Market-Based Battery Operations

COMPETITIVE OFFERS, MARKET POWER MITIGATION, AND OFFER TIMING

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Market-Based Battery Operations: Competitive Offers, Market Power Mitigation, and Offer Timing

OBJECTIVE OF PRESENTATION

1. **Competitive battery offers:** Describe a framework for understanding competitive battery offer prices based on inter-hour opportunity costs; show that estimating these offers for market power mitigation is more complex and underestimates more consequential

2. **Offer timing in real-time (RT):** Show how PJM's t-65-minute offer price lock can interfere with competitive battery offer, identify implications

AGENDA

- **Batteries and resource adequacy in PJM -** batteries' growing role in meeting PJM's reliability needs (potentially 4 GW by 2030)
- **Battery operations and offers** – profile of efficient, reliable battery operations in real-time; alternative market-based approaches; competitive battery offer prices
- **Market power mitigation -** preserving competitive efficiencies; application to batteries
- **Potential issues with market power mitigation** – measures that can unintentionally undermine opportunity-cost offers
  - Cost-based offers that exclude or suppress opportunity cost estimates
  - t-65-minute offer lock that prevents offer increases when opportunity costs spike
  - Status-quo fallback of physical hold-back to manage state-of-charge is inefficient
- **Appendix**: ISO/RTO approaches to battery market power mitigation

Growing Battery Fleet Warrants Revisiting Market Power Mitigation Rules to Ensure Consistency with Competitive Behavior and Efficiency

Multi-hour batteries are here: 0.2 GW now, 4 GW in 2030, 16 GW in 2035

- PJM energy market now seeing 170+ MW of battery output for several hours (a new 150 MW/600 MWh battery came online in June, 2026)
- Hundreds of MW UCAP of new batteries expected to enter service in 2027
- Compare with 16 GW batteries installed in each of ERCOT and CAISO today

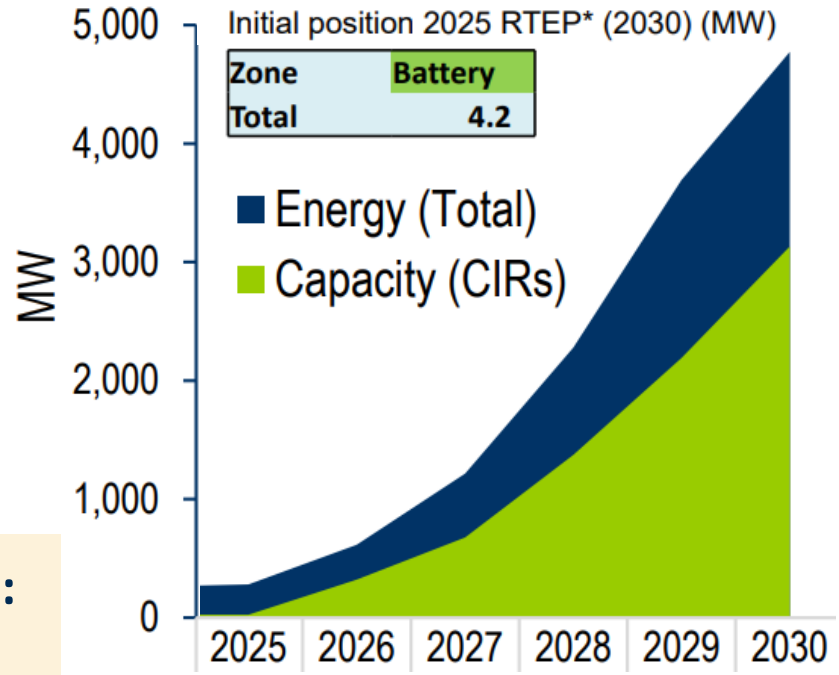
These batteries use PJM's offer-driven Energy Storage Resource (ESR) Participation Model developed in 2019 under FERC Order 841

- **Relies on seller offer behavior for optimal dispatch and reserve assignments**
- Based on the standard market engine (i.e., no look-ahead, fuel-based mitigation)

At this scale, market power mitigation rules pose reliability/cost questions:

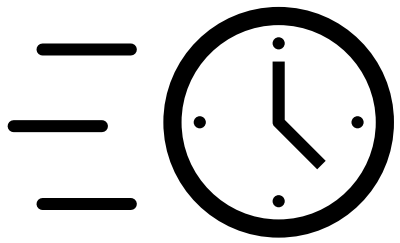
- Can market power mitigation designed for fossil-fuel generators achieve optimal reliability and efficiency from battery dispatch under PJM's offer-driven approach?
- In particular, what are the implications of excluding opportunity costs in mitigated offer prices? What about the t-65min offer price lock?

CUMULATIVE BATTERIES IN PJM QUEUE BY YEAR IN SERVICE



Source: 4 GW in 2030 (and inset above) from PJM, Informational Base Scenario Update, Oct. 2025, p.17; 16 GW from PJM, 2026 RTEP – Capacity Expansion Scenarios for 8-year cases (2034), June 2026, p. 22; Figure: PJM, Enhancing PJM's Energy Storage Resource Model for Anticipated Battery Growth, June 3, 2026

Focus on Market Power Mitigation in Real-Time Energy Markets



This presentation focuses on market power mitigation in RT energy and ancillary service markets, because:

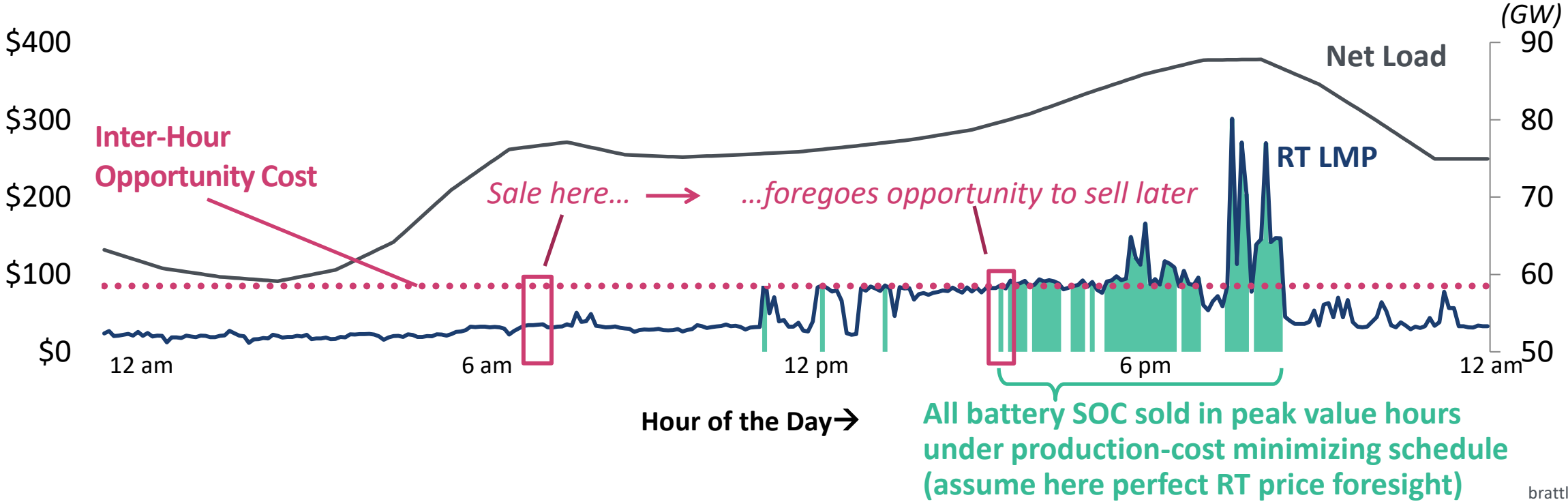
- Batteries do not generally need to take a hedge against physical inflexibility, as e.g., a steam generator would
- Batteries are less likely to affect day-ahead market prices, since day-ahead (DA) energy prices in PJM have been set by virtual traders 80% – 99% of the time
- Batteries are less likely to affect day-ahead schedules of physical participants, which are determined by their offers relative to DA market prices

Optimal Battery Operation is Supported by Offer Prices that Include Inter-Hour Opportunity Cost

Optimal battery operation **retains SOC for only the highest-value hours of a day**, displacing highest production-cost supply; this commonly maximizes reliability, since LMP reflects reserve scarcity

Inter-hour opportunity cost (the anticipated cost of foregoing a sale later in the day due to selling energy now) is a key concept for using offer prices to optimally retain SOC for the highest-value periods; it includes a seller's forecast of: (1) energy revenue; (2) ancillary service revenue; (3) PAI exposure

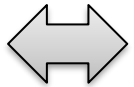
CHART OF SIMULATED OPTIMAL BATTERY DISCHARGE DURING A HISTORICAL DAY WITH DYNAMIC PRICES



Centralized vs. Offer-Driven Approaches for Retaining Battery SOC for Times of Peak Value

Centrally-planned approach to optimal battery operation

24-hour look-ahead market engine determines the optimal schedule given battery capability (no offer prices, just parameters for MW, MWh, and efficiency)



Offer-driven approach to optimal battery operation

Battery offers **allowed to include inter-hour opportunity-costs** reflecting the value of stored energy given anticipated prices later in the day, such that batteries do not clear in lower-value early hours

This is the approach PJM seems to be taking

These two approaches would theoretically result in the same operations and market prices assuming perfect foresight from all parties

- In the centrally-planned approach, PJM provides foresight as an input to the market engine; in the offer-driven approach, foresight is incorporated into battery seller offers

Recap of Market Power Mitigation in PJM: Preserving The Reliability and Efficiency of Competitive Outcomes by Restraining Market Power Exercise

Goal of market power mitigation: Prevent market power exercise from sellers that can move prices to the benefit of their portfolio, without distorting efficient offers at the competitive level

Targeted approach: Only mitigate sellers that fail a structural test, like the Three Pivotal Supplier test (TPS)

If failed:

- Formulate a conceptual model of competitive behavior
- Enforce competitive behavior with mitigated offers subject to a cap ("cost-based offers"), minimizing unintended consequences that degrade reliability and efficiency

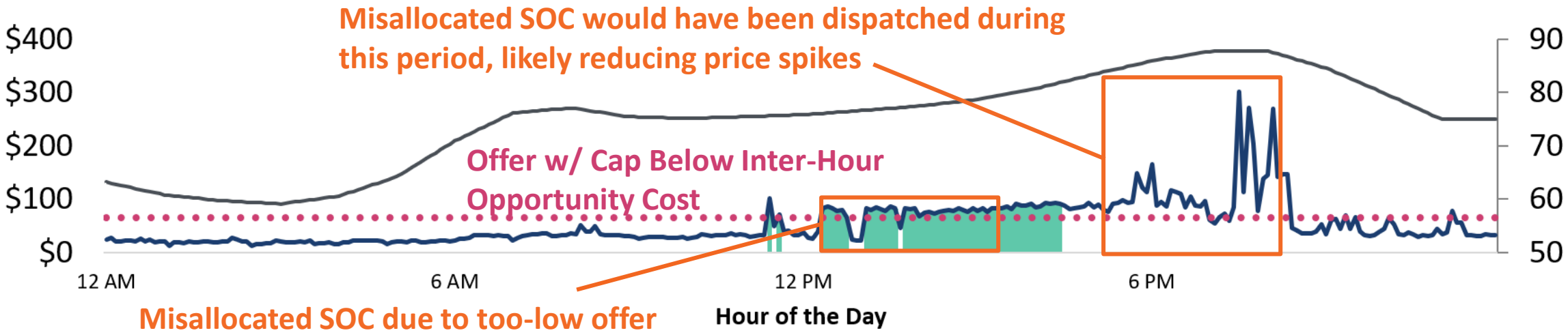
Issue with conventional market power mitigation of batteries: mitigated offer too low to achieve optimal dispatch

The next slide illustrates this with backcast-based analysis of battery market operations on March 31, 2025 (a mild day with a mid-day jump in prices plus price spikes)

Under Offer-Driven Approach, Market Power Mitigation w/o Opportunity Cost Can Lead to Misallocated Early Discharge, Impacting Reliability and Efficiency

Unmitigated Offer w/ Inter-Hour Opportunity Cost Only Clears the Market During Highest-Value Hours

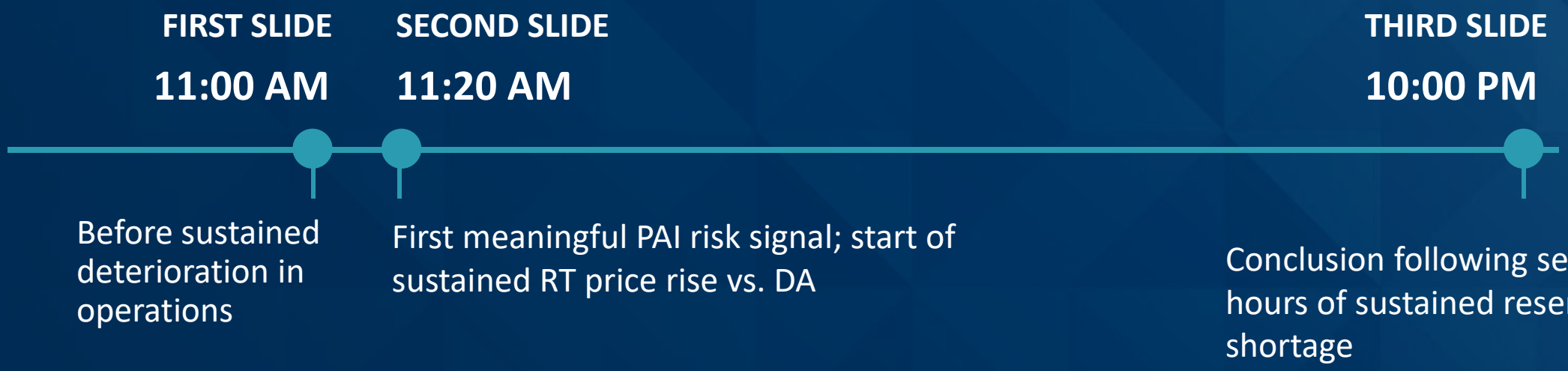
Offer Mitigated Below Inter-Hour Opportunity Cost Clears the Market Too Early, Leading to Higher Cost Later



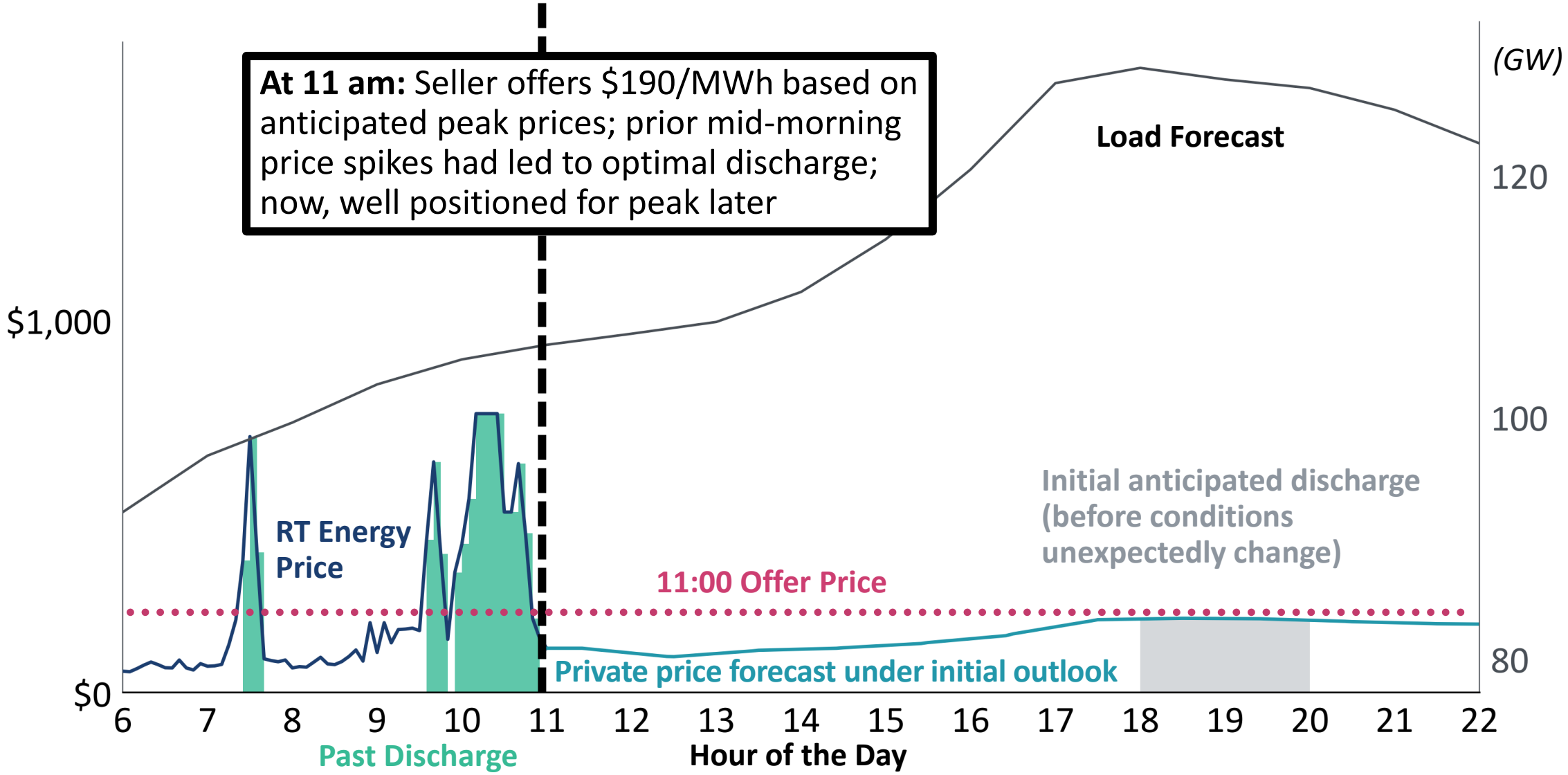
Note: Figures represent a backcast of a 4-hour battery dispatch on March 31, 2025, starting the day at 100% state-of-charge (SOC) under PJM RT price data. Offer with inter-hour opportunity cost set to the 48th highest RT LMP. Mitigated offer capped at highest DA LMP. Battery discharges every time the offer is less than the RT LMP, subject to rolling SOC limitations.

Conventional market power mitigation of batteries: the t-65-minute offer price lock can cause reliability problems and poor efficiency

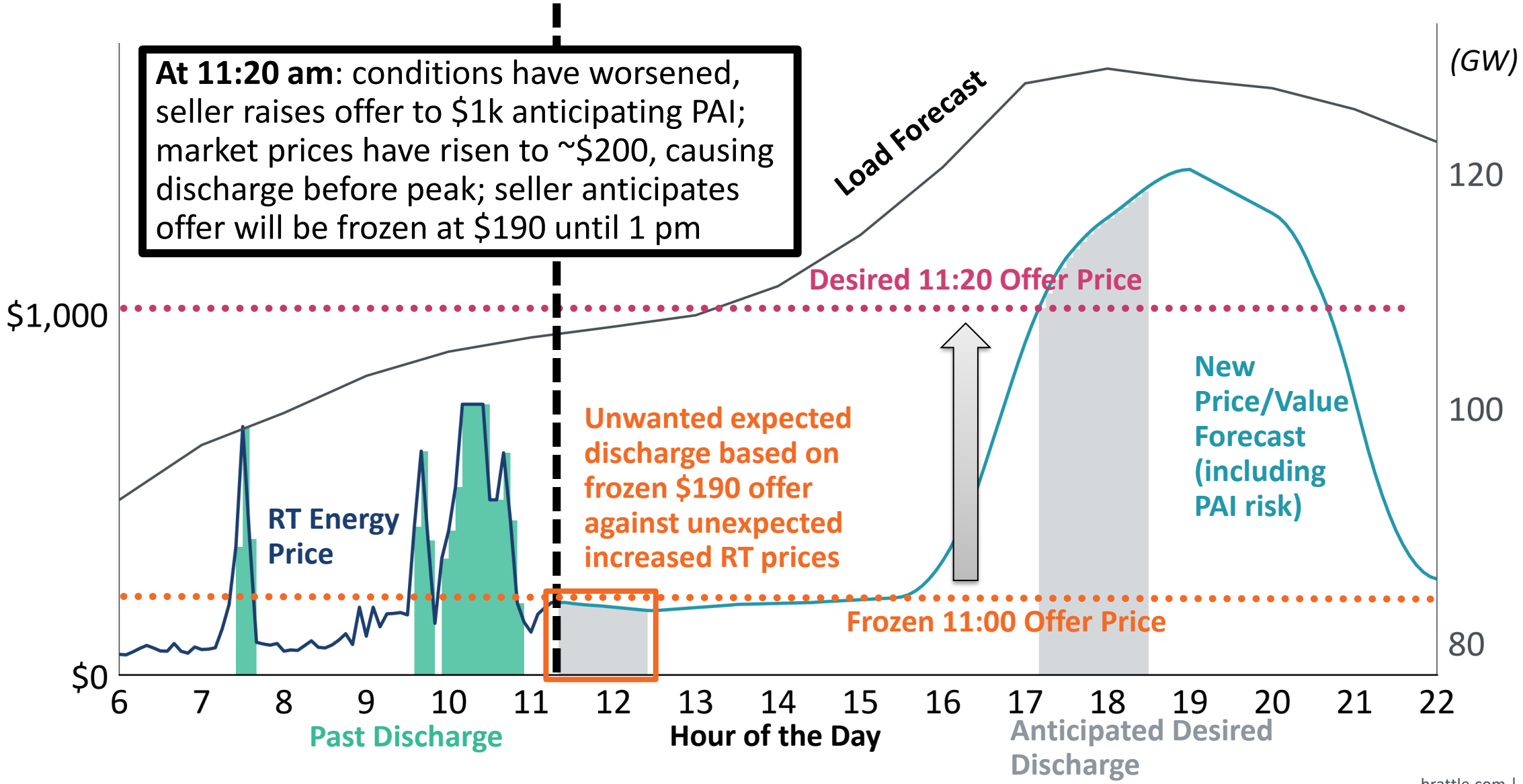
The three upcoming snapshot slides illustrate this with backcast-based analysis of battery market operations on December 23, 2022 (the first severe day of Winter Storm Elliott)



11 am: Efficient Operations As Battery is Awaiting Peak Conditions

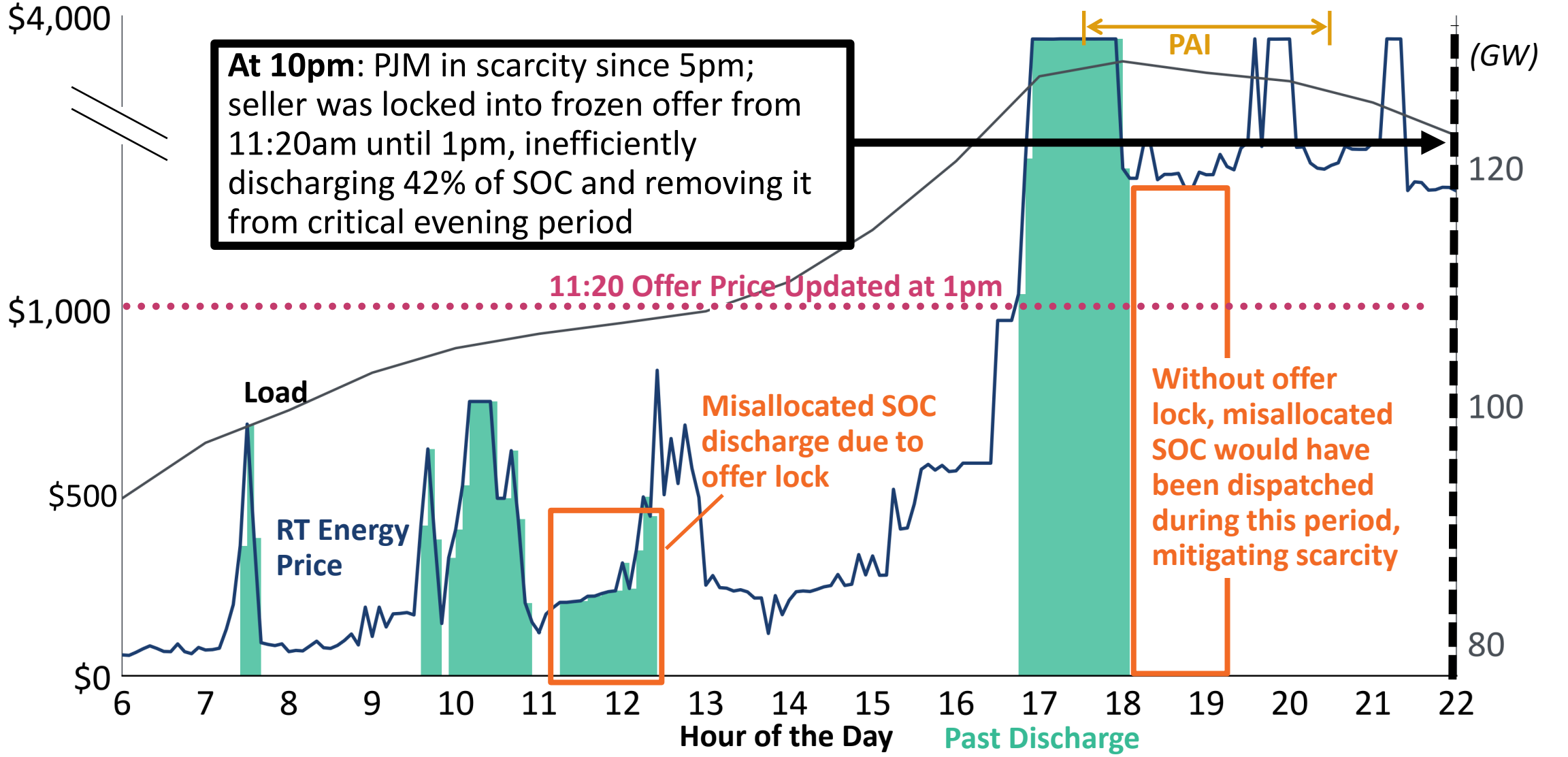


11:20 am: Battery Seller Price/Value Forecast Increases Sharply, and RT Prices Now Exceed Offer Price, Causing Early Discharge



10:00 pm: 42% of Battery SOC Misallocated Awaiting Price Update

Takeaway: offer price lock can lock-in discharge that runs counter to reliability, efficiency needs



Solution for Optimal Offer-Based Storage Schedules Under Changing Real-Time Conditions

Problem: Offer price lock can lock-in discharge that runs counter to reliability, efficiency needs

Solution: allow intra-hour offer price updates

REFORM CASE STUDY ercot

- **Initial rule (pre-2021):** Real-time energy offers were locked at the end of the Adjustment Period for the upcoming Operating Hour; subsequent updates became effective only in the next Operating Period
- **Storage carve-out (April, 2021):** NPRR986 allowed ESRs—but not thermal generators—roughly five-minute offer updates
- **Full reform (August, 2024):** NPRR1058 extended intra-hour bid and offer updates to all Resources, with QSEs required to provide a reason for updates submitted after the Adjustment Period

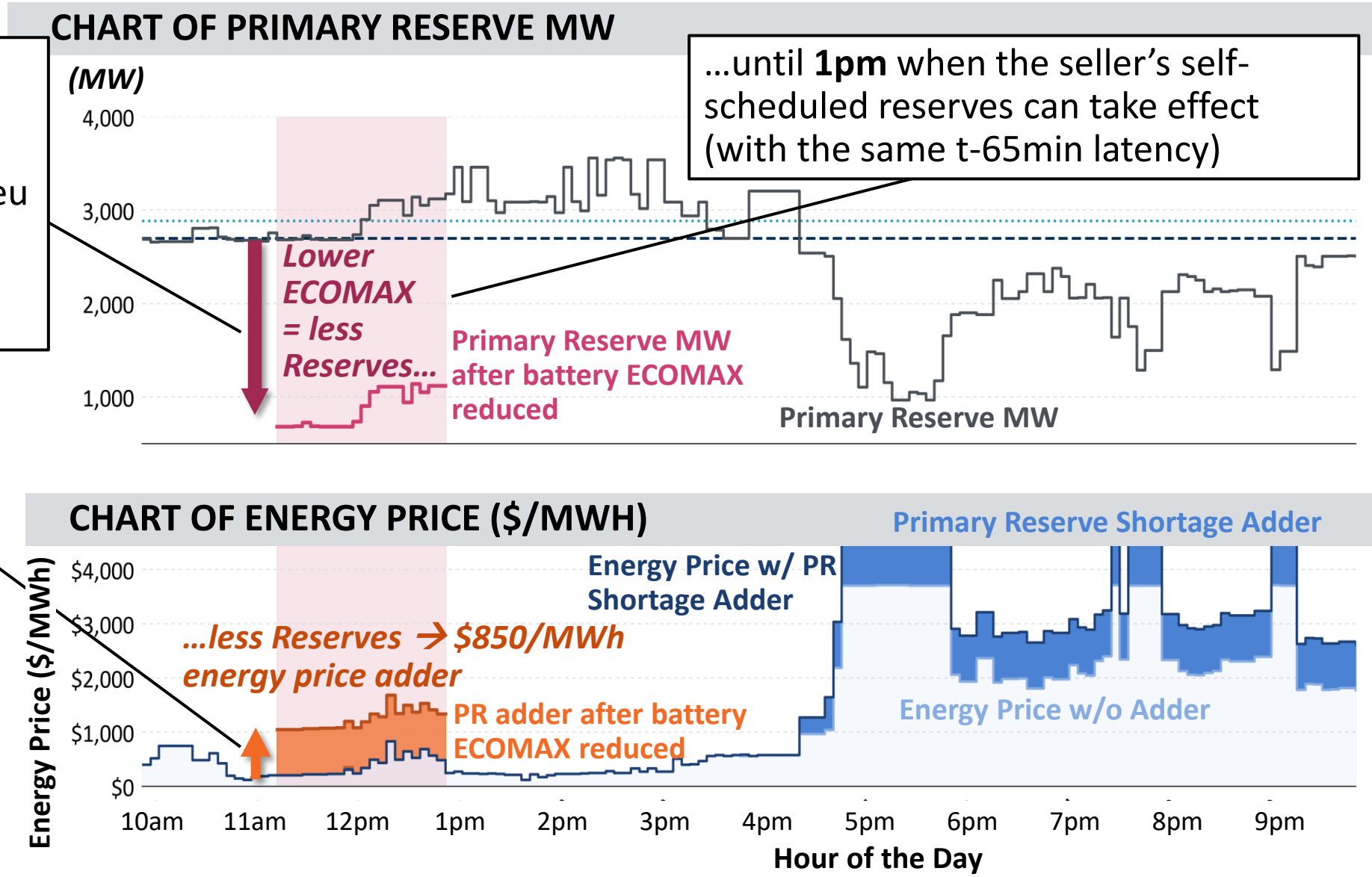
Issue with current fall-back to managing SOC without offer prices: physical hold-back for retaining SOC of batteries is an inefficient alternative to including of inter-hour opportunity cost in offers with frequent updates

Continuing the Example w/ Historical Prices and Reserves from Dec. 23, 2022: Reducing ECOMAX to Preserve SOC Would Increase Energy Prices

At 11:20 am: to preserve SOC for the time of peak need, the ESR seller might reduce ECOMAX to preserve SOC in lieu of increasing the offer price; this would reduced Primary Reserve…

…pushing the system into scarcity…

Takeaway: physical alternative to low-latency offer updates causes other inefficiency and price formation problems that can be avoided with fast offer price updates



Conclusions

Takeaways: Optimal Storage Operations Hold Charge for Period of Peak Value; Offer Prices Yield this Outcome with Inter-Hour Opportunity Cost

Mitigating storage offers at competitive inter-hour opportunity cost is both more complex and more consequential than mitigating offers from fuel-fired resources

	Offers from Fuel-Fired Resources	Offers from Storage
Complexity of estimating competitive cost-based offer	Simple calculation based on fuel price × heat rate; **relatively easy to accurately estimate**	Complex calculation based on the value of retaining stored energy given anticipated prices later in the day; **hard to accurately estimate**
Efficiency implications of too-low cost-based offer	Too-low cost-based offer leads to higher daily production costs and generally **lower overall prices**	Too-low cost-based offer leads to higher daily production costs and often **higher overall prices**
Reliability implications of too-low cost-based offer	None	**Suboptimal reliability due to misallocated early discharge of SOC**

Appendix: ISO/RTO Approaches to Battery Market Power Mitigation

ISO/RTOs Allowing Opportunity Costs in Mitigated Offer Prices

RTO	Is Inter-hour Opportunity Cost Bidding Allowed?	Market Power Mitigation Description
PJM	No	• Offers that fail Three Pivotal Supplier Test are mitigated • Mitigated offers in DA and RT based on charge cost and efficiency factor • Cannot increase RT offers above cleared DA offers (“Intraday Offers” rule)
ERCOT	Yes*	• Mitigation based on Constraint Competitiveness Test (the resource is mitigated only if it is under an uncompetitive constraint and has a shift factor below -0.2) • Storage offers are limited to alleviate congestion to avoid incurring costs above shadow price cap; allows batteries mitigated offers to be the highest price SCED will dispatch the battery to reduce congestion without manual actions • Batteries with a state of charge below 25% can bid up to the price cap even if they fail the Constraint Competitiveness Test
CAISO	Yes	• Market power mitigation based on the failure of Pivotal Supplier Test • CAISO-calculated opportunity cost allowed, can depend on SOC • RT mitigation uses DA prices; DA mitigation uses shadow prices from DA optimization
MISO	Yes	• Conduct + impact test. If resource fails, the bid is mitigated to a cost-based reference level • Allows for consultation between Market Participant and IMM to understand opportunity costs which can be used to set reference level
NYISO	Yes	• Allow the supplier to offer according to their own opportunity costs, by having any ex-ante mitigation (that exists only in zone J) incorporate opportunity costs that the supplier provides for each hour • Outside of zone J, there is no ex ante mitigation and all batteries can submit their own opportunity costs into the market with ex post review
ISO-NE	Yes	• Market power mitigation based on failure of Conduct + Impact Test • MPs can submit their own calculated opportunity costs but they must be able to analytically support the opportunity costs they submit with the IMM

*Note: ERCOT’s mitigated offer methodology is not based on opportunity costs directly, but resources with less than 25% state of charge are unmitigated meaning those resources can bid up to their opportunity costs. Mitigation of resources with greater than 25% state of charge is relatively lenient, but not directly tied to opportunity costs.

ISO/RTO Comparison of Opportunity Cost Calculation Engines

RTO	Opportunity Cost Calculation Process
PJM	• No opportunity cost engine for batteries • Opportunity cost engine for environmentally restricted fossil units that calculates opportunity costs based on a projection of annual profits from generating in the highest priced hours of the year (optimal dispatch for the generator) • The engine uses three projected forward series with different levels of volatility and an opportunity cost adder resulting from this engine is included in mitigated offers for these environmentally limited resources
ERCOT	• No centralized engine to calculate opportunity costs
CAISO	• CAISO-calculated opportunity cost allowed which can depend on a resource's state of charge • RT mitigation uses DA prices; DA mitigation uses shadow prices from DA optimization • The outputted sloped offer curve is based on battery SOC with bottom end set at either marginal cycling cost or the 4th highest DA LMP of the day and the slope set based on the difference between the 1st and 4th highest prices hour of the day
MISO	• No centralized engine calculate opportunity costs for storage resources (sellers can consult directly with the IMM to set opportunity costs)
NYISO	• NYISO allows the seller to offer according to their own opportunity costs, by having any ex-ante mitigation (that exists only in Zone J) incorporate opportunity costs that the seller provides for each hour • Outside of Zone J, there is no ex ante mitigation and all batteries can submit their own opportunity costs into the market with ex post review • However, If batteries choose not to submit their own opportunity costs, NYISO will estimate opportunity costs using a centralized opportunity cost calculation engine • For opportunity cost in the DA Market: NYISO opportunity cost calculation relies on prices from the past 90 days; For RT: NYISO opportunity cost calculation relies on DA prices for the same day
ISO-NE	• No centralized engine to calculate opportunity costs (sellers can meet with IMM to discuss opportunity costs calculation method)

Real-Time Offer Flexibility Across RTOs

Key observation: Other RTOs provide flexibility to increase unmitigated storage offers, unlike PJM

RTO	Can offers increase in real time?	Real Time Bid Latency (before dispatch)
PJM	**No**	65 minutes before dispatch hour
ERCOT	**Yes**	5 minutes before dispatch interval
CAISO	**Yes**	75 minutes before dispatch hour
MISO	**Yes**	30 minutes before dispatch hour
NYISO	**Yes**	75 minutes before dispatch hour
ISO-NE	**Yes**	30 minutes before dispatch hour

REFORM CASE STUDY: ercot

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Appendix: Sources for ISO/RTO Comparisons

RTO	Sources
PJM	• Sources: PJM, Manual 15: Cost Development Guidelines, November 25, 2024, pg. 82.
ERCOT	• Sources: ERCOT, NPRR 1255 Discussion, May 19, 2025; ERCOT, ERCOT Nodal Protocols, July 21, 2025, pg. 6-17.
CAISO	• Sources: CAISO, Energy Storage Enhancements: State of Charge Implementation Update, October 2, 2023; CAISO, Fifth Replacement FERC Electric Tariff, Section 39, June 25, 2025.
MISO	• Sources: MISO, FERC Electric Tariff, November 30, 2024, pgs. 29, 210; MISO, Business Practice Manual 2: Energy and Operating Reserve Markets, September 30, 2024, pg. 86.
NYISO	• Sources: NYISO, NYISO Market Services Tariff, July 16, 2025; NYISO, NYISO Market Services Tariff: Attachment F – Bid Restrictions.
ISO-NE	• Sources: ISONE, Market Rule 1 Appendix A: Market Monitoring, Reporting and Market Power Mitigation, February 28, 2025, pgs. 37-49; ISONE, Market Rule 1: Standard Market Design, February 28, 2025, pgs. 59, 61, 62, 83, 100; ISONE, Day-Ahead Energy Markets: New England Wholesale Energy Markets (NEWEM) , May 21-22, 2025.