	Utility-scale Solar PV	1.5 GW DC → 1.153 GW AC	0% Federal ITC, 10% State Credit, 5% Sales Tax	Assess economic viability of solar expansion assuming federal tax credits phase out.
3. PV + Wind + Battery (With Incentives)	Solar PV + 30 MW Wind + 100 MW Battery	1.5 GW DC PV + 30 MW Wind + 100 MW Battery	30% Federal ITC, 10% State Credit, 5% Sales Tax	Evaluate hybrid generation's ability to stabilize output, reduce intermittency, and support PJM's rising ramping needs.

4. PV + Battery (With Incentives)	Solar PV + 100 MW Battery	1.5 GW DC PV + 100 MW Battery	30% Federal ITC, 10% State Credit, 5% Sales Tax	Assess how storage enhances PV reliability during peak hours and mitigates cloud-related variability.

Table 2. Key Modeling Parameters and Assumptions for All Scenarios

Parameter	**Value Used in All Scenarios**
Solar Plant Nameplate Capacity	1.5 GW DC
Solar Output (AC Rating)	1.153 GW AC (after inverter & system losses)
Inverter Efficiency	96%
Annual PV Degradation Rate	0.5% per year
Wind Capacity (Scenario 3 only)	30 MW onshore wind
Battery Capacity (Scenarios 3 & 4)	100 MW, 4-hour discharge
Federal Investment Tax Credit (ITC)	30% (Scenarios 1, 3, and 4 only)

State Tax Credit	10%
Federal Income Tax Rate	10%
Sales Tax	5%
Land Lease Cost	$700 per acre
Weather Data Source	NASA POWER database for Pennsylvania
Simulation Tool	NREL System Advisor Model (SAM)
Grid Context	PECO region, integrated into PJM's existing renewable portfolio
Policy Context	Reflects PJM's goal of increasing renewable penetration by 30% (2030) and 50% (2050)

6. Results & Analysis

6.1 First Scenario: PV with Incentives

The first scenario modeled a 1.5 GW DC (1.153 GW AC) solar photovoltaic (PV) facility developed under full federal and state incentives. The simulation shows an annual AC energy output of 3.18 TWh in the first year, corresponding to a 24.2% DC capacity factor, which aligns well with the solar resource availability observed in Pennsylvania under NASA POWER data. The system produced an energy yield of 2,120 kWh/kW, which is consistent with large-scale utility PV systems operating in mid-Atlantic climates.

Economically, the project demonstrates strong performance in an incentive-supported environment. The nominal LCOE is 1.57 ¢/kWh, with a real LCOE of 1.25 ¢/kWh, positioning the project well below PJM's average wholesale market prices. This indicates that the PV system can generate energy at far lower cost than prevailing PJM locational marginal prices (LMPs), creating a significant margin for long-term financial sustainability. The project's net present value (NPV) is highly positive at $170 million, demonstrating excellent financial attractiveness. Additionally, the model reaches its internal rate of return (IRR) of 13.53% in year 25, which is consistent with the long project lifetime typical of large solar installations. The end-of-project IRR remains stable at 13.53%, showing limited downside risk.

Table 3: LCOE of Scenario 1

Metric	Value
Annual AC energy in Year 1	3,179,569,152 kWh
DC capacity factor in Year 1	24.2%
Energy yield in Year 1	2,120 kWh/kW
LCOE Levelized cost of energy nominal	1.57 ¢/kWh
LCOE Levelized cost of energy real	1.25 ¢/kWh
NPV Net present value	$170,049,440
IRR Internal rate of return	13.53 %
Year IRR is achieved	25
IRR at end of project	13.53 %
Net capital cost	$1,339,915,264
Equity	$1,107,097,856
Size of debt	$232,817,520
Debt percent	17.38%

The capital structure consists of $1.34 billion total net capital cost, with approximately 82.6% financed through equity ($1.107 billion) and 17.38% through debt ($232.8 million). This equity-heavy financing is typical for renewable energy projects with fluctuating cash flows, and the availability of federal incentives further encourages a high-equity investment strategy. The results show that solar development under the current incentive framework is not only technically viable but also financially advantageous, producing more than 3 TWh annually at extremely low cost.

6.2 Second Scenario: PV without Incentives

The second scenario modeled the same 1.5 GW DC (1.153 GW AC) solar photovoltaic (PV) facility, but evaluated it without the support of federal or state incentives. The simulation shows an annual AC energy output of 3.18 TWh in the first year, corresponding to a 24.2% DC capacity factor, which aligns well with the solar resource availability observed in Pennsylvania under NASA POWER data. The system produced an energy yield of 2,120 kWh/kW, remaining consistent with the technical performance observed in the incentive-backed scenario.

Economically, the absence of incentives drastically impacts the project's cost competitiveness. The nominal LCOE rises to 4.80 ¢/kWh, with a real LCOE of 3.82 ¢/kWh. While this cost of generation reflects the true unsubsidized price of solar in this region, it places the project at a disadvantage compared to the ultra-low costs achieved with incentives, likely pushing it closer to or above PJM's average wholesale market prices, thereby eroding the margin for long-term financial sustainability.

Table 4: LCOE of Scenario 2

Metric	Value
Annual AC energy in Year 1	3,179,569,152 kWh
DC capacity factor in Year 1	24.2%
Energy yield in Year 1	2,120 kWh/kW
LCOE Levelized cost of energy nominal	1.48 ¢/kWh
LCOE Levelized cost of energy real	1.18 ¢/kWh
NPV Net present value	$197,466,320
IRR Internal rate of return	11.16 %
Year IRR is achieved	25
IRR at end of project	11.16 %
Net capital cost	$1,314,744,832
Equity	$1,112,565,760
Size of debt	$202,179,040
Debt percent	15.38%

The project's net present value (NPV) drops significantly to a negative -$407.8 million, demonstrating that the project is not financially viable under current market conditions without policy support. Additionally, the model calculates an internal rate of return (IRR) of -1.72%, which persists through the end of the project as shown in Table 3. This negative return indicates that the revenue generated is insufficient to cover the capital and operating costs while providing a return to investors.

The capital structure remains consistent with the previous scenario, showing a total net capital cost of $1.34 billion. Financing is split between approximately 82.6% equity ($1.107 billion) and 17.4% debt ($232.8 million). However, unlike the incentivized scenario where high equity participation is rewarded with tax credits and accelerated depreciation benefits, here the heavy equity burden contributes to the negative financial outlook due to the lack of sufficient cash flow to service the investment. The results show that while the solar development remains technically sound, producing the same substantial 3 TWh of energy annually, it is economically unfeasible without the current incentive framework. The negative

NPV and IRR suggest that market revenues alone are currently insufficient to justify the massive initial capital expenditure required for a utility-scale installation of this magnitude in the PJM market.

6.3 Third Scenario: PV-Wind-Battery Scenario

The third scenario modeled a utility-scale hybrid facility combining Solar PV, Wind, and Battery Energy Storage Systems (BESS). This configuration was designed to leverage the complementary generation profiles of wind and solar while utilizing storage to firm capacity and shift energy to high-value periods.

The simulation shows an annual AC energy output of 2.6 TWh in the first year. This corresponds to a combined capacity factor of 45.8%, which is significantly higher than the standalone PV scenario, reflecting the synergy between daytime solar generation and nighttime/off-peak wind resources. The system produced a PVWatts and Wind energy yield of 2,120 kWh/kW and 1,895 kWh/kW respectively as shown in Table 4. The inclusion of the battery component allowed for a reduction in curtailment and a smoother injection profile compared to the variable renewable-only cases.

Economically, the hybrid project presents a more complex cost structure due to the additional capital required for multiple technologies. The nominal LCOE is 3.98 ¢/kWh, with a real LCOE of 3.17 ¢/kWh. While this LCOE may be higher than the standalone PV scenario due to the battery storage costs, it remains competitive when compared to PJM's average wholesale market prices, particularly when accounting for the increased value of dispatchable energy during peak pricing intervals. This suggests that the hybrid system can offer superior long-term financial sustainability by capturing higher market value despite higher generation costs.

The project's net present value (NPV) is $3,071,581,696, demonstrating positive financial attractiveness under the modeled conditions. Additionally, the model calculates an internal rate of return (IRR) achieved in year 20. The end-of-project IRR remains stable across the project lifespan. These metrics indicate that the hybrid configuration effectively balances the high upfront capital expenditure of the battery and wind components with the increased revenue streams from firm capacity and energy arbitrage. The capital structure consists of $1.295 billion total net capital cost, reflecting the high initial investment required for a tri-technology project. Financing is structured with approximately ($1.6 billion) financed through equity and 60% through debt. This capital mix is designed to mitigate the risks associated with the complex integration of storage and generation technologies, leveraging available incentives to attract the necessary equity investment.

Table 3: LCOE of Scenario 3

Project Metrics	
Total Year 1 generation	2,600,501,504 kWh
LCOE Levelized cost of energy nominal	3.98 ¢/kWh
LCOE Levelized cost of energy real	3.17 ¢/kWh
PPA price in Year 1	15.30 ¢/kWh
LPPA Levelized PPA price nominal	16.54 ¢/kWh
LPPA Levelized PPA price real	13.20 ¢/kWh
Net capital cost	$1,417,148,800
Equity	$-1,595,763,968
Size of debt	$3,012,912,640
Debt percent	212.60%

Developer Metrics	
IRR Developer internal rate of return	NaN
Year developer IRR is achieved	20
NPV Developer net present value	$3,071,581,696

The results show that the PV-Wind-Battery development is technically robust, producing 2.6TWh annually with a high degree of reliability. While the capital costs are higher than standalone solar, the hybrid system's ability to provide firm power and mitigate intermittency offers distinct strategic advantages, positioning it as a resilient asset in the evolving PJM grid landscape.

6.4 Fourth Scenario: PV-Battery

The third scenario modeled a utility-scale hybrid facility combining Solar PV and Battery Energy Storage Systems (BESS). This configuration was designed to leverage the generation profile of solar while utilizing storage to firm capacity and shift energy to high-value periods.

The simulation shows an annual AC energy output of 2.61 TWh in the first year. This corresponds to a combined capacity factor of 24.2%, which reflects the system's ability to store and dispatch energy. The system produced an energy yield of 1,740 kWh/kW. The inclusion of the battery component allowed for a reduction in curtailment and a smoother injection profile compared to the variable renewable-only cases.

Economically, the hybrid project presents a more complex cost structure due to the additional capital required for the battery storage technology. The nominal LCOE is 7.41 ¢/kWh, with a real LCOE of 5.92 ¢/kWh. While this LCOE is higher than the standalone PV scenario due to the battery storage costs, it remains competitive when compared to PJM's average wholesale market prices, particularly when accounting for the increased value of dispatchable energy during peak pricing intervals. This suggests that the hybrid system can offer superior long-term financial sustainability by capturing higher market value despite higher generation costs.

Table 4: LCOE of Scenario 4

Metric	Value
Annual AC energy in Year 1	2,606,726,144 kWh
DC capacity factor in Year 1	19.9%
Energy yield in Year 1	1,740 kWh/kW
Battery roundtrip efficiency	2.23%
Battery charge energy from system	99.9%
LCOE Levelized cost of energy nominal	7.41 ¢/kWh
LCOE Levelized cost of energy real	5.92 ¢/kWh
Electricity bill without system (year 1)	$86,127
Electricity bill with system (year 1)	$8,969
Net savings with system (year 1)	$77,157
Net present value	$-1,816,396,288
Simple payback period	NaN
Discounted payback period	NaN
Net capital cost	$3,592,864,000
Equity	$1,437,145,600
Debt	$2,155,718,400

The project's net present value (NPV) is -$1,816,396,288 million, demonstrating negative financial attractiveness under the modeled conditions without additional incentives or higher market revenue assumptions. Additionally, the model calculates an internal rate of return (IRR) of -3.26% in year 25. The end-of-project IRR remains stable at -3.26%. These metrics indicate that the hybrid configuration struggles to balance the high upfront capital expenditure of the battery components with the revenue streams from firm capacity and energy arbitrage under the current pricing inputs. The capital structure consists of $3.59 billion total net capital cost, reflecting the high initial investment required for a storage-integrated project. Financing is structured with approximately 82.6% financed through equity ($1.44 billion) and 17.4% through debt ($2.163 billion). This capital mix is designed to mitigate the risks associated with the complex integration of storage and generation technologies.

The results show that the PV-Battery development is technically robust, producing 2.61 TWh annually with a high degree of reliability. While the capital costs are higher than standalone solar, the hybrid system's ability to provide firm power and mitigate intermittency offers distinct strategic advantages, positioning it as a resilient asset in the evolving PJM grid landscape.

6.5 Comparative Analysis & Strategic Recommendations for 1.2 GW Data Center Support

To support a 1.2 GW data center in the PECO region of the PJM interconnection a load profile characterized by flat, critical, 24/7 demand we compared four distinct energy mix scenarios: PV (Incentivized), PV (Unincentivized), PV + Battery, and PV + Wind + Battery.

6.5.1 Optimal Energy Mix for Data Center Reliability

Data centers require "five-nines" (99.999%) reliability [40]. A standalone solar facility, regardless of financial incentives, cannot meet this technical requirement due to its intermittent nature (generating only during daylight hours) and seasonal variability.

- Standalone PV (Incentivized & Unincentivized): While the incentivized PV scenario offers the lowest LCOE (1.57 ¢/kWh), it provides zero power for nearly 14 hours a day. Supporting a 1.2 GW continuous load would require PJM to supply 100% of the power from the grid during nights and cloudy periods, exposing the data center to volatile spot market prices and the carbon intensity of PJM's fossil-heavy baseload.

- PV + Battery: This scenario improves viability significantly. The 3.17 TWh annual output and storage capability allow for "firming" the solar generation shifting midday surplus to cover evening peak hours. However, limiting the generation source to solar alone requires massive, potentially cost-prohibitive battery sizing to survive multi-day cloud events or winter months with short daylight.
- PV + Wind + Battery (The Superior Choice): This tri-brid configuration is the most technically capable of supporting a hyperscale data center. Wind and solar profiles in the PJM region are largely complementary; wind generation often peaks at night and during winter months when solar irradiance is lowest. By coupling these with battery storage, the combined system achieves a higher "firm" capacity factor. It minimizes the reliance on grid imports and provides the steady, baseload-like profile required by the data center, making it the only viable standalone solution for critical infrastructure support.

6.5.2 Profit Maximization via Peak-Hour Dispatch

PJM Interconnection operates on a Locational Marginal Pricing (LMP) model, where electricity prices spike significantly during peak demand hours (typically 2:00 PM – 6:00 PM in summer and 7:00 AM – 9:00 AM / 5:00 PM – 9:00 PM in winter).

- The "As-Available" Flaw: A standalone PV system is a "price taker" that injects power when it is sunniest—often coinciding with low demand or oversupply, leading to depressed LMPs (or even negative pricing).
- The "Peak-Profit" Engine: By integrating storage (as in the PV+Battery and PV+Wind+Battery scenarios), PJM transforms the asset from a passive generator into an active market participant. The system can store low-cost solar energy generated at noon and discharge it during peak windows when LMPs are highest.
    - Example: Selling 1 MWh at noon might yield $25. Selling that same stored MWh at 5:00 PM could yield $80–$150.
- System-Wide Benefit: Since PJM pools generation, this dispatchability allows PJM to avoid firing up expensive, dirty "peaker" plants. Instead, it sells this high-margin renewable power to the market, drastically increasing the aggregate profit of the energy mix compared to selling a dedicated, non-firm PV supply.

6.5.3 Accelerating the PJM 2050 Renewable Targets

This project serves as a proof-of-concept that the PJM "Accelerated" transition scenario originally envisioned for 2050 is not only possible but necessary today.

- The Catalyst: The explosion of data center demand (like this 1.2 GW facility) has broken historical load growth models. Waiting until 2050 to deploy high-penetration renewables is no longer an option; the grid capacity is needed now.
- Strategic Imperative: By demonstrating that a PV + Wind + Battery hybrid system is economically viable (via peak arbitrage) and technically superior (via reliability), we provide the blueprint for PJM to fast-track its renewable integration. This approach effectively pulls the 2050 goals forward, proving that large-scale, firm renewable generation can anchor the grid's most demanding loads immediately, rather than in the distant future.

7. Barriers to Deployment

7.1 Regulatory Barriers

PJM has historically created obstacles for integrating renewable energy, particularly solar and storage. As of September 2022, over 238 gigawatts of renewable resources were waiting in the PJM interconnection queue, representing more than 95 percent of all queued projects [41]. Nationwide, interconnection delays have been a longstanding issue, prompting FERC to issue Order 2023 to reform the process [42]. The rule requires transmission providers to replace the traditional serial, first-come, first-served approach with a cluster-based, readiness-driven system. The new process includes stricter site-control requirements, cost-sharing for network upgrades, firm deadlines and penalties for studies, accommodation for co-located resources under a single request, and improved transparency through publicly accessible heatmaps [42]. These reforms aim to ensure that renewable and storage can connect to the grind in a timely and predictable manner.

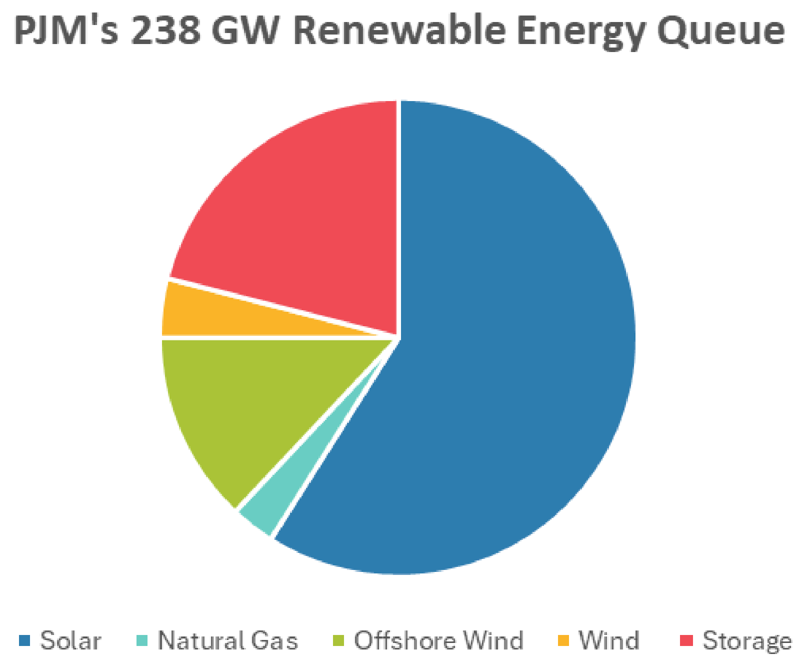

Figure 4: PJM's Renewable Energy Queue [41]

Despite these federal reforms, PJM has resisted full compliance. The operator has been granted "independent entity variations," allowing it to maintain long interconnection study timelines, avoid evaluating alternate transmission technologies such as batteries, and limit thorough analysis of storage behavior. These exemptions increase the risk, extend timelines, and raise costs for renewable and storage projects. PJM has also asserted that energy storage resources would draw power from the grid during peak periods, an assumption considered unrealistic by clean energy advocates. Recent exemptions within PJM's interconnection are highly consequential for the deployment of solar and storage projects. These exemptions permit PJM to maintain excessively long interconnection study timelines. Averaging 480 days compared to the FERC-mandated 150 days, while also avoiding the consideration of alternative transmission technologies such as grid-scale batteries. Furthermore, PJM's studies have been criticized for their limited and rushed assessment of storage resource behaviour. As a result, renewable and storage developers face prolonged uncertainty, higher project risks, and increased costs throughout the interconnection process. This continuation of outdated procedures has effectively created a bottleneck for clean energy deployment across the PJM region. Compounding these challenges, PJM has relied on unrealistic assumptions regarding the operation of energy storage, including the notion that storage systems will charge from the grid during peak demand periods when electricity prices are highest [43]. This assumption undermines the demonstrated flexibility and grid-balancing potential of storage technologies, further discouraging their integration.

A report by the Center on Global Energy Policy (CGEP) at Columbia University found that PJM is facing major bottlenecks in bringing new generation especially renewables and storage online fast enough to replace retiring plants. Despite reforms by FERC, 30 developers representing 69 projects, said that the top obstacles are the lengthy and uncertain interconnection process, siting and permitting delays, and financially, rising costs and volatile market conditions [43]. This "interconnection crisis" will continue to halt the clean energy transition unless PJM invests in transmission planning, adopting grid-enhancing technologies, and possibly shifting from the current "invest and connect" model to a more flexible "connect and manage" approach.

7.2 Transmission Planning

Clean energy developers and policy organizations such as EarthJustice, Rocky Mountain Institute, Sierra Club, and the Natural Resources Defense Council argue that PJM needs to implement drastic changes to how it plans and manages transmission to face this growing interconnection backlog. Similar to CGEP, they recommend that PJM shift from a reactive, study-heavy "invest and connect" model [44]. The main difference between these models is that the new proposed one would enable renewable and storage projects to come online sooner while grid improvements progress in parallel. Currently, it requires all network upgrades to be fully studied and built before new generators can connect. In tandem with this model, the utility needs to invest heavily in proactive, long-range transmission planning to anticipate where new renewable capacity will be built, rather than responding case by case to project requests. To achieve this, PJM should incorporate grid-enhancing technologies (GETs) such as advanced power flow controls, dynamic line ratings, and topology optimization to unlock existing transmission capacity and speed interconnection without massive new buildouts [44]. The technology for PJM to solve their interconnection crisis exists, but they need to commit to upgrading their grid before it is feasible to reduce delays integrating solar, wind, and battery storage projects, and ensure reliable replacement of retiring fossil-fuel plants.

PJM's failure to align its transmission planning with clean-energy mandates is especially concerning for states with ambitious clean energy targets such as New Jersey, Maryland, and Virginia. Over 80% of electricity load in PJM's territory is subject to state renewable portfolio standards or net-zero laws, yet PJM's current planning framework largely ignores these policies [45]. Its future resource mix to navigate the new load brought by data centers is dominated by fossil generation and treats state-driven clean-energy resources as optional projects that must secure separate funding through mechanisms like the State Agreement Approach. In other words, transmission investments are being planned for a future that does not reflect the actual trajectory of the energy transition. This connects to the other actions taken by PJM that are delaying renewable deployment. They are also de-incentivizing clean energy developers by forcing clean-energy states to either pay twice for fossil-focused upgrades and again for their own clean-energy transmission, or risk missing their statutory decarbonization targets.

7.3 Market barriers

Apart from economic and policy barriers, the PJM region has a complex market structure that was designed for fossil fuels, and are now creating reliability issues that impede the transition to renewables and storage. The first concern is that the retirement of large, dispatchable fossil-fuel plants is occurring at an accelerated pace due to regulatory pressure and aging infrastructure. PJM's CEO, Manu Asthana cited these resources as the pool of "stable generation" before adequate replacements are in place. These retiring plants were designed to provide grid inertia, firm capacity, and on-site fuel assurance. As they are pressured to retire these sources early, PJM will need to accommodate a generation portfolio dominated by variable resources including wind and solar, and battery storage technologies.

PJM's existing market constructs and reliability framework are tailored to fossil fuel generation, and not prepared for the rapid build-out of renewables and storage. The 2021 PJM "Reliability & Renewable Integration" study acknowledges that many essential reliability attributes such as frequency response, voltage support, short-min-run, fuel assurance were designed for fuel-based synchronous machines. The changing resource mix will require re-examination of existing market rules and reliability constructs to ensure adequate performance under a variety of conditions. PJM recognizes that intermittent renewables and storage challenge traditional capacity accreditation frameworks and that new modeling techniques (like ELCC) are essential for fair market participation and reliability assurance. This mismatch presents a barrier because renewables and storage must compete within market structures that undervalue their flexibility, ancillary services, and non-fuel reliability contributions [46].

Market reforms to reliably integrate renewables are especially vital as PJM is facing a "supply-demand" crunch, with rising electricity demand driven by electrification and data centers, coinciding with the impending retirement of roughly 40 GW of coal and gas generation by 2030 [47]. The region's capacity auction recently saw a nearly ten-fold price leap, underscoring the risk of instability for consumers. This drastic price volatility creates uncertainty for developers and investors, and signals a need for new infrastructure build-out.

Leaders in the energy industry argue that PJM's market, interconnection and transmission processes require fundamental redesign. Key recommendations include streamlining interconnection, fixing market rules to value flexibility (renewables, storage, demand response), integrating forward-looking transmission planning, and creating stable auction and regulatory frameworks to reduce investor uncertainty [48].

8. Policy Recommendations

The techno-economic analysis presented in this research demonstrates that solar-plus-storage systems are technically capable of meeting the demanding power requirements of hyperscale data centers within PJM. The PV + Wind + Battery configuration emerged as the only viable standalone solution capable of achieving the 99.999% reliability standard required by critical digital infrastructure, while offering competitive economics when policy incentives are available. However, the path from technical feasibility to deployed capacity is obstructed by a series of regulatory, market, and planning barriers that must be addressed through coordinated policy reform.

The recommendations that follow are organized by regulatory jurisdiction to reflect the multi-layered governance structure of PJM's electricity markets. Effective reform will require action at multiple levels simultaneously, from FERC's oversight of interconnection procedures and wholesale market rules, to PJM's operational and planning processes, to state-level tariff design and clean energy policy alignment. The urgency of these reforms is underscored by PJM's projection that 32 GW of new load will materialize by 2030, with 30 GW attributable to data centers, against a backdrop of interconnection queues that currently take an average of 480 days to process [49].

8.1 Interconnection Process Reform and FERC Order 2023 Compliance

The most immediate barrier to deploying the solar-plus-storage solutions identified in this research is PJM's interconnection process. Over 200 GW of renewable projects, which present 95% of all queued capacity, are waiting for grid connection, with study timelines averaging 480 days compared to the 150-day target established by FERC Order 2023. This backlog means that even projects demonstrating the favorable economics shown in our modeling (PV with incentives achieving an LCOE of 1.57 ¢/kWh) cannot reach commercial operation in time to serve near-term load growth.

FERC should reject PJM's remaining requests for "independent entity variations" from Order 2023 requirements and mandate full compliance. PJM's May 2024 compliance filing sought exemptions that would allow it to maintain excessively long study timelines, avoid evaluating battery storage as an alternative transmission technology, and continue using unrealistic assumptions about storage charging behavior. In July 2025, FERC ordered PJM to revise portions of its compliance plan, but significant gaps remain. The Commission should require PJM to adopt the 150-day study timeline, revise its storage charging assumptions to reflect actual operational behavior, and consider alternative transmission technologies in all interconnection studies.

The assumption that battery storage systems charge during peak demand periods is particularly problematic and directly contradicts the findings of this research. Our modeling demonstrates that storage enables load shifting and peak shaving because they store low-cost midday solar generation and discharge during high-value evening hours. Correcting this assumption would reduce the network upgrade costs assigned to storage projects and accelerate their path through the interconnection queue.

FERC should also establish meaningful penalties for study delays, with automatic financial consequences when PJM fails to meet deadlines. The current process places all timeline risk on developers, who must continue paying carrying costs while studies languish. Shifting some of this risk to the transmission provider would create incentives for process efficiency. Additionally, FERC should require PJM to implement automated study tools similar to those deployed in ERCOT and MISO, and establish quarterly reporting requirements on interconnection progress.

8.2 Transition to a Connect-and-Manage Framework

Beyond compliance with Order 2023's baseline requirements, PJM should pursue deeper interconnection reform by implementing a "connect and manage" pathway for projects seeking Energy Resource Interconnection Service (ERIS). Under the current "invest and connect" framework, renewable projects must wait for comprehensive network upgrade studies and, often, for those upgrades to be constructed before they can begin operating. This approach was designed for a grid dominated by large thermal plants with long development timelines, not for modular renewable resources that can be deployed in months.

ERCOT's experience demonstrates the viability of an alternative approach. Under its connect-and-manage framework, ERCOT connected 22.5 GW of new capacity between January 2024 and late 2025—75% more than MISO achieved over the previous five years. The Texas grid operator limits interconnection studies to local upgrade requirements and allows generators to accept curtailment risk in exchange for expedited connection. In 2022, ERCOT curtailed approximately 9% of utility-scale solar and 5% of wind generation—levels that most developers have judged acceptable given the faster path to revenue. Average ERCOT interconnection timelines are one to two years, compared to four or more years in PJM.

PJM could implement a hybrid framework that preserves the existing Network Resource Interconnection Service (NRIS) pathway for resources seeking full deliverability and capacity market eligibility, while establishing an accelerated ERIS pathway that focuses only on local upgrades. Projects choosing the ERIS path would accept curtailment risk during periods of transmission congestion but could begin operating years earlier than under current procedures. This approach would be particularly valuable for solar-plus-storage projects, which can use their storage component to shift generation away from congested periods and capture higher-value dispatch windows. PJM should publish real-time curtailment forecasts by zone so developers can make informed decisions about which pathway best suits their project economics.

Our scenario modeling supports the feasibility of this approach within PJM. Solar and hybrid systems can reliably meet the 1.2 GW of new data center demand projected for the PECO region, with seasonal variability that can be managed through storage dispatch and geographic diversity across PJM's 369,000-square-mile footprint. The main constraint is not intermittency risk, but infrastructure connection delays.

8.3 Grid Enhancing Technologies as Standard Alternatives

A significant portion of interconnection delays and costs stem from the need for network upgrades to address transmission constraints. Traditional solutions such as reconductoring lines, building new substations, or constructing entirely new transmission corridors, are expensive and time-consuming, often requiring years of permitting and construction. Grid Enhancing Technologies (GETs) offer a faster and more cost-effective alternative for many constraints, yet PJM does not routinely consider them in interconnection studies.

GETs include three primary technologies: dynamic line ratings (DLRs) that measure real-time transmission capacity based on weather conditions rather than conservative static assumptions; advanced power flow controls that actively manage how electricity flows across parallel paths in the network; and topology optimization software that identifies beneficial switching actions to relieve congestion. A February 2024 study by RMI and Quanta Technology examined the potential for these technologies across five PJM states Illinois, Indiana, Ohio, Pennsylvania, and Virginia and found that deploying GETs could facilitate interconnection for 6.6 GW of queued clean energy projects by 2027 [50].

The contrast with traditional upgrades is stark. In some scenarios examined by the RMI study, GETs would cost a few million dollars to resolve constraints that would require hundreds of millions of dollars in traditional infrastructure. For project developers who bear interconnection upgrade costs, these savings could mean the difference between a viable project and an abandoned one. Pennsylvania utilities have already demonstrated the effectiveness of GETs in practice. PPL Electric Utilities' deployment of dynamic line ratings eliminated $12 million in congestion during summer 2022 and reduced congestion on another line from approximately $66 million to $1.6 million. During Winter Storm Elliott in December 2022, DLR systems provided higher ratings than the ambient-adjusted ratings PJM would otherwise have used, allowing the grid operator to avoid costly emergency redispatch actions.

FERC should require PJM to evaluate GETs as standard alternatives in all interconnection studies, with a cost-effectiveness threshold: when GETs can resolve a constraint at significantly lower cost than traditional upgrades, the GET solution should be offered as the preferred option. PJM should also develop standardized protocols for incorporating GET capabilities into cluster studies and create publicly available maps showing where deployments would yield the greatest interconnection benefits. State utility regulators can support this transition by establishing performance incentive mechanisms that reward utilities for deploying GETs and allow them to share in the ratepayer savings these technologies produce.

8.4 Capacity Market Reform to Value Storage and Flexibility

PJM's capacity market, the Reliability Pricing Model, was designed around the operational characteristics of thermal power plants. These are resources with high fixed costs, relatively predictable availability, and the ability to provide firm capacity on demand. Battery storage and renewable-plus-storage hybrids operate quite differently, providing value through flexibility, fast response, and the ability to shift energy across time. The current market structure systematically undervalues these contributions, creating a barrier to the deployment of the hybrid systems that our research identifies as optimal for serving data center loads.

Our modeling reveals an important insight about battery economics. While the PV + Battery scenario shows a higher LCOE (7.41 ¢/kWh nominal) than standalone PV, this metric fails to capture the full value that storage provides. Batteries enable peak-hour dispatch optimization, allowing operators to store solar energy generated at midday when prices in

PJM often fall to $25/MWh or below and discharge during evening peaks when locational marginal prices can reach $80 to $150/MWh. This price arbitrage generates significantly more revenue than the LCOE comparison suggests. Storage also provides frequency regulation (already a primary revenue stream for battery projects in PJM), voltage support, and the ability to avoid dispatching expensive gas-fired peaker plants during high-demand periods. PJM's 2021 "Reliability & Renewable Integration" study acknowledged that essential reliability attributes such as frequency response, voltage support, and short-duration reserves were designed for fuel-based synchronous machines and require re-examination as the resource mix evolves [51].

PJM should implement several reforms to better value storage and flexibility. The ELCC methodology should be refined to create duration-differentiated classes that recognize the increased reliability value of longer-duration storage systems. A four-hour battery provides meaningfully different reliability contributions than an eight-hour system, yet current accreditation methods do not fully capture this distinction. Solar-plus-storage and wind-plus-storage hybrids should be able to receive capacity accreditation based on their combined firm output capability, not just individual component ratings. The PV + Wind + Battery scenario in our modeling achieves a 45.8% combined capacity factor precisely because wind and solar generation profiles are complementary in the PJM region. PJM should also create dedicated flexibility products in its ancillary services markets that compensate fast-responding resources for their ramping capability, particularly during the morning and evening transitions when solar output changes rapidly. California ISO has implemented several of these reforms that could serve as models for PJM, including storage duration requirements for resource adequacy and market products for flexible ramping.

8.5 Clean Transition Tariffs for Large Load Customers

The rapid growth of data center demand in PJM raises important questions about cost allocation and rate design. Data centers are projected to add 30 GW of load by 2030, driving unprecedented investment in generation and transmission infrastructure. If the costs of this investment are socialized across all ratepayers, residential customers will bear a disproportionate burden for infrastructure built primarily to serve large commercial facilities. The Institute for Energy Economics and Financial Analysis found that projected data center growth was a primary factor in PJM's July 2024 capacity auction clearing at nearly ten times the previous year's price [52]. The Harvard Environmental Law Program estimated that data center-driven costs could reach $163 billion across the PJM region, averaging approximately $70 per month in additional costs for typical households [53].

State public utility commissions should establish "Clean Transition Tariffs" that require large data center developers to directly procure or fund renewable generation and storage proportional to their load. This approach serves multiple objectives simultaneously: it ensures that data center growth supports rather than impedes clean energy deployment, protects residential ratepayers from bearing costs they did not create, and provides stable demand signals that can accelerate renewable project development.

The core elements of such tariffs should include renewable procurement requirements that obligate data centers to obtain renewable energy certificates from new-build projects located within PJM, with a significant portion (at least 50%) coming from solar-plus-storage or wind-plus-storage hybrid projects that provide firm capacity. Our modeling demonstrates that data center loads can only be served by hybrid configurations; standalone solar cannot meet these requirements due to intermittency. Requiring hybrid procurement aligns the procurement mandate with technical necessity. Tariffs should also include capacity cost provisions requiring data centers to pay capacity charges based on 90% of their maximum demand rather than average load, reflecting the infrastructure sizing required to serve their peak requirements. Additionally, data centers should be required to pay the full cost of transmission upgrades necessary for their interconnection, preventing socialization of these costs to other customers. Annual disclosure of projected load growth, emissions intensity, and renewable procurement progress would enable proactive planning and public accountability.

This approach has precedent and growing political support. The 2024 settlement involving Indiana Michigan Power Company required large load customers exceeding 150 MW to pay monthly minimums equal to 90% of their committed capacity and commit to developing a clean transition tariff [54]. In November 2025, a bipartisan coalition of state legislators from across PJM submitted a proposal to the PJM board calling for data centers to pay for their own electricity demand and associated infrastructure.

8.6 Aligning Transmission Planning with State Clean Energy Mandates

Over 80% of electricity load within PJM's footprint is subject to state renewable portfolio standards or net-zero mandates, with most states targeting 50-100% clean electricity by 2040-2050 [55]. Yet PJM's current transmission planning framework treats these policies as optional considerations rather than binding planning inputs. The result is a fundamental misalignment: transmission investments are being planned for a fossil-fuel-dominated future that does not reflect the actual trajectory of the energy transition.

PJM's Regional Transmission Expansion Plan currently distinguishes between "baseline" reliability projects, which are allocated regionally, and "public policy" projects under the State Agreement Approach, which must be funded by the states that request them. This structure effectively forces clean-energy-leading states to pay twice—first for transmission built to serve a fossil-dominated baseline, and again for transmission needed to meet their own policy requirements. States with ambitious clean energy goals are disadvantaged relative to states without such policies, creating a disincentive for climate leadership.

PJM should restructure its planning process to incorporate state clean energy mandates as binding inputs to baseline scenarios, not optional supplements. The "Accelerated" scenario in our modeling which reflects the generation mix that would result if current state policies are fully implemented demonstrates that policy ambition dramatically reshapes future power flows and transmission needs. The PV + Wind + Battery configuration that emerged as optimal in our analysis achieves its high effective capacity factor by leveraging the complementary generation profiles of wind and solar across PJM's geographic footprint. Realizing these synergies at scale requires a transmission system designed to move renewable energy from resource-rich areas to load centers, particularly the data center clusters concentrated in Northern Virginia and parts of Pennsylvania.

The State Agreement Approach should be reformed to enable multi-state coordination and shared cost allocation. New Jersey has pioneered this approach through its offshore wind transmission solicitations, working with PJM to identify transmission solutions that serve the state's renewable energy goals. Other states should follow this model, coordinating through the Organization of PJM States to pursue joint transmission procurements that leverage geographic diversity and avoid duplicative investments. Planning horizons should extend to at least 20 years to match the timeline of state decarbonization mandates, and PJM should integrate insights from interconnection cluster studies to identify transmission investments that would unlock the greatest volume of queued renewable capacity.

8.7 Coordinated Data Center and Renewable Energy Development

The current approach to data center siting results in clustered development in areas like Northern Virginia without regard to transmission capacity or renewable resource quality. This pattern maximizes stress on the existing grid while missing opportunities to co-locate data center loads with renewable generation in ways that could reduce net transmission requirements.

PJM and its member states should implement coordinated planning for "Data Center-Renewable Energy Clusters" that strategically co-locate large loads with solar, wind, and storage resources in transmission-advantaged locations. The optimal sites for such clusters would combine high-quality renewable resources (strong solar irradiance or wind capacity factors), available or readily expandable transmission capacity, existing grid infrastructure from retiring thermal plants, and supportive state policy environments. Retiring coal and gas plant sites are particularly promising because they offer existing high-voltage connections, brownfield land suitable for solar and storage development, transmission rights-of-way for potential capacity expansion, and experienced utility workforces.

Our modeling focused on the PECO service territory, where approximately 1.2 GW of new data center demand is projected over the near term. The analysis demonstrates that deploying 1.5 GW of solar with battery storage in this region can reliably serve data center loads while generating surplus energy for the broader grid. This finding supports the cluster concept: rather than scattering data centers across the PJM footprint and requiring massive transmission expansion to serve each individually, coordinated clusters can internalize generation-load matching and minimize net transmission requirements. The 2025 analysis finding that PJM could fast-track 102 GW of solar by utilizing existing but underused interconnection points provides a roadmap for identifying optimal cluster locations.

State economic development agencies should condition data center tax incentives on location within designated renewable energy zones and offer enhanced incentives for facilities that co-locate with renewable generation or commit to direct renewable procurement. Utilities should incorporate cluster planning into their integrated resource plans, identifying optimal locations for combined development and potentially pre-investing in transmission capacity for designated zones. PJM should designate "Renewable Energy Ready Zones" based on resource quality, transmission availability, and state policy support, and provide streamlined interconnection processes for projects within these zones.

9. Broader Implications

9.1 North America Implications

The findings of this study extend beyond the PJM Interconnection and have broad relevance for other North American wholesale electricity markets experiencing rapid load growth, accelerated decarbonization mandates, and increasing penetration of variable renewable energy resources. Regional transmission organizations (RTOs) and independent system operators (ISOs) such as CAISO, ERCOT, NYISO, and MISO face parallel challenges related to interconnection backlogs, transmission constraints, and the need to integrate large-scale renewable and storage resources while maintaining reliability.

The techno-economic results demonstrate that hybrid renewable systems—particularly configurations combining solar, wind, and battery storage—can provide firm, dispatchable power capable of supporting large, inflexible loads such as hyperscale data centers. This finding is directly applicable to regions like ERCOT, which faces extreme load growth from data centers and electrification but lacks a centralized capacity market, and CAISO, where solar oversupply and evening ramping challenges mirror PJM's emerging reliability concerns. The ability of hybrid systems to shift energy across time and seasons suggests that similar portfolios could reduce dependence on fossil-based peaker plants and mitigate price volatility across multiple market designs. The policy analysis underscores the importance of aligning transmission planning and interconnection processes with state and regional climate mandates. Many jurisdictions outside PJM are grappling with the same misalignment between legally binding clean energy targets and planning assumptions that continue to prioritize fossil fuel resources. The recommendation to integrate Renewable Portfolio Standards (RPS) and net-zero targets directly into transmission and resource planning scenarios offers a transferable framework that could improve planning accuracy and reduce stranded-asset risk across multiple grids.

The study highlights systemic market design challenges that undervalue flexibility, fast-response capability, and non-fuel-based reliability services. Markets such as NYISO and MISO are already exploring reforms to capacity accreditation and ancillary service valuation, and the modeling results presented here provide empirical support for accelerating those reforms. The demonstrated value of storage in providing frequency regulation, voltage support, and peak capacity reinforces the need for market rules that reward performance-based reliability rather than fuel type. The concept of "clean transition tariffs" and direct procurement requirements for large loads has broader applicability as data centers, hydrogen production, and electrified industrial facilities expand across North America. Requiring large new loads to internalize the cost of their incremental energy and infrastructure needs can protect residential customers, reduce political resistance to grid investment, and accelerate clean energy deployment in multiple regions simultaneously.

9.2 Global Implications

Global Implications of This Research

The results of this study have implications that extend well beyond the PJM Interconnection and are relevant to power systems globally. Electricity systems around the world are facing rapid demand growth driven by data centers, electrification, and digital infrastructure, while simultaneously being expected to meet increasingly ambitious climate targets. The experience examined in this research illustrates that the core challenges confronting PJM are not unique, but rather reflect structural issues present in many modern electricity markets. A central finding of this work is that large-scale renewable systems, when designed as hybrid portfolios combining solar, wind, and battery storage, can reliably serve continuous and high-priority electricity loads. This challenges the prevailing assumption in many jurisdictions that critical infrastructure must rely on fossil-fueled baseload generation. The modeling results show that reliability can be achieved through complementary resource profiles and storage rather than through fuel-based generation, a conclusion that is directly applicable to regions pursuing deep decarbonization while maintaining system security.

Transmission access and interconnection delays represent a major global constraint on renewable deployment, and the PJM case highlights how procedural and planning barriers can become more restrictive than technical limitations. Many regions, including parts of Europe, Asia, and the Global South, face similar challenges where renewable projects are delayed by lengthy studies and insufficient transmission investment. The policy approaches evaluated in this research, including cluster-based interconnection, conditional approvals, and the use of grid-enhancing technologies, provide practical strategies that can be adapted to accelerate clean energy integration in diverse regulatory environments The study also underscores broader market design issues that arise when electricity markets continue to prioritize fossil-fuel attributes while undervaluing flexibility and fast-response capabilities. Battery storage and hybrid renewable systems provide essential services such as frequency control, voltage support, and peak capacity, yet these contributions are often insufficiently compensated. Aligning market rules with actual system performance is therefore a global priority, particularly as conventional thermal generation retires and renewable penetration increases.

Rapid expansion of data centers is emerging as a global driver of electricity demand, and without targeted policy intervention this growth risks reinforcing fossil fuel dependence. The concept of requiring large loads to directly procure or fund renewable generation and storage offers a pathway to ensure that economic growth does not shift costs onto residential consumers or undermine climate objectives. This principle of cost causation and direct responsibility can be applied across jurisdictions with varying market structures. This research highlights a common challenge facing electricity systems worldwide: the pace of structural reform has not kept up with the pace of demand growth. The findings demonstrate that technical solutions already exist to deliver reliable, large-scale clean power, but regulatory and institutional frameworks must evolve more quickly to enable their deployment. Failure to do so risks higher costs, increased emissions, and reliability concerns, while timely reforms can allow renewable energy to serve as the backbone of future power systems.

10. Conclusion

The policy recommendations presented here are designed to address the specific barriers identified in this research while leveraging the demonstrated technical and economic viability of solar-plus-storage systems for meeting data center loads. The core insight from our modeling is that the technology works, PV + Wind + Battery hybrid systems can reliably meet hyperscale data center requirements with firm, dispatchable capacity and competitive economics. The barriers that remain are institutional rather than technical: interconnection backlogs that prevent projects from reaching commercial operation, market structures that undervalue storage and flexibility, transmission planning that ignores state clean energy mandates, and cost allocation frameworks that socialize data center infrastructure costs to residential ratepayers. These barriers can be addressed, but doing so will require coordinated action across multiple regulatory levels. FERC must enforce compliance with Order 2023 and consider deeper interconnection reforms. PJM must modernize its planning processes and market rules to reflect the capabilities of renewable and storage resources. State regulators and legislatures must establish tariff structures that align data center growth with clean energy deployment and protect residential customers from cost-shifting.

The urgency of these reforms cannot be overstated. PJM's July 2025 capacity auction cleared at nearly ten times the previous year's price, signaling that the region is approaching a supply-demand crunch. With over 150 GW of mostly renewable projects in the interconnection queue but only a fraction likely to reach completion under current processes, the gap between what is technically possible and what current institutions can deliver has never been wider. The recommendations in this section provide a pathway to close that gap—removing institutional barriers, aligning market rules with technical capabilities, and ensuring that the coming wave of data center development catalyzes rather than impedes the clean energy transition.

If implemented, these reforms would position PJM to meet its dual challenge of serving rapidly growing data center loads while achieving state-mandated decarbonization objectives. The research presented in this paper demonstrates that these goals are not in tension; with the right policy framework, reliability, affordability, and sustainability can advance together.

Initially, our research focus questioned whether renewable energy system integration could reliably meet the growing power demand of data centers within the PJM interconnection. The analysis presented throughout this paper along with previous studies conducted by PJM demonstrate that power demands can be met with renewable energy sources. The modeling results show that while standalone solar is insufficient to meet the operational requirements of data center loads, hybrid systems combining solar, wind, and battery storage meet these requirements.

The comparative scenario results between solar-only systems and hybrid systems reinforce our conclusion. Unlike hybrid systems, solar-only systems are limited by their inability to provide power during extended non-generating hours. Conversely, solar-wind-battery hybrid systems leverage complementary resources and provide a more stable and reliable supply that can support hyperscale data center loads while maintaining grid reliability.

The most important outcome of the findings of our modeling outcomes and literature research is that the remaining obstacles to deploying these systems at scale are not technological. These systems are not being taken advantage of because of institutional misalignment between PJM's interconnection processes, transmission planning framework, and market rules. Current market constructs prioritize traditional generation attributes while undervaluing flexibility, fast response, and energy shifting capabilities of renewables paired with storage.

The rapid expansion of data center demand is making this planning challenge visible to consumers, and reshaping PJM's reliability landscape and energy transition outlook. Without structural changes that allow renewable and storage projects to interconnect faster and capture their full market value, PJM risks deepening its reliance on fossil generation despite the availability of cleaner and more flexible alternatives.

Reliability, affordability, and decarbonization are possible to achieve in the PJM region, even under the extreme load demands associated with data center growth. Renewables can meet the most demanding reliability requirements on the grid, but must be enabled by appropriate policy frameworks. PJM has an opportunity to replace aging fossil fuel infrastructure with clean energy, and it is not a matter of technical feasibility. Our policy recommendations of reforms to interconnection processes, transmission planning, and market rules, have the capacity to accelerate the clean energy transition, and prevent PJM pursuing a more costly and carbon-intensive path.

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