Scaling Clean

Assessing Market Options for Clean Energy and Capacity in PJM

Report / March 2022

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Acronyms

ACRONYM	DEFINITION
ACP	Alternative Compliance Payment
ACR	Avoidable Cost Rate
CEAC	Clean Energy Attribute Credit
CO2	Carbon Dioxide
CONE	Cost of New Entry
E&AS	Energy and Ancillary Services
EFORd	Equivalent Demand Forced Outage Rate
ELCC	Effective Load Carrying Capability
FCEM	Forward Clean Energy Market
FERC	Federal Energy Regulatory Commission
FRR	Fixed Resource Requirement
GATS	Generation Attribute Tracking System
GW	Gigawatt
ICCM	Integrated Clean Capacity Market
LSE	Load Serving Entity
MCOE	Marginal Cost of Energy
MOPR	Minimum Offer Price Rule
MW	Megawatt
NREL ATB	National Renewable Energy Lab Annual Technology Baseline
OPSI	Organization of PJM States, Inc
PJM	PJM Interconnection
PPA	Power Purchase Agreement
PV	Photovoltaic
RASTF	Resource Adequacy Senior Task Force
REC	Renewable Energy Credit
RGGI	Regional Greenhouse Gas Initiative
RPM	Reliability Pricing Model
RPS	Renewable Portfolio Standard
RTO	Regional Transmission Organization
UCAP	Unforced Capacity
VOM	Variable Operations and Maintenance
ZEC	Zero Emission Credit

About RMI

RMI is an independent nonprofit founded in 1982 that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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Executive Summary

Spurred by state decarbonization policy, strong customer demand, and rapidly improving technology, carbon-free energy is playing a growing role in PJM, the United States' largest wholesale electricity market. However, the pace of PJM's energy transition is much too slow to avoid the worst impacts of climate change.[1] To accelerate and sustain decarbonization while retaining reliability and affordability, PJM will need to better incorporate and account for the capabilities and services of carbon-free resources in its markets.

Today, PJM is considering significant changes to its capacity market rules, including the creation of a voluntary clean energy market. In this report, we review two clean energy market designs under consideration, share analysis that clarifies the opportunities that clean energy markets provide, and make recommendations to PJM and its stakeholders as they consider next steps.

Our analysis considers how market participant behavior, technology carve-outs, and different levels of clean energy demand impact outcomes in three clean procurement options: today's decentralized clean energy procurement, a Forward Clean Energy Market (FCEM), and an Integrated Clean Capacity Market (ICCM). We find:

- Accounting for the capacity value of clean energy resources lowers costs and reduces emissions.
- If we assume all market actors accurately account for the capacity value of clean resources, the markets produce identical, "optimal" outcomes.
- State carve-out policies have meaningful cost and emissions implications that should be considered together with their benefits.
- If a centralized clean energy market helped attract new buyers, the increased voluntary demand would accelerate clean energy deployment and fossil asset retirement.

Based on our findings and conversations with stakeholders, we make the following recommendations:

1. **PJM and the Resource Adequacy Senior Task Force stakeholders should keep "clean procurement" in the task force's scope and pursue reforms that remove barriers to the participation of clean energy resources in the capacity market.** Our analysis shows that fully incorporating clean energy resources' capacity and energy contributions in PJM markets reduces system-wide costs and carbon emissions. Therefore, we believe that PJM and stakeholders should continue discussing clean procurement options together with the other "key work activities" that could improve how the markets account for clean energy's capacity value.

2. **States should collaboratively define a standardized clean energy product that can be competitively procured throughout PJM.** States have a lot to gain from meeting the bulk of their clean energy goals through a competitive, region-wide process. If state decision makers can agree on a common product definition for a clean energy credit (i.e., a CEAC), they can streamline clean energy credit transactions and likely lower costs and accelerate emissions reductions.

3. **A regional clean energy procurement process should foster participation from all potential buyers.** Our analysis shows that increased demand from voluntary buyers such as corporate customers and municipalities would meaningfully support clean energy deployment and accelerate PJM emissions reductions. However, to attract additional demand, the clean energy product must meet these buyers' needs.

4. **PJM and stakeholders should prioritize approaches that accelerate near-term decarbonization, can adapt to a more deeply decarbonized grid, and are politically feasible.** Both the FCEM and ICCM designs have the potential to secure multistate support, attract new buyers (and thus accelerate decarbonization), and lay a foundation for continuing to scale clean energy reliably. Importantly, by supporting efficient clean energy resource participation in PJM's markets, clean energy markets are also likely to lower both capacity costs and energy costs region-wide, benefiting states and buyers without clean energy goals.

Introduction

Today, the PJM Interconnection is convening a consequential stakeholder process to consider significant changes to its capacity market. The capacity market reforms being discussed in the Resource Adequacy Senior Task Force (RASTF) could either facilitate or frustrate decarbonization efforts in the region. PJM is the largest regional transmission organization (RTO) in the country in terms of peak load, and the second-largest in terms of carbon emissions. Therefore, the RASTF's decisions have important implications for the broader US energy transition.

Since their inception, restructured electricity markets have held the dual objectives of affordability and reliability. Now, the urgent need to mitigate climate change by reducing greenhouse gas emissions—enshrined in many state energy policies and increasingly central to federal policy—is forcing RTOs to consider another objective: decarbonization. In our view, this is required because electricity is a major source of emissions today and is almost certain to grow in importance as other energy sectors electrify to avoid burning fossil fuels in end uses. By ensuring their markets and grids enable rather than hinder decarbonization, RTOs could support both long-run market stability and clean energy deployment at the speed and scale required by the climate crisis.

Indeed, in February 2021, PJM CEO Manu Asthana highlighted the need for PJM's markets to facilitate decarbonization: "Recognizing the magnitude of the climate change issue and the unique position PJM holds and the role we fulfill, PJM will enable decarbonization efforts by policymakers and consumers in a reliable, cost-efficient manner utilizing at-scale, market-based solutions whenever possible."[2]

PJM and its stakeholders discussing capacity market reforms are partially motivated by the controversial and short-lived expansion of the Minimum Offer Price Rule (MOPR), which exposed a disconnect between state policy directives and regional market outcomes. The MOPR has since been scaled back, but as part of the RASTF discussions, PJM is considering new regional clean energy markets that would supplement or integrate with the existing capacity and energy markets.

Over the past year, we have been exploring whether a centralized clean energy market could help scale clean energy deployment in PJM, support reliability, and manage costs. We have strived to understand the key questions that stakeholders must weigh as they consider different market options. To that end, we have held many conversations with states, utilities, clean energy developers, companies interested in procuring clean energy, environmental advocates, and independent wholesale market experts. We also developed a tool to simulate different clean energy market designs, enabling us to study how the actions of market participants affect market outcomes.

In this report, we share our analysis and findings in order to clarify the opportunities and challenges of different regional clean energy market designs. We begin by highlighting the increasingly significant demand for clean energy in the region and the case for considering a regional clean energy market. We then outline how clean energy is procured today (the status quo), and the two centralized clean energy market design options: a Forward Clean Energy Market (FCEM) and an Integrated Clean Capacity Market (ICCM). Next, we share findings from our analysis based on simulations of clean energy and capacity procurement in each market design. Lastly, we provide recommendations based on our analysis and our conversations with diverse PJM stakeholders.

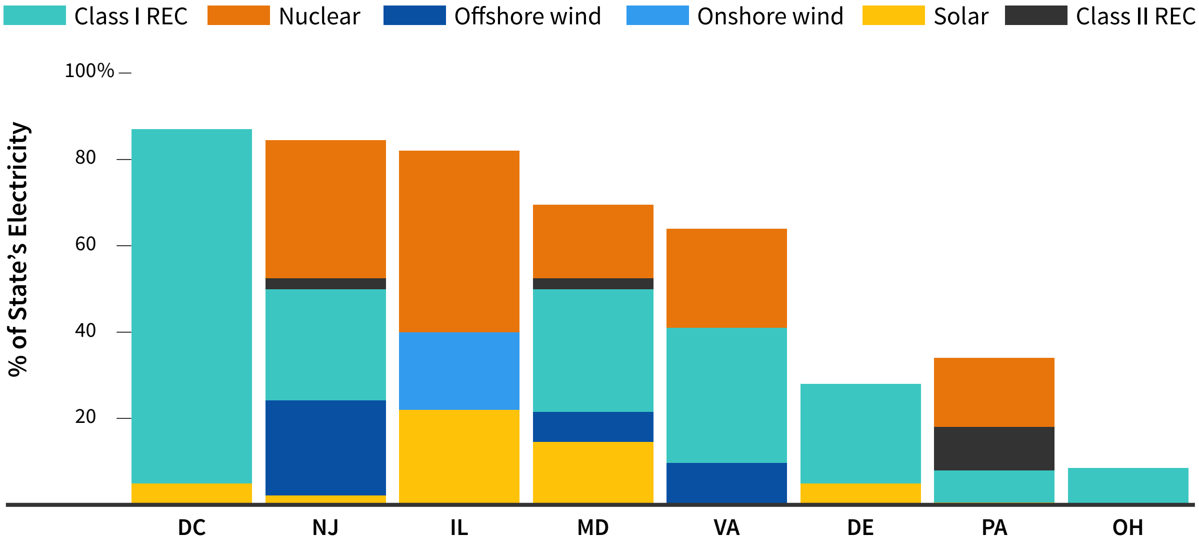
Clean Energy Goals in PJM and the Case for Considering a Centralized Market

Within PJM, nine states and Washington, D.C., have renewable portfolio standard (RPS) policies. In aggregate, the share of renewable energy required by these policies today represents 16% of PJM load. By 2030, existing state policies would require renewable energy in the region to account for 27% of load. These RPS policies direct the state's utilities, or load-serving entities (LSEs),[i] to meet yearly clean energy targets that are tracked by the purchase and retirement of renewable energy credits (RECs).

Increasingly, state clean energy and climate policies are ratcheting up in ambition, as demonstrated by Delaware and Illinois raising their RPS targets in 2021,[3] Pennsylvania moving toward joining the Regional Greenhouse Gas Initiative (RGGI),[4] and North Carolina mandating a 70% reduction in electricity sector emissions by 2030.[5] Several states in the region (Illinois now included) are targeting 100% clean electricity in the coming decades. Most state policies also include carve-outs for specific generation technologies like in-state renewables, offshore wind, nuclear, or community solar. These carve-outs reflect the various environmental, economic, or social benefits that such resources can deliver, including fostering economic development or advancing equity outcomes. Exhibit 1 shows a breakdown of state clean energy targets in PJM.

Exhibit 1

PJM states' renewable and carbon-free targets for 2030, based on current policy



Source: "Comparison of Renewable Portfolio Standards (RPS) Programs in PJM States," PJM, January 3, 2022, https://www.pjm-eis.com/-/media/pjm-eis/documents/rps-comparison.ashx

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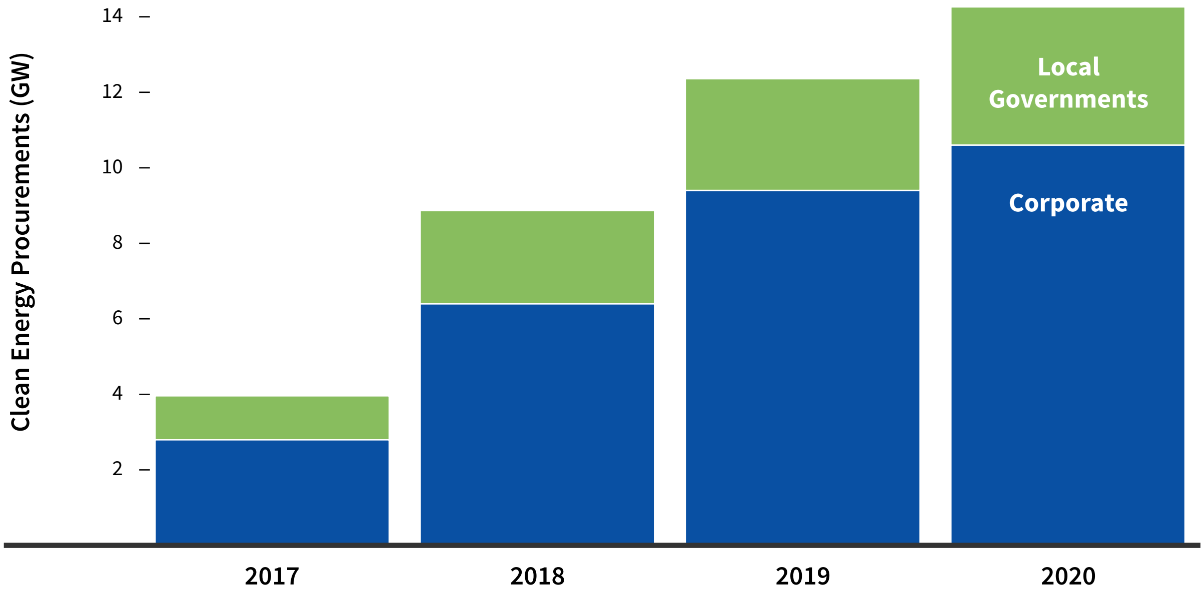
[i] LSEs are defined as all entities with state or local authority to serve end-use customers. LSEs include investor-owned utilities, electric cooperatives, public power providers, load aggregators, and power marketers.

In addition to states, corporations and local governments are increasingly demanding renewable electricity. As shown in Exhibit 2, commercial and industrial buyers in the United States procured 10.6 GW of renewables in 2020, and nearly 100 cities and counties across 33 states completed deals for another 3.7 GW, collectively helping to drive roughly one-third of the year's wind and solar capacity additions.[6]

Exhibit 2

Corporate and municipal renewable energy procurement in the United States, 2017–2020



Note: For comparison, there is approximately 15 GW of wind and solar energy nameplate capacity in PJM today.

As clean energy demand scales to larger and larger fractions of total PJM load, some stakeholders and analysts worry that the decentralized and "ad hoc" system of REC procurements currently in place will become impractical. Economist Paul Joskow suggests a need to "replace today's somewhat ad hoc approach to the selection of clean energy resource types with a rationally derived 'indicative plan' designed to work in conjunction with markets."[7]

From conversations with stakeholders and our own analysis, we identify the following challenges with today's ad hoc, decentralized system of procuring clean energy credits:

- **The many definitions of RECs limit competition and increase transaction costs.** Because most states with RPS goals have both specific carve-outs and different definitions for "Class 1" (or Tier 1) RECs, the clean energy market is separated into many different REC types. These smaller markets require additional regulation, reduce the number of buyers and sellers for each product, and increase procurement complexity. All of these factors tend to increase the costs to procure carbon-free electricity.

- **The capacity value of clean energy resources is not fully accounted for in procurement.** In conversations with market participants, we heard varying opinions about the extent to which clean energy project owners considered the capacity value of their projects. Today, all clean energy resources provide some capacity value, but this value—and how it is likely to evolve—is not well understood by all market participants. Some clean energy projects do not participate in the capacity market, and capacity market revenues are not always considered when negotiating bilateral contracts.

- **Procuring clean energy is more complex than it needs to be.** Today's bilateral contracts for bundled RECs and energy are complex and time-consuming to negotiate. While brokers and clearinghouses (and support from organizations like the Clean Energy Buyers Association) make the process manageable for many buyers, a "one-stop shop" clean energy market administered through a centralized auction would likely reduce barriers to entry.

To overcome these challenges, PJM is considering centralized clean energy market designs that would function at the regional level, alongside or integrated with existing RTO markets. In the next section, we describe the procurement pathways for the status quo, Forward Clean Energy Market, and Integrated Clean Capacity Market.

Overview of Clean Energy and Capacity Procurement in the Status Quo and Centralized Market Designs

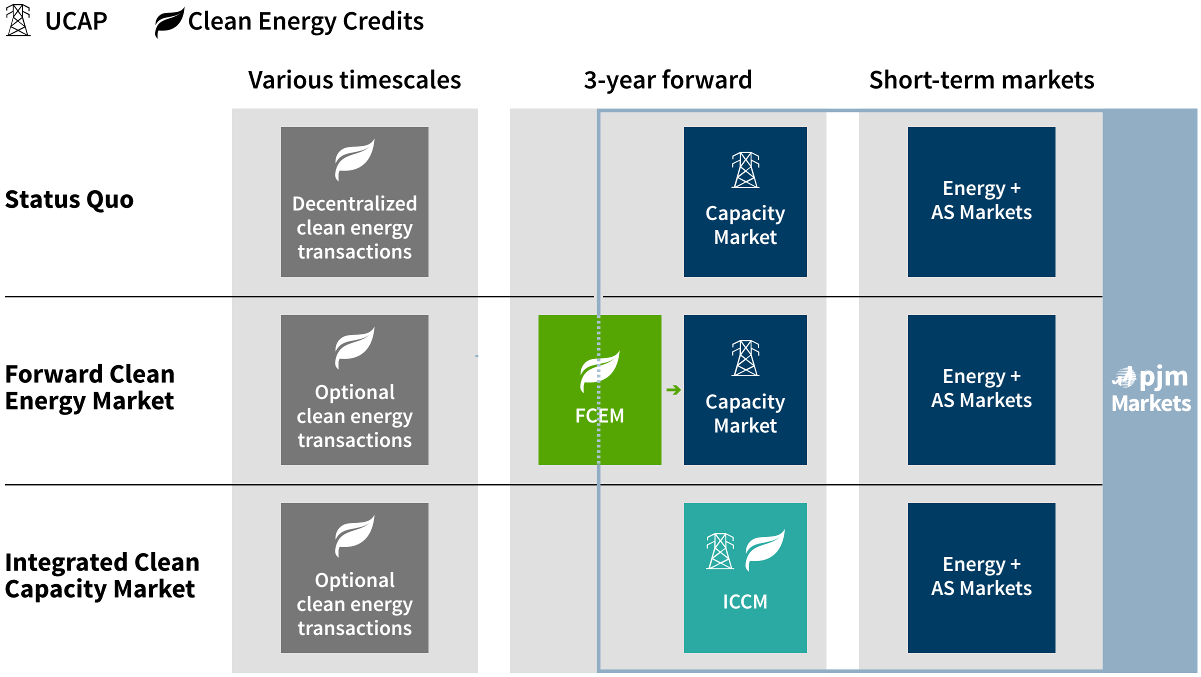
In this report, we consider three clean procurement options:

1. **Status quo:** Maintaining REC/ZEC procurements and the existing PJM capacity market
2. **FCEM:** Introducing a Forward Clean Energy Market and the existing PJM capacity market
3. **ICCM:** Introducing an Integrated Clean Capacity Market

Both the FCEM and ICCM introduce a forward market for clean energy credit procurement, linking it more closely (or directly) with the forward capacity market. In this section, we summarize each of these designs in more detail. Exhibit 3 provides a high-level overview and timeline of events for the three designs. We include additional depictions of the sequencing and procurement in each market design in Appendix A.

Exhibit 3

Overview of the three clean energy and capacity procurement pathways



Note: The markets in the 3-year forward and short-term columns are administered by PJM and under FERC jurisdiction; the FCEM has a dashed line through it to indicate that it could be administered either by PJM or by an independent entity.

Status Quo: Decentralized REC/ZEC Procurement

Clean Energy Procurement

Today, LSEs, corporate customers, and municipalities meet their clean energy targets by procuring RECs, zero emission credits (ZECs), or specific generation types (carve-outs) separately from the PJM markets. Typically, one REC is associated with 1 MWh of renewable electricity produced by an eligible generator (wind, solar, hydroelectric, and geothermal resources, most commonly). Each state with an RPS defines its own resource requirements for RECs and sets a target––or multiple targets for specific types of RECs — to procure.[8] To meet the RPS targets, states require their LSEs to procure appropriate types and quantities of RECs or pay an alternative compliance payment (ACP). Additionally, some PJM states compensate their nuclear generators for the zero-carbon electricity they provide by awarding them ZECs.

Clean energy buyers often contract bilaterally with developers or brokers for RECs. These RECs can be purchased on their own or bundled together with the energy that these projects generate. Contract lengths vary widely, from spot market trades to multiyear contracts to 20-year power purchase agreements (PPAs). Some RECs are procured through state-facilitated procurements, such as Maryland's offshore wind program. PJM's Generation Attributes Tracking System (GATS) tracks the purchase and retirements of RECs and also publicizes purchase requests and sale offers through its Bulletin Board. Third-party brokers and services facilitate the trading of RECs and help streamline PPAs between nonutility buyers and renewables developers.

Separately from REC sales, clean energy projects participate in the PJM capacity, energy, and ancillary service markets. Generally, the revenues from these markets flow either to the developer or, if the project has a PPA contract, to the purchaser of the PPA.

Capacity Procurement

PJM ensures there is sufficient capacity to maintain resource adequacy through its capacity market, the Reliability Pricing Model (RPM).[9] The RPM runs an annual three-year forward auction for unforced capacity, or UCAP,[ii] that clears resources needed to meet PJM's anticipated peak load plus a planning reserve margin.[iii]

Clean energy resources that have received REC or PPA contracts offer into the capacity market, together with other resources. If a clean energy supplier has signed a bilateral contract that meets its revenue requirements, it can be a capacity market "price taker" and offer at near zero. Some clean energy suppliers forgo participating in the capacity market because they would face penalties if they cannot meet their capacity obligation. All resources that clear are assigned a capacity commitment for the delivery year and paid the clearing price multiplied by their accredited capacity. PJM allocates the cost of the procured capacity to LSEs through a Locational Reliability Charge that accounts for the locational constraints associated with meeting reliability requirements in each part of the region.

[ii] Unforced capacity (UCAP) is a resource's accredited capacity in the PJM capacity market. UCAP values reflect a resource's installed capacity adjusted for its expected outage rate (EFORd) or "effective load carrying capability" (ELCC) in the case of renewables.

[iii] In practice, the PJM capacity auction has tended to procure more capacity resources than required, due in part to the downward-sloping demand curve.

Forward Clean Energy Market

Clean Energy Procurement

The Forward Clean Energy Market (FCEM) design, developed by the Brattle Group, introduces a voluntary, three-year forward regional market for clean energy attribute credits (CEACs) that would complement and partially replace today's REC procurement.[10] Like RECs, CEACs are envisioned as a product based on the emissions-free attributes (thus, inclusive of nuclear) associated with 1 MWh of clean electricity generation, separate from the capacity, energy, and ancillary service values. Critically, PJM stakeholders would need to agree on the specific CEAC definition and which generators would qualify. A logical starting point for this conversation could be Class 1 (or Tier 1) RECs, which have substantial overlap between states.

CEAC buyers would have a straightforward and simplified role in the FCEM: LSEs, corporate customers, and municipal buyers could choose to submit all or a portion of their demand for clean energy into the FCEM. As articulated in Brattle's design, the market administrator would use the aggregate regional demand to define a downward-sloping demand curve. Eligible suppliers would offer their CEACs at a competitive price. Through an annual centralized auction, the FCEM would clear the set of CEAC offers that meet the regional CEAC demand, allocating revenues to suppliers and costs to buyers. While commitments are envisioned to be annual, the FCEM could include a multiyear CEAC price lock-in for new resources. Another design option to consider (if nuclear were included in the product definition) is a potential cap on nuclear CEAC prices, as the ZEC subsidies that exist today are likely to be lower than CEAC clearing prices.[11]

Capacity Procurement

The FCEM is designed to precede the capacity market auction, which would remain unchanged. This back-to-back clean energy and capacity procurement offers two potential advantages: first, it may better enable resources to efficiently spread their costs between the FCEM and capacity market because they occur sequentially, thus incentivizing higher-capacity-value generators. Likely, clean energy suppliers with higher capacity value (and thus higher expected capacity market revenues) would offer into the FCEM at a lower price than resources with less capacity value. Second, it allows for more flexibility in implementation. Because the FCEM remains separate from the capacity market, any qualified organization could serve as the FCEM operator, including PJM, a PJM affiliate (similar to GATS), or a third party (similar to RGGI). Thus, implementing an FCEM may not require a FERC-approved tariff change.

Integrated Clean Capacity Market

Clean Energy and Capacity Procurement

The Integrated Clean Capacity Market (ICCM) design, also developed by the Brattle Group and further studied by the New Jersey Board of Public Utilities (BPU) in its Investigation of Resource Adequacy Alternatives, is a three-year forward market that would procure both CEACs and capacity simultaneously.[12] The market administrator would run a co-optimized auction clearing process to select the least-cost combination of resources that meets both clean energy and reliability requirements. The ICCM produces two clearing prices, one for CEACs (in $/MWh) and one for capacity (in $/MW UCAP-day), with revenues and costs allocated to sellers and buyers according to their bids.

As with the FCEM, CEAC demand bids would be optional, and LSEs, corporates, and municipal buyers could submit their desired level of CEAC demand into the market. LSE capacity obligations would be assigned according to the LSEs' share of regional load, as today.

On the supply side, generators that produce both CEACs and capacity would submit offers to supply both products at a single price, reflecting their going-forward costs for the delivery year, net of expected energy and ancillary service (E&AS) revenues. All cleared resources would be assigned CEAC and capacity obligations for the delivery year and paid: (1) the CEAC clearing price multiplied by the quantity of CEACs they offered (in MWh), and (2) the capacity clearing price multiplied by their accredited capacity (in MW UCAP). All other resources—coal and gas, as well as storage and demand response—would submit capacity offers as they do today and, if they clear, would only receive capacity revenues.[iv] As in the FCEM, CEAC revenues for nuclear facilities could be capped, possibly near today's ZEC prices.

With a combined auction for CEACs and capacity, the market can select the optimal resource mix that meets both objectives at least cost. This removes the need for clean energy suppliers to estimate revenues from one market to make efficient supply offers in the other. However, this integration also adds complexity and legal risk to the implementation pathway. An ICCM would require either a FERC-approved PJM tariff change or the creation of a new approach to resource adequacy through a multistate Fixed Resource Requirement (FRR).

Additionally, PJM has recently contemplated a market design with a "clean capacity constraint" in the RPM.[13] In this construct, LSEs could specify that a share of their capacity requirements must be met from qualifying "clean" capacity resources (including renewables, nuclear, storage, demand response, and energy efficiency). Due to time constraints, we have not analyzed this design but would expect additional analysis and discussion of the idea pending stakeholder interest.

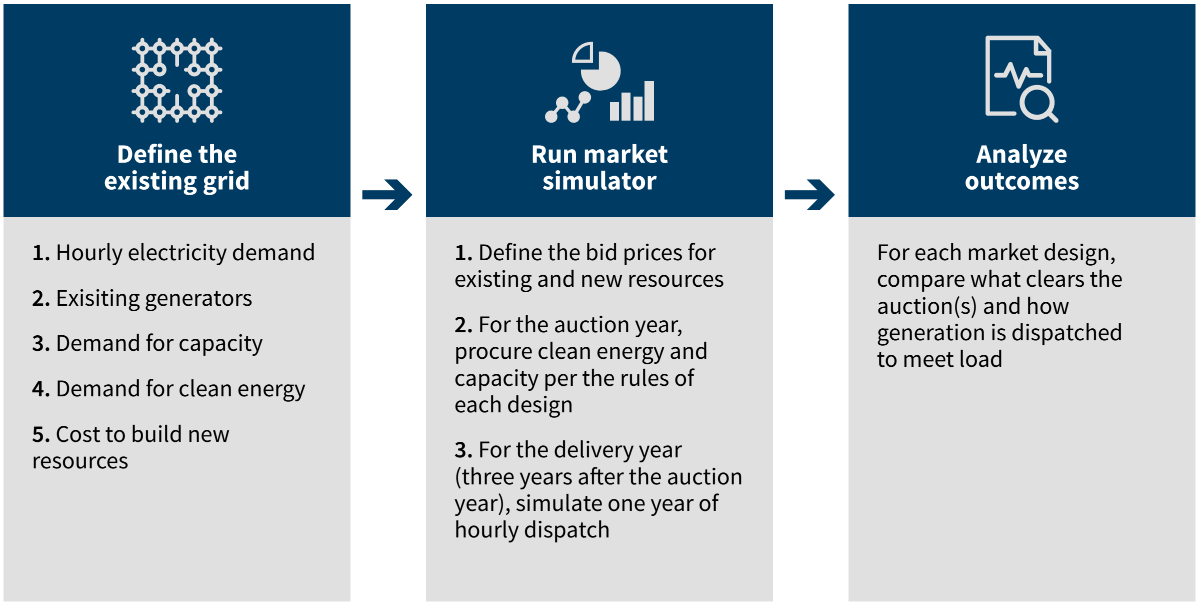
[iv] Most explorations of the ICCM do not allow batteries, energy efficiency, or demand response to submit offers for CEACs. In theory, it is possible to include these resources: batteries can charge from clean energy that would otherwise be curtailed and deliver additional clean energy to the grid, energy efficiency delivers the same emissions-free service as clean energy ("negawatt-hours"), and demand response can be used to reduce carbon dioxide emissions by shifting load away from hours when carbon-intensive resources (like coal) are running.

Insights from Simulations of Clean Energy and Capacity Procurement

To gain insight into how the status quo, FCEM, and ICCM would impact clean energy adoption and capacity market outcomes, we created a model that simulates each market design. In setting up the analysis, we developed assumptions for the modeled grid system, including technology costs, bidding behaviors, technology-specific carve-outs, and clean energy demand. For a given set of assumptions, the model provides resource-build, cost, and emissions outcomes in each market.

Exhibit 4

Process diagram for the clean energy and capacity market simulator



Define the existing grid

1. Hourly electricity demand
2. Exisiting generators
3. Demand for capacity
4. Demand for clean energy
5. Cost to build new resources

→

Run market simulator

1. Define the bid prices for existing and new resources
2. For the auction year, procure clean energy and capacity per the rules of each design
3. For the delivery year (three years after the auction year), simulate one year of hourly dispatch

→

Analyze outcomes

For each market design, compare what clears the auction(s) and how generation is dispatched to meet load

Defining the Grid

Before running our market simulator, we must characterize the existing grid, including electricity demand, system resources, and reliability and clean energy requirements.

- **Electricity demand:** We use the 2010 PJM hourly load profile, scaled so the peak is 152 GW, PJM's 2019 peak demand.[v]

- **Reliability requirement:** We set the regional reliability requirement (to be met by capacity procurement) equal to the system's peak load plus a reserve margin.[vi]

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[v] We use this older profile because we have hourly energy efficiency and demand response data for the same year.

[vi] We do not include locational constraints, which exist in PJM's RPM, which means our findings do not address the geographic considerations that also play a role in capacity procurement.

- **Existing resources:** We assume a set of resources that have already been built, in quantities proportional to PJM's grid mix. We assign these resources a UCAP value based on PJM's methodology, further detailed in Appendix B. These resources bid into the capacity and/or CEAC markets at their going-forward costs.

- **New resources:** We assume that new resources bid into the capacity and/or CEAC markets at their net cost of new entry (or Net CONE).[vii] See Appendices B and C for the full list of new resources included in this analysis, along with their costs.

- **Clean energy demand:** We set system-wide targets for a certain quantity of RECs and ZECs, or CEACs, by aggregating LSE, state, and voluntary demand.[viii] We define "clean energy" as energy that comes from non-emitting resources.

- **Carve-outs:** In one part of our analysis, we assume that there is a carve-out requirement for specific resources (see Finding 3 below).

Running the Market Simulator

All of the resources (generators) in our defined grid then participate in each market according to the market design's rules. Procurement occurs in the "auction year," and the cleared resource mix as well as energy dispatch reflects the "delivery year" (three years later). The market simulator performs the following functions:

- **Procuring clean energy credits (auction year):** Clean energy credits are procured per the rules of each market design, in sufficient quantities to meet our predetermined demand. In the status quo, clean energy credits match demand; in the FCEM and ICCM, the downward-sloping demand curve enables the goal to be exceeded when it is cost-effective to do so.

- **Procuring capacity (auction year):** Capacity is procured through a forward auction to satisfy the regional reliability requirement. For the status quo and FCEM, we assume that any new clean energy resources cleared to receive REC or CEAC payments are committed to being built and offer into the capacity market at zero (i.e., as a price taker).[ix] In the ICCM, capacity and clean energy are procured simultaneously through an integrated auction.

- **Simulating the energy market for the delivery year:** The cleared resource mix is input into a simple energy dispatch model to simulate hourly generation for the delivery year.

[vii] "Net" refers to net of expected E&AS revenue.

[viii] The clean energy target can be thought of as a system-wide clean electricity standard. Our target is intended to be a realistic, but not precise, reflection of demand that exists in the PJM region.

[ix] We recognize that it is a simplification to assume that all resources that win REC contracts or clear the FCEM will be price takers in the capacity market. However, we do not believe this materially impacts our findings.

Analyzing Outcomes

The market simulator results include:

- **Resource mix:** Which resources clear the capacity and/or CEAC markets and which retire
- **Cost:** REC/CEAC prices, capacity auction clearing prices, and total costs
- **Energy delivery:** Costs, emissions, and expected unserved energy metrics from the energy market simulation

In our analysis, the assumptions about market participant behavior make a material difference in the results. For example, in accounting for state carve-outs for specific resources, we must make assumptions about which specific resources states require (through carve-outs), the quantity of those carve-outs, and how close the resulting contracts reflect actual build costs. Similarly, in simulating centralized clean energy markets, we must make assumptions about whether LSEs and other buyers continue to rely primarily on REC procurements or shift to meeting much of their clean energy demand through CEACs. Because these assumptions are material to the outcomes of each simulation, our analysis cannot claim to reveal the "best" market design. However, by changing the sets of assumptions, our analysis does reveal the actions of market participants that are most consequential in the different market designs.

Our analysis builds on previous work from the Brattle Group and the New Jersey BPU in developing these centralized market design concepts by:

- Articulating the mechanics of each market design option through illustrative examples
- Highlighting the comparable outcomes that result when resources' clean energy and capacity values are accurately captured in these procurement processes, and the conditions in each market that enable these outcomes
- Exploring the impact that increased clean energy demand could have on the system

In Appendix B we describe our analysis and underlying assumptions in further detail.

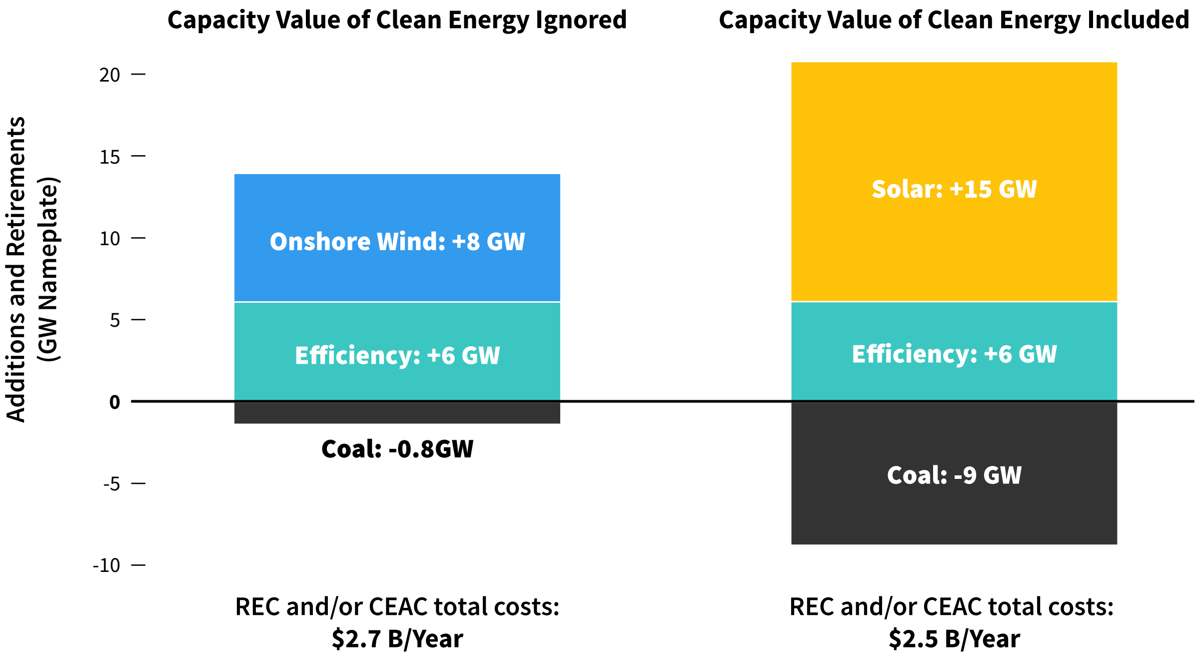
Finding 1: Accounting for the capacity value of clean energy resources lowers costs and reduces emissions.

In order to better understand the connection between clean energy procurement and the capacity market, we ran a simulation to compare scenarios in which the capacity value of clean energy resources is ignored versus accounted for. In the first scenario, we assume that clean energy suppliers price their clean energy credits anticipating $0 in capacity market revenues (reflecting a situation in which they would either not participate or not expect to clear the capacity market). In the second, we assume that clean energy suppliers correctly factor in $115/MW UCAP-day in capacity market revenues (the clearing price from our "optimal" simulation, discussed below) to their offers.

As shown in Exhibit 5, these assumptions change which resources clear the auctions. If clean energy suppliers assume no capacity market revenue, new wind is picked to provide clean energy credits in place of solar because wind produces energy at a lower cost.[x] If suppliers include capacity value in their offers, solar developers reduce their REC/CEAC offer prices more than wind developers, allowing solar to outcompete wind. Further, including clean energy resources' capacity value reduces total REC or CEAC costs by nearly 10%. Additionally, because solar provides more accredited capacity, the procured solar displaces substantially more existing fossil capacity in the capacity market.

Exhibit 5

Capacity additions and retirements for scenarios that ignored vs included clean energy resources' capacity value



This simulation points to a more general insight: system-wide capacity costs and emissions may decrease if more clean energy resources participate in the capacity market. Based on our analysis of data from the US Energy Information Administration (EIA) and PJM,[14] 7 GW of wind and solar in PJM were not receiving capacity revenues in 2020, representing approximately 30% of all wind and 90% of all solar resources online at the time. If these resources had cleared the capacity market, they would have displaced 2.7 GW of more expensive power plants (likely coal), which might then have been retired.[xi]

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[x] Wind's capacity value, however, is less than that of solar; in this simulation, the effective load carrying capability (ELCC) for wind is 0.15 and the ELCC for solar is 0.54. See Appendix B for a full description of our capacity accreditation methodology.

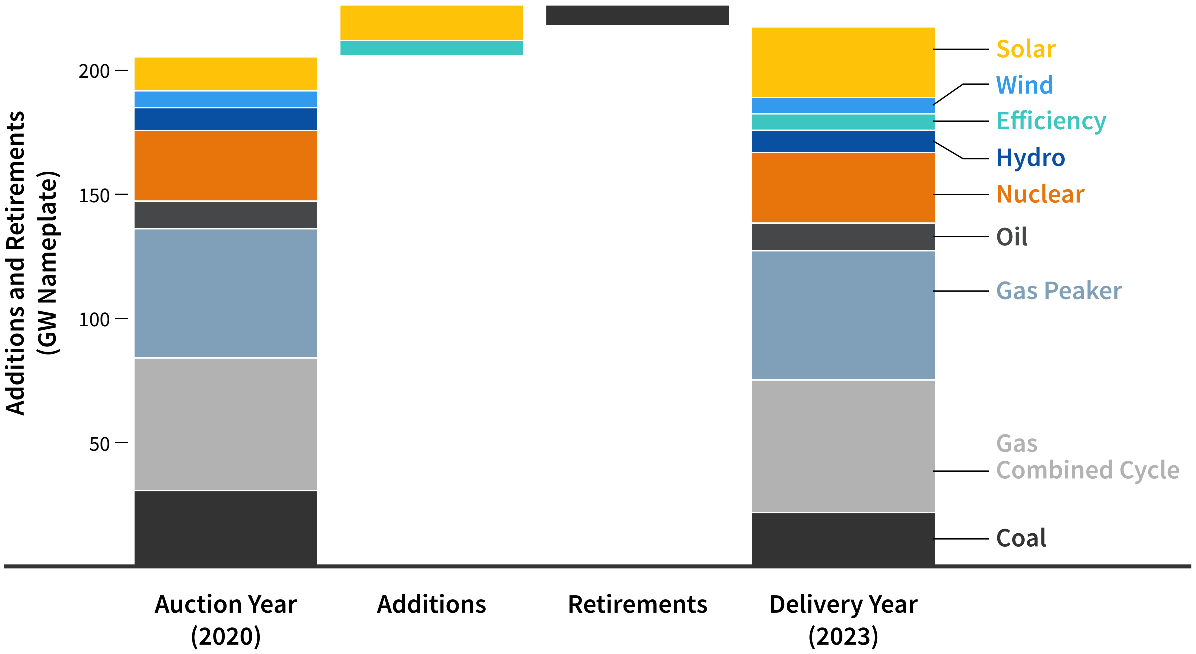
[xi] Existing generators may decide to continue operation even if they do not clear the capacity market.

Finding 2: If we assume market actors fully realize the capacity value of clean resources, the markets produce identical, "optimal" outcomes.

Today, PJM receives approximately 35% of its energy from clean (carbon-free) resources. In this simulation, we defined a grid with an existing generation mix similar to what exists in PJM today and set clean energy demand at 40% of the system's energy generation. Further, we assumed that FCEM bids and bilateral contracts (in the status quo) were made assuming capacity values identical to those chosen by the ICCM. **We find that with this assumption of perfect information and competitive behavior, all three markets produce identical results.** In Exhibit 6, we show the resulting capacity additions and retirements.

Exhibit 6

System capacity evolution resulting from a simulation run that increases clean energy from 35% to 40% of total delivered energy



Note: The bar on the left shows existing capacity in the modeled auction year, and the bar on the right shows the capacity after market-based additions and retirements.

The simulator finds that new solar is the most cost-effective clean energy resource in the near-term due to its relatively high capacity value and expected energy market revenues.[xii] The clean energy and capacity procurements select new solar and energy efficiency to meet the 40% clean energy target and the capacity requirement. New solar sets the REC and CEAC price at $16/MWh.[xiii] In the capacity market, coal is the marginal resource and sets the capacity market clearing price at $115/MW UCAP-day. One-third of the existing coal fleet does not clear and is retired.

We call this the "optimal" result because it satisfies both the clean energy and reliability requirements at the least cost (given our technology cost and capability assumptions). The enabling conditions for each

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[xii] As previously noted, we use PJM ELCC estimates for renewables, including solar. We expect both the ELCC and expected energy market revenues for solar to decline over time as more solar is added to the system.

[xiii] See Appendix C, Exhibit C1, for the specific price formation for REC, ZEC, and CEAC prices for this simulation.

market design to achieve this outcome are summarized in Exhibit 7 below.

Exhibit 7

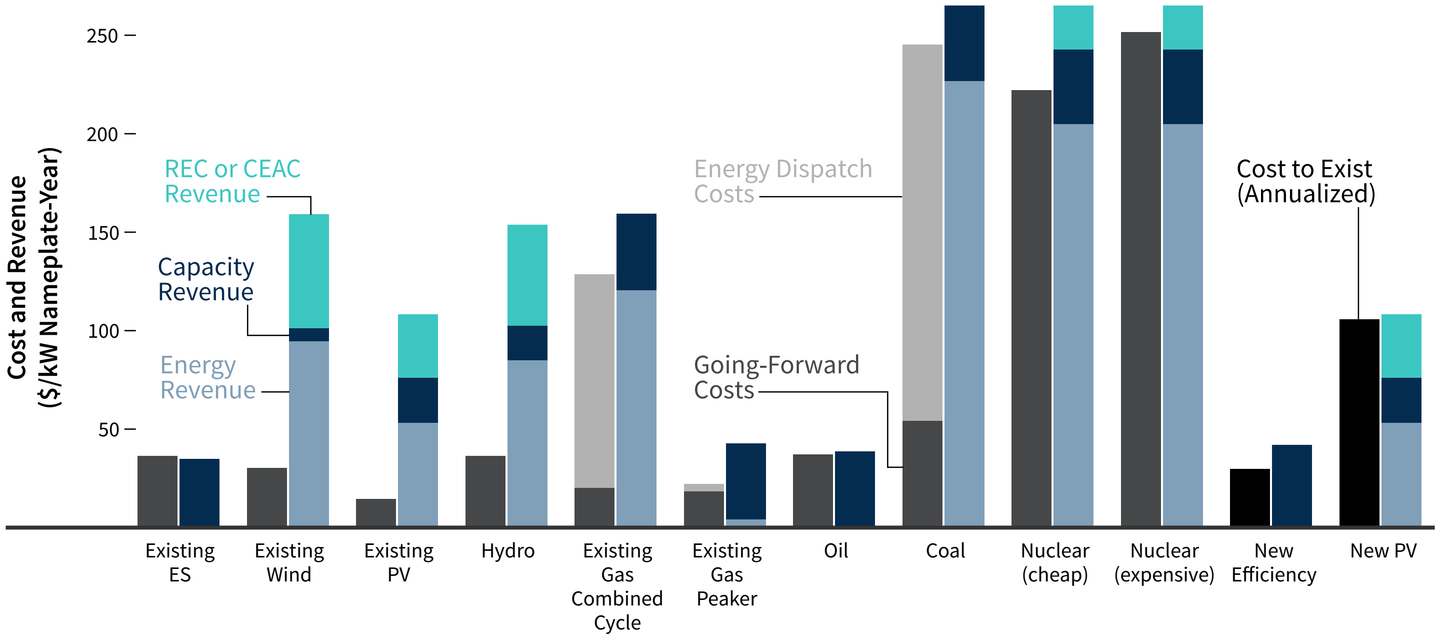
How each market design achieves "optimal" results

Market design	***How must market participants behave for this market to achieve clean energy and capacity targets at the least cost?***
Status quo	• Buyers must choose the least-cost REC and ZEC offers to meet their clean energy targets. • REC and ZEC suppliers must accurately predict their capacity market revenues and net these out of REC/ZEC offer prices.
FCEM	• Buyers must choose to meet their clean targets through CEAC purchases. • CEAC suppliers must accurately predict their capacity market revenues and net these out of CEAC offer prices.
ICCM	• Buyers must choose to meet the clean target through CEAC purchases.

Exhibit 8 shows the cost and revenue streams for each generator type that clears the auctions, and Exhibit 9 shows the total system costs, broken down by energy market, capacity market, and RECs, ZECs, or CEACs. Since the cleared resource mixes are identical across market designs, the costs are also the same.[xiv]

Exhibit 8

Annual costs and revenues for each resource that clears the capacity market

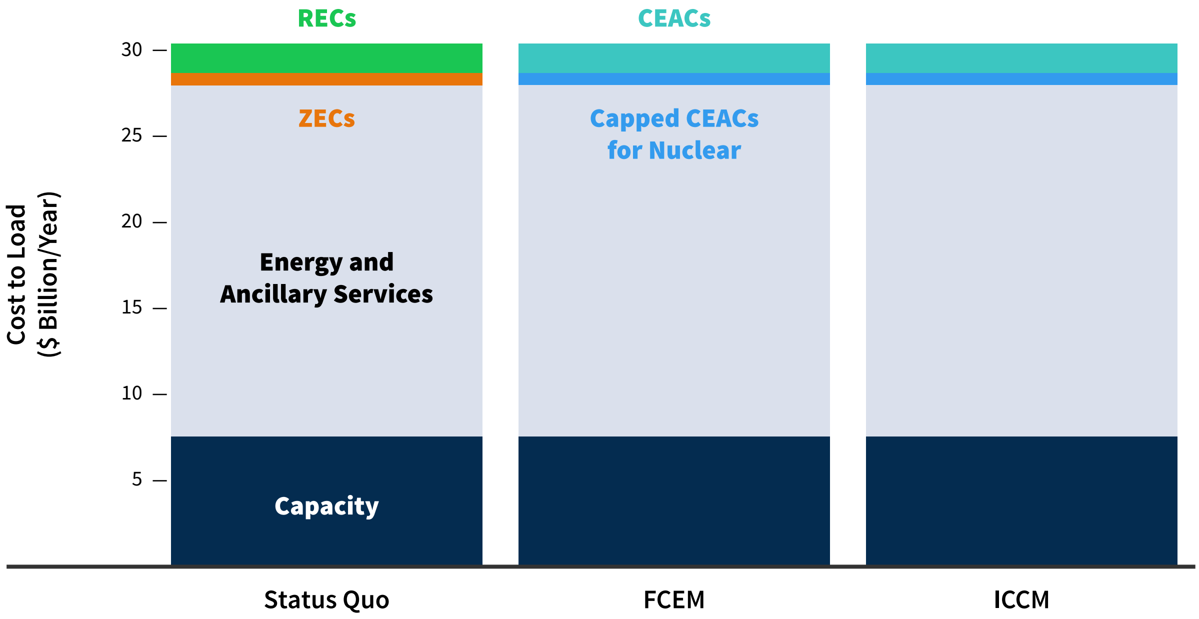


Note: The costs and revenues by market type for each resource shown in this figure are for 2023, the delivery year of the simulation. The profit or loss for each resource is the difference between the sum of the "cost" bars (left) and "revenue" bars (right). These values may change substantially in future years, especially in a higher-renewables grid with periods of low or even negative hourly energy prices and declining ELCCs.

[xiv] We enforce a price cap on CEAC payments for existing nuclear resources that is equal to the ZEC price of $3.17/MWh. This ZEC price is determined by following the price formation approach described in Appendix B using data provided in Appendix C. See Exhibit C1 for the exact formulation.

Exhibit 9

Total cost to load in each market design, assuming market participants have perfect information and act competitively



Finding 3: Carve-outs have meaningful cost and emissions implications that should be considered together with their benefits.

Most state RPS policies include carve-outs for specific generation types such as in-state solar or offshore wind. These carve-outs can serve valid and valuable policy goals. They also carry trade-offs due to their higher costs and, in some cases, limited capacity value, which we seek to surface here. To assess the cost and carbon emissions impact of carve-outs in comparison to a policy that procures only CEACs, we run three scenarios in a simulation of the ICCM:

1. **No carve-outs:** Only CEACs are procured to meet a 50% clean energy target.
2. **Limited carve-outs with a cost cap:** A mix of in-state solar carve-outs, offshore wind carve-outs, and CEACs are procured, with total costs capped at a comparable level to Scenario 1. In this simulation, the resulting grid is 40% clean.
3. **Full carve-outs without a cost cap:** A mix of carve-outs and CEACs are procured to meet a 50% clean energy target. The carve-out tranches are sized to reflect existing state policy.

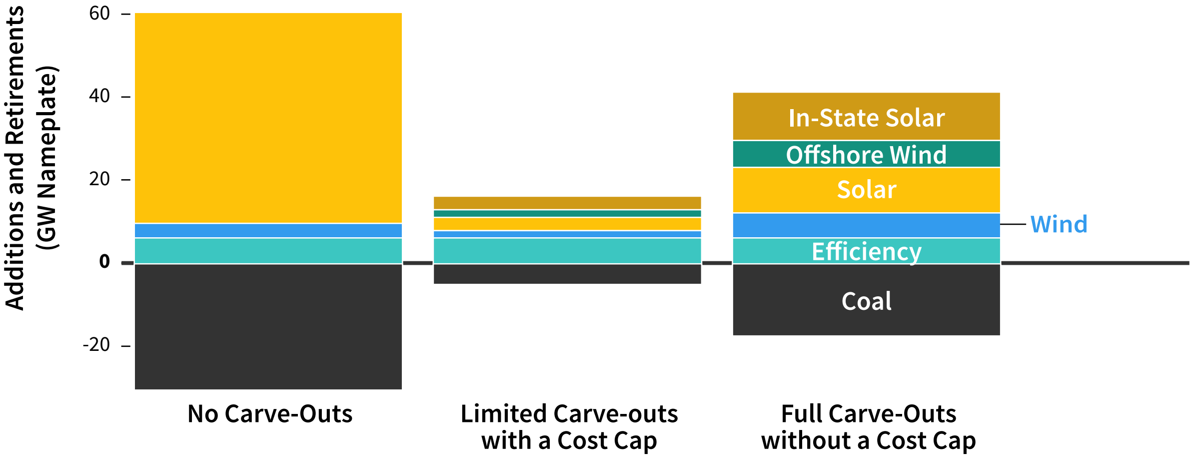
For this analysis, we assume that in-state solar and offshore wind subsidies are ~6X and ~5X higher, respectively, than the $16/MWh CEAC clearing price; this is consistent with the range of REC prices seen in PJM today.[xv] Exhibit 10 below shows the capacity additions and retirements, delivered energy, and clean energy and capacity procurement costs for each scenario.

[xv] See Exhibit C1 in Appendix C for the specific price formation for each resource.

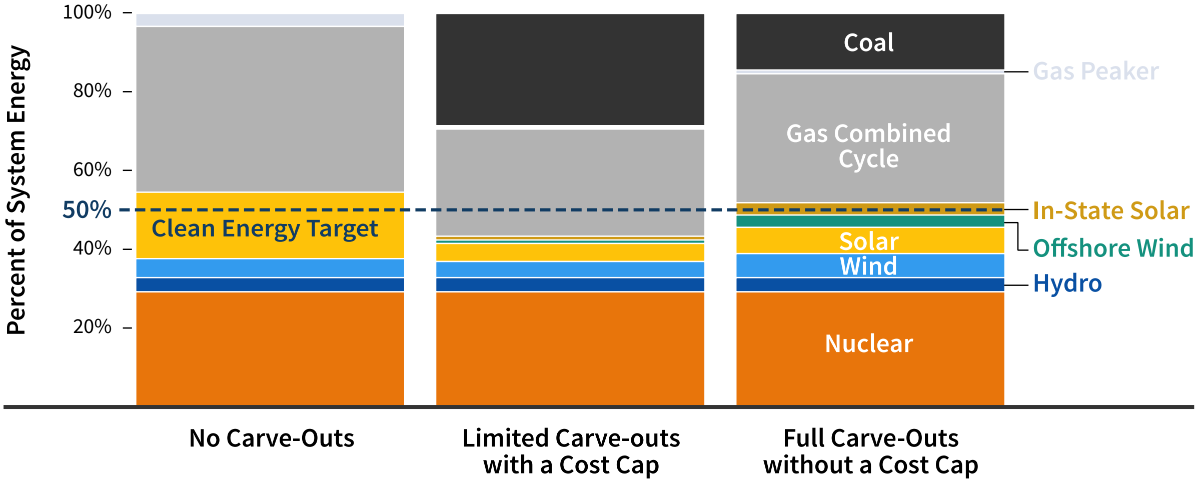
Exhibit 10

Capacity changes (a), delivered energy (b), and cost to load (c) in the three carve-out scenarios

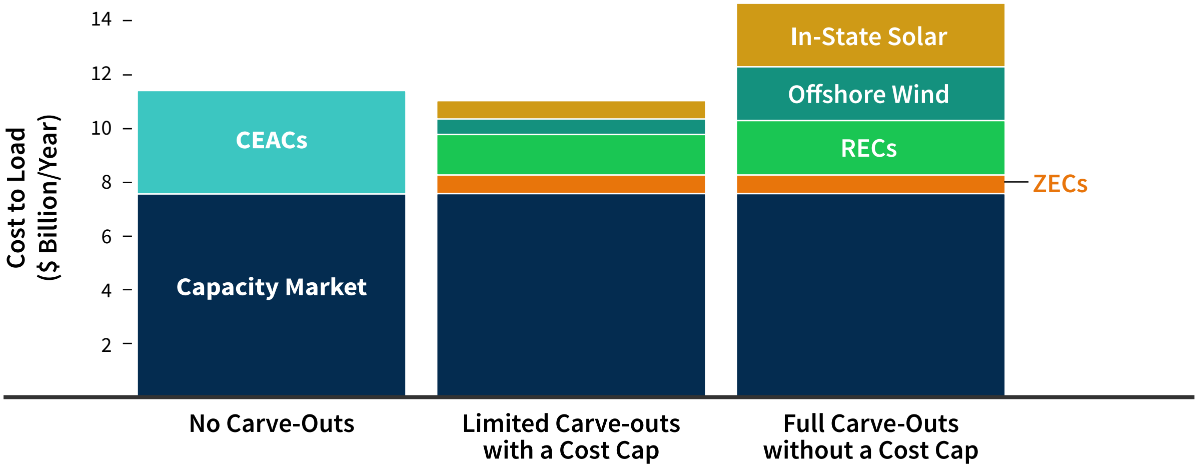
(a) Capacity additions and retirements



(b) System energy generation



(c) Annual capacity and clean energy attribute costs



In Scenario 1 (no carve-outs), new regional solar, onshore wind, and energy efficiency clear the market. Together with existing nuclear, these resources provide 50% of delivered energy. Further, none of the system's coal clears and so is assumed to retire. Scenario 1 reduces carbon dioxide emissions dramatically from 0.42 ton/MWh to 0.16 ton/MWh.

In Scenario 2 (limited carve-outs with a clean energy cost cap), we allocate a similar clean energy procurement budget as in Scenario 1 but, instead of procuring CEACs, we procure onshore wind, regional solar, offshore wind, and in-state solar in proportions comparable to existing state carve-out programs.[15] The volume of all clean resources procured is limited by the cost cap. With the reduced additions of higher-capacity regional solar and wind, most coal still clears the market. In Scenario 2, carbon-free sources supply 40% of system needs (mostly from the existing nuclear plants) and emissions are 0.37 ton/MWh.

In Scenario 3 (full carve-outs without a clean energy cost cap), we simulate clean energy procurement so that states procure in-state solar and offshore wind carve-outs, as well as regional RECs to meet the 50% clean energy target. In this scenario, both the proportions and volumes of carve-outs are comparable to existing state programs. While Scenario 3 procures a similar quantity of clean energy MWhs as Scenario 1, the capacity value of the clean generation fleet is lower, allowing some coal to continue clearing the market. Scenario 3 also costs ~50% more than Scenarios 1 and 2. Emissions are reduced to 0.25 ton/MWh.

Together, the three scenario outcomes in Exhibit 10 show that carve-out programs for more expensive or lower-capacity resources could meaningfully increase costs and/or limit emissions reductions. States and other buyers will need to balance the legitimate benefits of carve-out programs with these cost and emissions implications.

Finding 4: Increased voluntary demand can accelerate clean energy deployment and fossil asset retirement.

If development of an FCEM or ICCM achieved widespread buy-in, we hypothesize that new clean energy buyers could be attracted to the market by its simplicity, affordability, and effectiveness at spurring clean energy deployment. To simulate the impact of this potential increased demand, we considered a scenario in which new buyers, including corporations and municipalities, added to CEAC demand in the ICCM.[xvi]

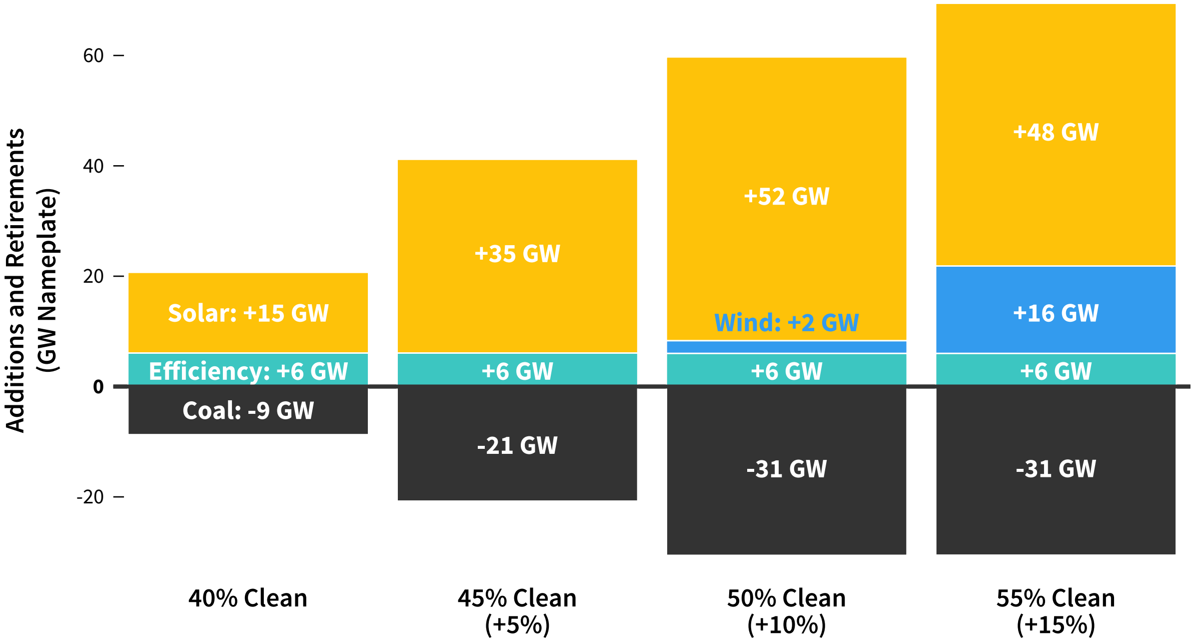
Exhibit 11 shows how the resource mix evolves when CEAC demand increases to 45%, 50%, and 55% of the system's energy generation. Because new solar is the marginal resource (as described above), an additional 5% in CEAC demand causes more solar to clear the market, while less coal clears. As we further increase clean energy demand, the additional low-cost capacity provided by clean resources (which are procured to meet CEAC demand) reduces the capacity market clearing price from $115/MW-day to $111/MW-day. When we add 10% or 15% to CEAC demand, new wind as well as new solar clears.[xvii]

[xvi] As with Finding 3, the results would be similar with an FCEM, assuming that developers reasonably anticipated and accounted for capacity market revenues.

[xvii] In our model, we assume an infinite potential supply of new solar at the same price. This simplification prevents the additional CEAC demand from raising the CEAC price in the FCEM and ICCM. In reality, solar (and other resources) would bid at a range of prices, and the additional CEAC demand would increase the CEAC clearing price.

Exhibit 11

The impact of additional clean energy demand on simulation procurement outcomes



The added clean energy demand dramatically reduces system-wide emissions. In the +15% case, the emissions intensity in our energy market simulation was more than cut in half, declining from 0.35 ton/MWh to 0.14 ton/MWh.

Additional insights from our analysis for a much cleaner PJM grid

The analysis described above considers how market designs, market actor behaviors, and clean energy demand would impact market outcomes in a PJM grid that looks very similar to PJM today. We also ran our simulation on a grid with considerably larger amounts of variable wind and solar generation, such as what PJM might look like in the late 2020s or 2030s. We do not share those results here because we found that the outcomes were very sensitive to our assumptions of ELCC values, REC/CEAC demand, and the precise mixes of preexisting generation.

In a much cleaner PJM grid, solar and wind ELCC values would decline significantly, and curtailment could reduce the REC or CEAC production that a given solar or wind project would deliver. The revenues for each resource would also look significantly different from those shown in Exhibit 8. Likely, very low or even negative energy prices would incent battery storage and possibly other technologies. Further, small differences in the assumed delivery year ELCC values, the extent of battery storage on the system, and how that storage is dispatched would lead to significant differences in curtailment, energy prices, and market outcomes. These challenges, where small changes to key parameters (like ELCC) lead to significant differences in market outcomes (and reliability), suggest that PJM may soon need to consider more fundamental reforms that can cost-effectively ensure resource adequacy and support ever-higher levels of clean energy demand.

Recommendations

From our analysis and many conversations with PJM stakeholders, we make the following recommendations:

Recommendation 1: PJM and RASTF stakeholders should keep "clean procurement" in the task force's scope and pursue reforms that remove barriers to the participation of clean energy resources in the capacity market.
In today's PJM grid, renewable and flexible resources like wind, solar, storage, and demand response contribute important capacity value that should be reflected in PJM's markets. Our analysis shows that fully incorporating clean energy resources' capacity and energy contributions in PJM markets reduces system-wide costs and carbon emissions. Therefore, we believe that PJM and stakeholders should continue discussing clean procurement options together with the other "key work activities" that could improve how the markets account for clean energy's capacity value.

Recommendation 2: States should collaboratively define a standardized clean energy product that can be competitively procured throughout PJM.
States have a lot to gain from meeting the bulk of their clean energy goals through a competitive, region-wide process. If state decision makers can agree on a common product definition for a clean energy credit (i.e., a CEAC), they can streamline clean energy credit transactions and likely lower costs and accelerate emissions reductions. This is likely true even if PJM does not introduce a centralized clean energy market. While agreeing on a standardized clean energy product will be challenging and will likely require states to revise their clean energy procurement policies, our analysis suggests that the payoff could be considerable. The ongoing OPSI Competitive Policy Achievement Working Group discussions are a promising step toward this needed multistate collaboration.

Notably, in the FCEM and ICCM designs considered here, states would not have to commit to procuring the entirety of their clean energy through a regional CEAC product. States (or their LSEs) could continue to use bilateral contracting to meet carve-outs or other policy goals. We encourage states to carefully consider how to balance carve-out program benefits with the cost and emissions implications highlighted by our analysis.

Recommendation 3: A regional clean energy procurement process should foster participation from all potential buyers.
New demand from voluntary buyers, such as corporate customers and municipalities, can accelerate the deployment of clean energy and the pace of emissions reductions in the region. However, to attract this demand, the clean energy product must meet these buyers' needs. From conversations with buyers, we believe corporate and municipal customers would be more likely to leverage a standardized clean energy product if it were easy to procure, competitively priced, and certain to both increase new clean energy construction and reduce emissions. Other city or corporate goals, such as 24/7 carbon-free targets, may still require bilateral procurement approaches.

Recommendation 4: PJM and stakeholders should prioritize approaches that accelerate near-term decarbonization, can adapt to a more deeply decarbonized grid, and are politically feasible.
This report considers two clean energy market designs: the FCEM and ICCM. Both designs have the potential to secure multistate support, attract new buyers (and thus accelerate decarbonization), and lay a foundation for continuing to scale clean energy reliably. Importantly, by supporting efficient clean energy resource participation in PJM's markets,

clean energy markets are also likely to lower capacity and energy costs region-wide, benefiting states and buyers without clean energy goals.[16]

To be effective, a centralized clean energy market should strive to incorporate or accommodate multiyear revenue commitments—an important component of current clean energy project finance—and should coexist with continued bilateral contracting for specific projects. Maintaining multiple avenues for clean energy procurement will help meet the diverse needs of clean energy buyers and suppliers in the region.

Our analysis and stakeholder conversations identified several additional criteria for success, as well as risks associated with each market design option. However, we did not assess the likelihood of achieving these criteria or of the downside risks materializing. Stakeholders should carefully consider the feasibility of these new market designs and weigh risks associated with each option as part of ongoing conversations in the RASTF.

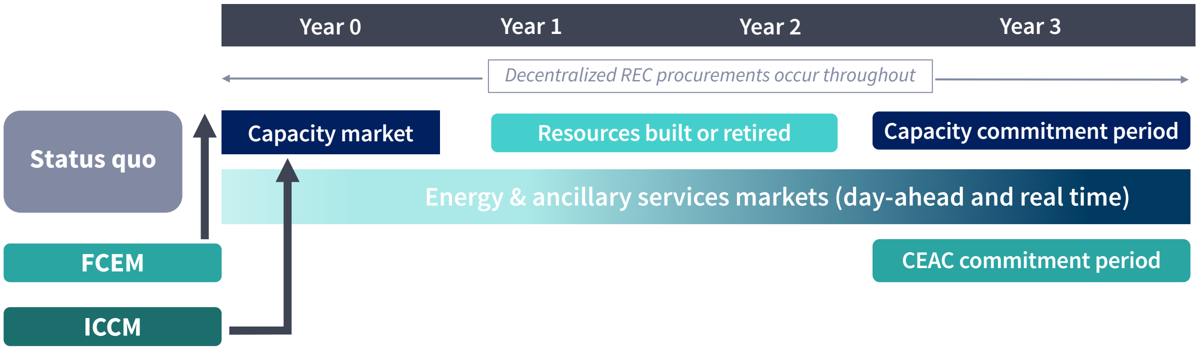
We have also heard some PJM stakeholders express concerns that centralized clean energy markets administered by PJM or in coordination with PJM's capacity market may raise questions regarding the boundary between state and federal jurisdiction over clean energy attributes. These concerns should be discussed and addressed to the greatest extent possible.

Ultimately, the question facing RASTF stakeholders regarding clean energy procurement options is, "What approach cost-effectively meets the needs of the diverse PJM ecosystem of suppliers, clean energy buyers, and states with decarbonization policies, now and in a deeply decarbonized future?" We applaud the ongoing stakeholder conversations and believe that they have the potential to yield meaningful changes that economically accelerate decarbonization in PJM.

Appendix A: Clean Energy and Capacity Procurement

Exhibit A1

Clean energy and capacity procurement timelines

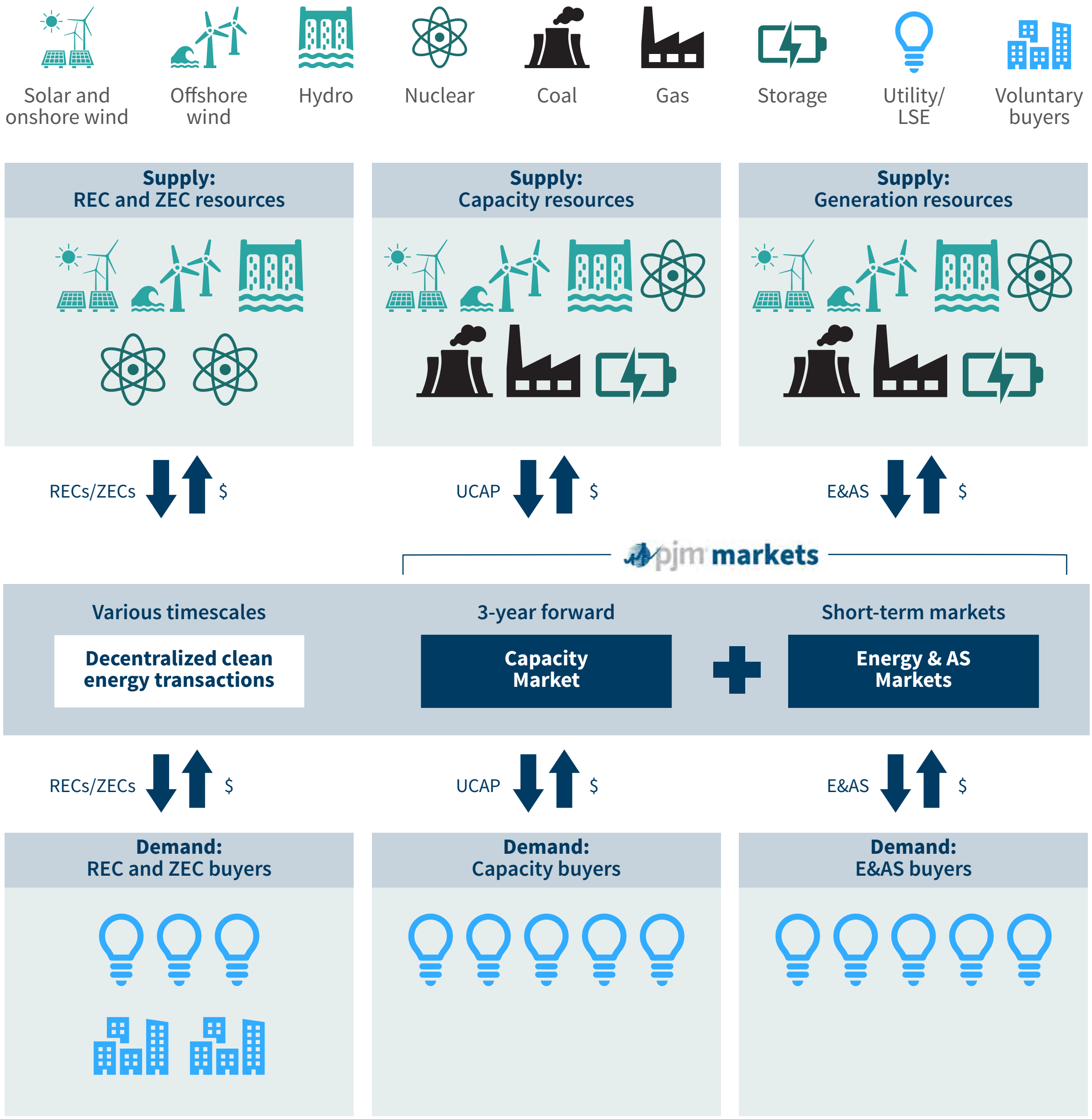


Note: Under the status quo, REC procurements are not necessarily sequenced with the capacity auction. In the FCEM, a clean energy auction directly precedes the capacity auction. In the ICCM, an integrated auction for clean energy and capacity replaces the current capacity auction. In all market design options, decentralized procurements for clean energy may happen throughout the process. Existing resources have the option of participating in the energy and ancillary service markets throughout, while new resources participate when they come online (Years 1-3).

Exhibit A2

Supply- and demand-side participation in clean energy procurement and PJM's capacity and E&AS markets under the status quo

Status quo REC/ZEC procurement + PJM markets

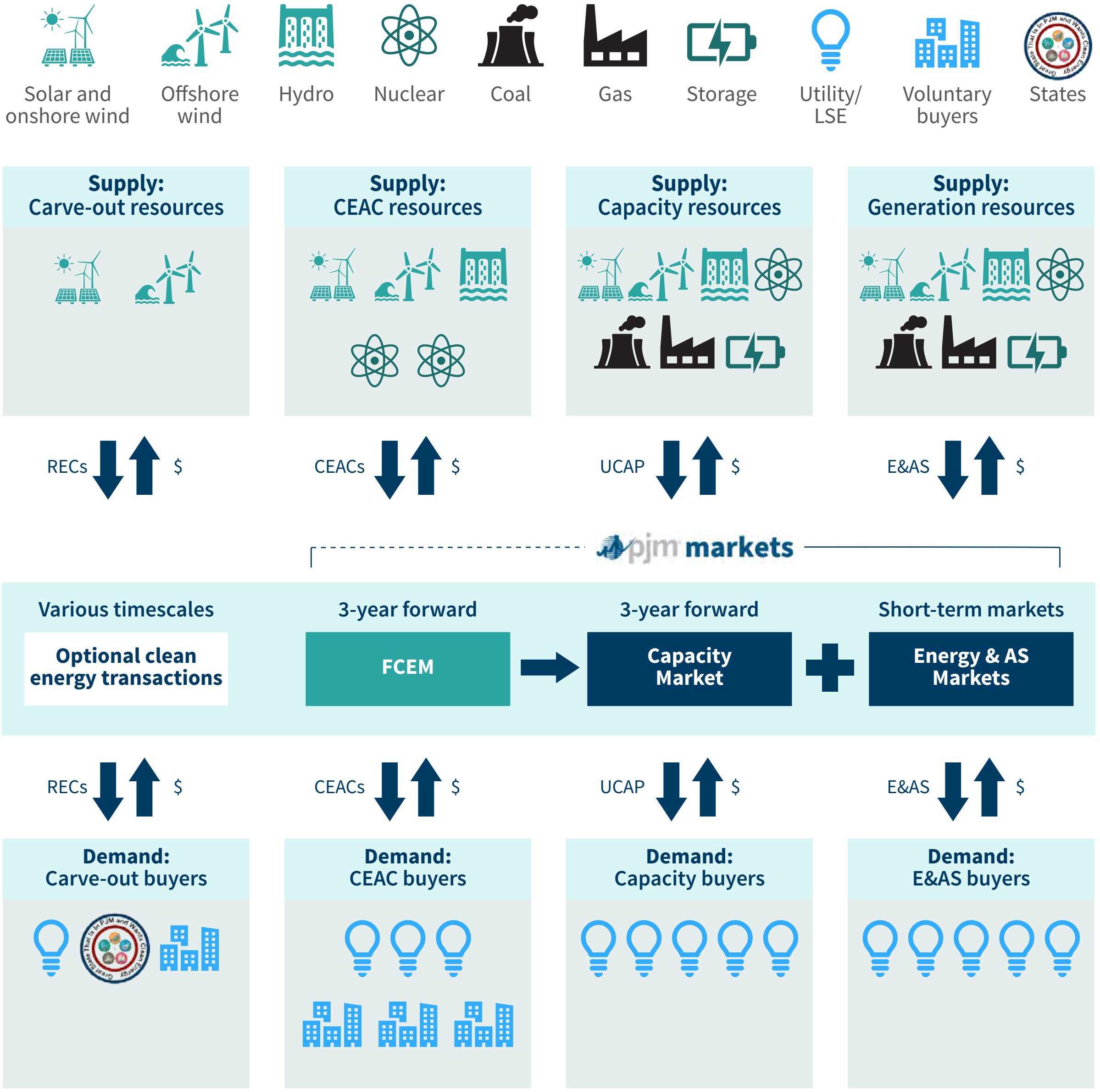


Note: Supply resources (top) offer REC/ZEC, firm capacity, energy, and ancillary service products into each respective market (center). Each market transacts or clears offers according to its rules and delivers the products to buyers (bottom).

Exhibit A3

Supply- and demand-side participation in the FCEM and PJM's capacity and E&AS markets

Forward Clean Energy Market + PJM markets

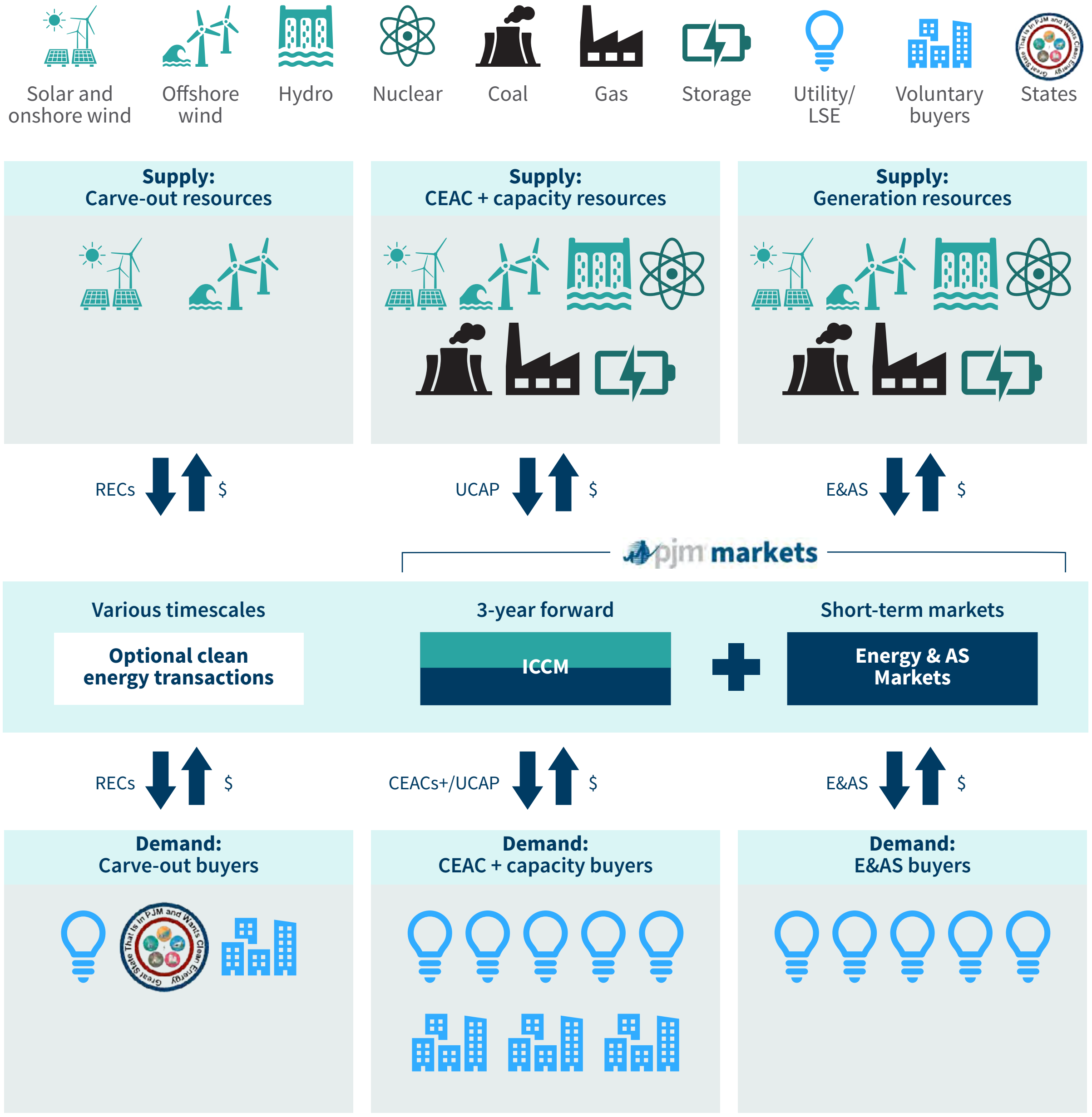


Note: Supply resources (top) offer REC, CEAC, firm capacity, energy, and ancillary service products into each respective market (center). Each market transacts or clears offers according to its rules and delivers the products to buyers (bottom). The FCEM could be a PJM-run market or administered independently, as denoted by the dashed bracket.

Exhibit A4

Supply-and demand-side participation in the ICCM and PJM's E&AS markets

Forward Clean Energy Market + PJM markets



Note: Supply resources (top) offer REC, CEAC, firm capacity, energy, and ancillary service products into each respective market (center). Each market transacts or clears offers according to its rules and delivers the products to buyers (bottom).

Appendix B: Methodology

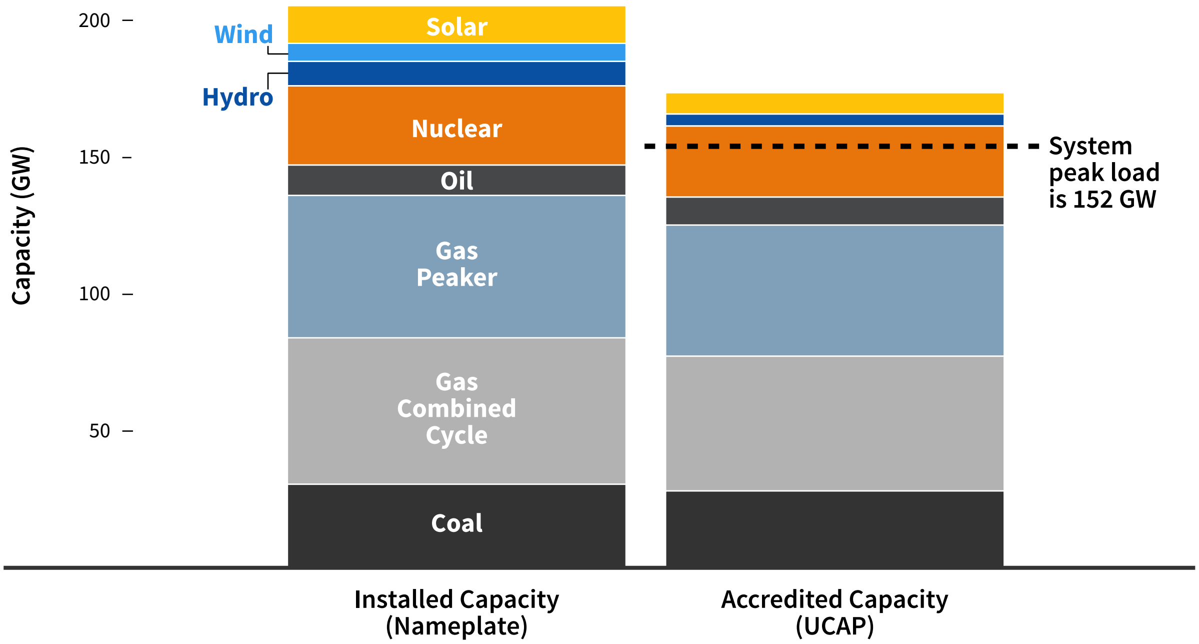
Setting Up the Markets

Grid System

The grid system in which we run our simulations is constructed as a simplified version of a regional grid like PJM's. We start by defining a system with an annual peak load of 152 gigawatts (GW). Exhibit B1 shows the existing resources on the system in units of nameplate capacity and unforced capacity (UCAP); system peak load is denoted by the dashed line. This system has enough capacity installed to satisfy resource adequacy requirements, which are defined as system peak load plus an installed reserve margin of 14.5%.

Exhibit B1

Existing supply stack entered as an input to the simulation



Note: The system has enough installed capacity to satisfy system peak load plus an installed reserve margin of 14.5%.

Our assumed mix of existing resources matches the supply from UC Berkeley and GridLab's 2035 Report data sets, which provide region-specific capacity expansion modeling results for decarbonizing the US grid 90% by 2035.[17]

Demand for Clean Energy and Capacity

Clean energy: We define one system-wide clean energy target, intended to reflect the aggregate demand for clean energy credits that exists in PJM or could exist in the future. This target is expressed as the percentage of total energy delivered on the system that is clean, or zero-carbon (e.g., 40% of total delivered energy must come from zero-carbon resources). The resource mix that each market simulation produces must meet this target (which we assess by simulating one year of hourly energy dispatch).

Capacity: We define one system-wide capacity target to meet regional reliability needs. This target is defined in terms of megawatts of accredited unforced capacity (MW UCAP) and is equal to system peak load (152 GW) plus an installed reserve margin of 14.5%. The resource mix that each market simulation produces must clear this minimum threshold.

Supply of Clean Energy and Capacity Resources

We input a set of supply offers that includes existing resources and new resources that, if cleared, will be built and added to the system. Our analysis assumes one supply offer for each resource type, with an exception for nuclear.[xviii] Each supply offer is defined by the following attributes:

- Resource type
- Size (MW nameplate)
- Capacity accreditation
- Annual clean capacity factor (average expected hourly energy output per unit of installed capacity)
- Offer price

Existing resource sizes are proportional to PJM's currently installed capacity. For new resources, we constrain the availability of new wind, new demand response, and new energy efficiency to reflect their relative shares in the current PJM queue. We assume all other new resources are unlimited (solar, combined cycle gas, combustion turbine gas, and battery storage), meaning the simulator can choose as much of them to build as necessary to meet demand if they are cost-competitive.

Each resource has a capacity accreditation value that is equal to its effective load carrying capability (ELCC) for renewables, or one minus an assumed equivalent demand forced outage rate (1 - EFORd) for thermal generators. Values for ELCC are taken from PJM's 2021 ELCC study,[xix] and values for EFORd are taken from Brattle's ICCM model, cited in the New Jersey Board of Public Utilities Notice of Work Session.[18] We use the capacity accreditation value to convert nameplate capacity, measured in MW nameplate, to its "firm" capacity, measured in MW UCAP. Each resource is also assigned an annual clean capacity factor, which is the average expected clean energy hourly output per unit of installed capacity. Values for clean capacity factor are taken from RMI's *Reinventing Fire*.[19]

[xviii] We have two "existing nuclear" resources: one that is priced to reflect the fleet-wide average, and another that is priced to reflect more expensive nuclear plants that have recently come close to retirement.

[xix] We expect that the ELCC for variable energy resources (e.g., wind and solar) and duration-limited resources (e.g., batteries) will decline over time as a function of these resources' penetration on the system. We use PJM's ELCC estimates when simulating markets in both the near term and for a future grid system with high penetrations of variable energy and duration-limited resources. For the specific ELCC values we assume, see Appendix C.

To develop offer prices for supply resources, we use default gross and net cost data from PJM. Annualized costs for existing resources are based on PJM values for gross avoidable cost rate (ACR),[20] and annualized costs for new resources are based on PJM values for gross cost of new entry (CONE).[21] CONE prices for energy efficiency and demand response were taken from Brattle's ICCM model.

We assume that, in order to be profitable, resources need to recover their gross annualized costs through revenue earned in the energy and ancillary service (E&AS) markets, the capacity market, and REC/ZEC/CEAC markets, if eligible. **In general, we assume that resources bid competitively, meaning that resources set their offer at the exact value of their "required revenue" (revenues needed from that particular market to recover costs; not to be confused with a revenue requirement).**

Throughout the analysis, we base the estimated net E&AS market revenues for each resource on the default values determined by PJM.[22,xx] This revenue is subtracted from resources' gross costs to form their offer prices for the capacity and clean energy markets. When a resource is bidding into the capacity market, it also estimates the revenue it will earn from REC/ZEC/CEAC markets and subtracts this revenue from its gross costs to form its offer price in the capacity market. The same is true for a resource setting its offer price for REC/ZEC/CEAC markets: the resource will estimate its capacity revenue and subtract this amount from its gross costs. The full set of supply offers can be found in Appendix C: Data. Exhibit B2 below provides offer price formulas for clean energy and capacity supply.

Exhibit B2

Formulas for supply offer price formation in each market

STATUS QUO	
REC/ZEC contracts	Offer price varies based on structure and duration of contract, bounded by REC pricing indices and historic ZEC values. Unless otherwise stated, the offer price for RECs and ZECs is set at the "required revenue": **REC/ZEC offer price** = **CONE or ACR** – **expected net E&AS revenue** – **expected capacity market revenue** *Note: to estimate capacity market revenue, bidders must estimate the capacity market clearing price, as follows:* Expected capacity market revenue ($/year) = capacity market clearing price ($/MW UCAP-day) ⋆ resource nameplate capacity (MW nameplate) ÷ resource ELCC (MW UCAP/MW nameplate) ⋆ 365 days/year
Capacity market	**Capacity offer price** = **CONE or ACR** – **expected net E&AS revenue** – **REC/ZEC revenue** Numerical example for an existing combustion turbine, shown in dollars per unit of firm capacity: **$2/MW UCAP-day** = **$46/MW UCAP-day** – **$44/MW UCAP-day** – **$0/MW UCAP-day**

[xx] PJM estimates the net energy and ancillary services revenue (net E&AS revenue) as the difference between a resource's hourly revenue from the energy and ancillary services markets minus its operating costs summed over all hours of the year. This term can be thought of as "energy and ancillary services market profit." In capacity auction bid price formation, we express this term in units of $/MW-day.

FCEM	
CEAC market	**CEAC offer price** = **CONE or ACR** – **expected net E&AS revenue – expected capacity market revenue** Numerical example for a new solar project, shown in dollars per unit of clean energy generated: **$16/MWh** = **$53/MWh** – $25/MWh – **$12/MWh** *Note: to estimate capacity market revenue, bidders must estimate the capacity market clearing price, as in the REC/ZEC contracts above.*
Capacity market	**Capacity offer price** = **CONE or ACR** – **expected net E&AS revenue – CEAC revenue** Numerical example for a new solar project: **$123/MW UCAP-day** = **$542/MW UCAP-day** – $256/MW UCAP-day – **$163/MW UCAP-day** *Note: for a solar project with an ELCC of 0.54 and an annual capacity factor of 23%, the values for CEAC revenue of $16/MWh and $163/MW UCAP-day are equivalent.*

ICCM	
Integrated market revenue	Clean energy and capacity offer price = **CONE or ACR – expected net E&AS** Numerical example for a new solar project: **$38/kW-y** = **$106/kW-y** – $68/kW-y In the ICCM, resources submit one price for two products: CEACs and capacity. In this example, a 1 MW new solar project would submit 2 GWh/year of CEACs and 0.54 MW UCAP of capacity. *Note: we show ICCM bids in units of dollars per kilowatt-year for ease of converting to a capacity- or clean energy-adjusted price.*

Note: Unit conversions between different market revenue streams have been made for simplicity.

Running the Market Simulator

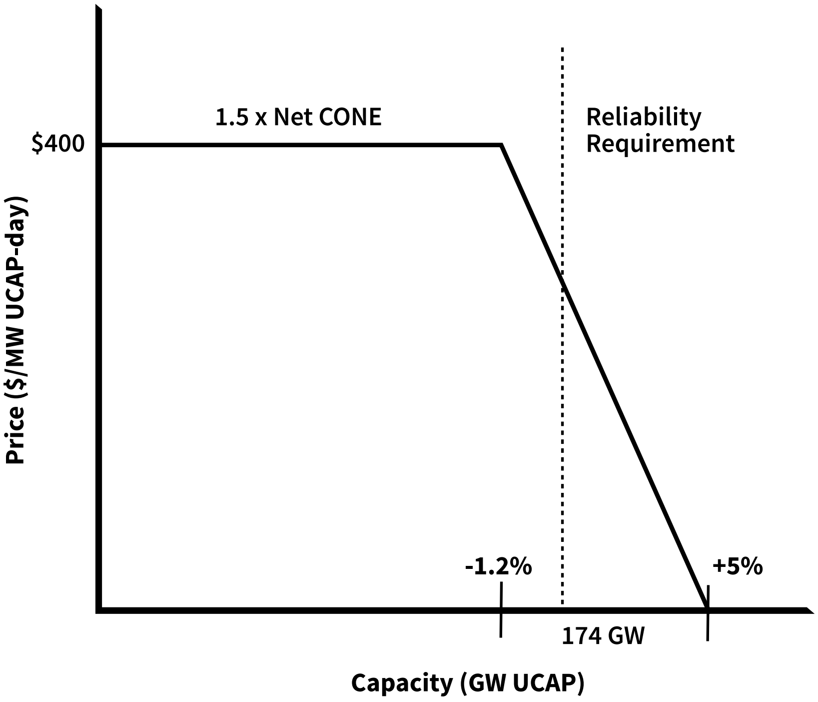
Clean Energy and Capacity Procurement in the Status Quo

In the status quo clean energy credit procurement option, we simulate existing REC and ZEC programs by exogenously choosing which resources will be used to satisfy clean energy demand and awarding them payments for their renewable and zero-carbon attributes. We limit the number of RECs and ZECs that are awarded so that they only go to resources that are needed to meet the system-wide clean energy target (i.e., there is no overprocurement through REC and ZEC programs). REC and ZEC prices are set at the "required revenue" that the marginal renewable or zero-emissions resource needs to be made whole and stay online. Unless otherwise noted, we satisfy clean energy demand by choosing the lowest-cost REC and ZEC resources available. This simulation ignores the diversity of actual REC and ZEC contracting timelines and pricing.

We simulate the capacity market by running an auction for unforced capacity (UCAP). We use a sloped demand curve anchored on the reliability requirement with slope parameters that match those used in PJM's capacity market.[23,xxi] The auction function determines which resources will receive capacity commitments by stacking supply offers in order of ascending bid price and clearing all offers up to the marginal offer, which is the offer that intersects the demand curve.[xxii] All cleared offers are paid the clearing price set by the marginal supply offer.

Exhibit B3

Capacity auction demand curve showing the reliability requirement, price cap, and parameters of the downward-sloping demand curve



Note: Given a peak load of 152 GW and a planning reserve margin of 14.5%, the reliability requirement for our simulated system is 174 GW. Net CONE is the assumed maximum cost of new entry for a capacity resource in PJM.[24] *In keeping with the parameters used to define PJM's capacity demand curve, the price for capacity is capped at $400/MW UCAP-day, the downward-sloping line starts at -1.2% of the reliability requirement, and it intersects with the x-axis at +5% of the reliability requirement.*

[xxi] PJM's demand curve is formed by connecting lines with two downward slopes. For simplicity, our capacity demand curve has only one downward slope: we use only the steeper line from PJM's curve and extrapolate it to the x-axis.

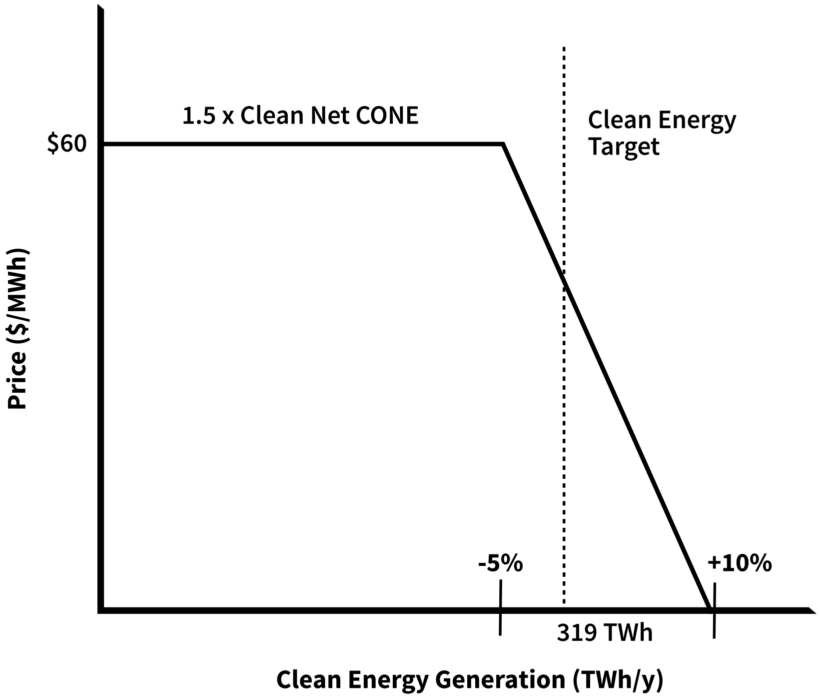
[xxii] We assume all capacity offers are fully rationable, meaning we allow offers to clear partially in the capacity auction.

Clean Energy and Capacity Procurement in the FCEM

For the FCEM, we model clean energy procurement by simulating a competitive auction for clean energy attribute credits (CEACs). Demand curve formation follows parameters used by Brattle.[25,xxiii] The auction function determines which resources will receive CEAC payments by stacking supply offers in order of ascending price and clearing all offers to up to the marginal offer.[xxiv] All cleared offers are paid the clearing price set by the marginal supply offer. Capacity procurement is simulated in the same way as in the status quo.

Exhibit B4

Clean energy attribute auction demand curve showing the clean energy target, price cap, and parameters of the downward-sloping demand curve



Note: Given our assumed electricity demand, a clean energy target of 40% equates to 319 terawatt-hours (TWh) per year for our simulation. Clean Net CONE is the assumed maximum cost of new entry for a clean energy resource in PJM. In keeping with the parameters used to define Brattle's clean energy demand curve, the price for clean energy is capped at $60/MWh. Note that this does not apply to carve-outs procured outside of a central auction. The downward-sloping line starts at -5% of the clean energy procurement target and intersects with the x-axis at +10% of the clean energy target.

[xxiii] For simplicity, our clean energy demand curve has only one downward slope: we use only the steeper line from Brattle's curve and extrapolate it to the x-axis.

[xxiv] We assume all clean energy attribute offers are fully rationable, meaning we allow offers to clear partially in the clean energy attribute auction.

Integrated Clean Energy and Capacity Procurement in the ICCM

The ICCM simulation uses an integrated auction to procure both CEACs and capacity. The CEAC and capacity demand curves are formed in the same way as in the status quo and FCEM auctions. On the supply side, each resource submits one or two quantities (one for the total clean energy credits it expects to produce in a year, if applicable, and one for firm capacity) and one price (the price needed to provide both products).

The integrated auction determines the least-cost portfolio of resources that can satisfy demand for both clean energy credits and capacity using a surplus maximizing objective function, as formulated by Brattle.[26] The optimization determines one clearing price for CEACs and one for capacity by calculating the intercept of cleared supply on the sloped demand curve. Using the clearing prices for CEACs and capacity, we can calculate adjusted offer prices for each resource. Cleared resources are paid the clearing price for CEACs (if eligible) and for capacity.

Energy Market Simulator

We simulate one year's worth of hourly dispatch to analyze outcomes like generation, curtailment, load violations, emissions, and energy market costs.

Our simulator uses economic dispatch to match supply to load. Any resource receiving capacity, CEAC, REC, or ZEC payments is assumed to be available for energy dispatch and enters the generation supply stack. Hourly generation profiles for wind, solar, energy efficiency, and demand response are taken from *Reinventing Fire*.[27] For nuclear, we assume a flat hourly output set by its capacity factor. We assume an hourly load profile equal to PJM hourly load from 2010.[28] We use 2010 load data to match the vintage of the hourly generation profiles for wind, solar, energy efficiency, and demand response.

We assume one grid system, ignoring security, unit commitment, and transmission constraints, and assume perfectly efficient electricity delivery.

For each hour, our dispatch follows the following steps:

1. Assume all zero-marginal-cost resources run according to hourly generation profiles.
2. If there is a surplus of renewable generation, charge the battery until it is full and curtail any excess generation.
3. If there is load not met by zero-marginal-cost resources, attempt to meet load by discharging the battery until the battery is empty.
4. For any remaining load, dispatch generators from the stack in merit order until load is met. In the event that load is unmet, note a load violation.
5. The hourly clearing price becomes the marginal cost of energy (MCOE) of the last dispatched generator. [xxv]

[xxv] Specific values for each resource are listed in Appendix C.

Because our energy market simulator makes many simplifying assumptions, it is only intended to provide directionally accurate results and illustrative insights into the impacts of clean energy and capacity auctions on the electricity system.

MCOE is calculated as the sum of a resource's variable operations and maintenance (VOM) costs and its fuel costs. VOM data are from RMI's *Economics of Clean Energy Portfolios*.[29] Fuel costs for coal, oil, and gas are from EIA.[30] Heat rates for coal and oil are from EIA.[31] Heat rates for combined cycle gas plants and gas peakers are from NREL ATB.[32]

The emissions intensity of each resource is calculated as the product of the carbon dioxide intensity of the fuel used by each resource times its heat rate. The carbon dioxide intensity of fuel is from EIA.[33]

Analyzing Outcomes

Exhibit B5 shows some top-level statistics from our simulation in Finding 2. For all simulations, we track the metrics shown in the table to ensure that our findings are realistic. We include this table here as an example.

Exhibit B5

Market outcomes for a simulation that increases from 35% to >40% clean energy

Capacity price	$115/MW-day UCAP
REC price	$16/MWh
ZEC price	$3.17/MWh
CEAC price	$16/MWh
Clean energy generation achieved	42% of system energy[xxvi]
Curtailment	<1% of wind and solar generation
Load violations	0 MWh unserved
Total capacity cost	One-quarter of system costs ($7.6 billion/year)
Total clean energy cost	One-tenth of system costs ($2.5 billion/year)

[xxvi] The actual clean energy generation achieved by the system may not exactly match the target for a few reasons. First, a downward-sloping demand curve means that, if clean energy prices are low, the auction may clear more than the target. Second, the capacity factors used to estimate annual generation of clean resources may not exactly match the amount of generation used by the system during our simulated dispatch if curtailment or other factors alter actual clean energy production.

Appendix C: Data

Exhibit C1

Gross cost, expected energy market revenue, expected capacity market revenue, and minimum REC/ZEC price needed to recover costs for clean resources for 2020

Note: All values are shown in $/MWh. We assume a price for capacity of $115/MW-day.

Resource	Which Attributes Can It Sell?	Gross Cost (Net CONE or Net ACR) in $/MWh (1)	Expected Energy Market Revenue (Net E&AS Revenue) in $/MWh (2)	Expected Capacity Market Revenue (3)	REC/ZEC Price (1-2-3)
New In-State Solar PV[xxvii]	In-State Solar Carve-Out, RECs, CEACs	$129.79	$18.76	$11.03	$100
New Offshore Wind	Offshore Wind Carve-Out, RECs, CEACs	$115.52	$27.30	$4.57	$83.61
New Wind	RECs, CEACs	$41.67	$23.81	$1.71	$16.14
New Solar PV	RECs, CEACs	$51.42	$24.60	$11.03	$15.79
Existing Nuclear (Expensive)	ZECs, CEACs	$31.90	$23.94	$4.80	$3.16
Existing Nuclear (Cheap)	ZECs, CEACs	$28.19	$23.94	$4.80	$0
Existing Solar PV	RECs, CEACs	$7.25	$24.60	$11.03	$0
Existing Wind	RECs, CEACs	$8.23	$23.81	$1.71	$0
Existing Hydro	RECs, CEACs	$11.26	$42.12	$5.45	$0

[xxvii] We assume a cost premium for in-state solar resources of $100/MWh. Actual costs for in-state resources may vary widely and can reach as high as $230/MWh.

Exhibit C2

Cost and performance parameters for resources used in any auction year

Resource	Nameplate Capacity (GW)	Capacity Credit	Clean capacity Factor	Gross CONE ($/MW Nameplate-Day)	Gross ACR ($/MW Nameplate-Day)	Net E&AS Revenue Offset ($/MW Nameplate-Day)	MCOE ($/MWh)	Emissions Intensity (tons CO2/MWh)
Demand Response	11.4	1.00	0%	$123	N/A	$0	$0	0
Efficiency	6.1	1.00	0%	$82	N/A	$0	$0	0
New Nuclear [xxviii]	Unlimited	0.90	90%	$2,000	N/A	$517	$0	0
Battery Storage	Unlimited	0.80	0%	$532	N/A	$116	$0	0
Combined Cycle Gas	Unlimited	0.92	0%	$320	N/A	$168	$24.60	0.340
Gas Peaker	Unlimited	0.92	0%	$294	N/A	$48	$35.45	0.504

[xxviii] PJM offers Gross CONE and Net E&AS Revenue Offset values for new nuclear plants. We include this resource in our supply curve of new resources to approximate a "clean firm" technology. It is not chosen in any simulations presented in this paper.

Exhibit C3

Cost and performance parameters for resources used for a 2020 auction year

Resource	Nameplate Capacity (GW)	Capacity Credit	Clean Capacity Factor	Gross CONE ($/MW Nameplate-Day)	Gross ACR ($/MW Nameplate-Day)	Net E&AS Revenue Offset ($/MW Nameplate-Day)	MCOE ($/MWh)	Emissions Intensity (tons CO2/MWh)
Nuclear (Cheap)[I]	7.1	0.90	90%	N/A	$609	$517	$0	0
Nuclear (Expensive)[I]	21.4	0.90	90%	N/A	$689	$517	$0	0
Hydro (Existing)	8.4	0.42	37%	N/A	$100	$374	$0	0
Onshore Wind (Existing)	6.7	0.15	42%	N/A	$83	$240	$0	0
Solar PV, Tracking (Existing)[II]	14	0.54	23%	N/A	$40	$139	$0	0
Battery Storage	0.9	0.83	0%	N/A	$100	$116	$0	0
Coal	30.7	0.92	0%	N/A	$149	$43	$21.89	1.006
Combined Cycle Gas	53.5	0.92	0%	N/A	$55	$168	$24.60	0.340
Gas Peaker	52.1	0.92	0%	N/A	$50	$48	$35.45	0.504
Oil	11.1	0.92	0%	N/A	$102	$48	$167.03	0.815
Onshore Wind	17.5	0.15	42%	$420	N/A	$240	$0	0
Offshore Wind	Unlimited	0.40	42%	$1,155	N/A	$273	$0	0
Solar PV, Tracking[II]	Unlimited	0.54	23%	$290	N/A	$139	$0	0
Battery Storage	Unlimited	0.83	0%	$532	N/A	$116	$0	0
In-State Solar[II, III, IV]	Unlimited	0.54	23%	N/A	N/A	$106	$0	0

I. We assign 25% of the existing nuclear fleet the "representative" ACR value and 75% the "high" ACR value.

II. We reduce expected energy market profit by 25% of PJM's 2020 estimate to account for anticipated hourly clearing price declines from new solar resources.

III. We assume a cost for new in-state solar of $100/MWh.

IV. We assume that expected energy market revenues for in-state solar reflect low-end estimates from across the region.

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