

Performance of Opportunity Cost Methodology in 2026 Select Emergency Conditions

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Purpose

Provide simulation-based analysis on the impact of reflecting opportunity costs in offer on ESR deployments during Winter Storm Fern and the July 2026 heatwave

Key Takeaways

- **Restricting offers to charging costs only results in sub-optimal dispatch:** Only reflecting charging costs in cost-based offers (status quo) leads to premature dispatch of battery storage resources, rendering them unavailable during the tightest system conditions.
- **“Max DA LMP” based Opportunity Cost performed remarkably well during the July heatwave:** Single interval dispatch based on offer reflecting Max DA LMP opportunity cost can emulate the optimal deployment almost exactly during the July 2026 heatwave.
- **“Max DA LMP” based Opportunity Cost would have been sub-optimal for some intervals during Winter Storm Fern:** For some days during the Winter Storm Fern, the RT LMP was above the Max DA LMP for an extended period. Consequently, during such periods, an ESR bidding in continuous mode would deviate from an optimal schedule when the offer is capped at Max DA LMP. On the other hand, the “Max DA LMP” approach still performs significantly better than the “charging cost only” approach.

Opportunity Costs for Energy Storage Resources in the Real-Time Market — Recap

Why do we Need to Account for Opportunity Cost?

- **Opportunity cost is a real cost for energy limited resources**
 - **Limited State of Charge:** ESRs have SOC limits; actions that deplete SOC in one interval make it unavailable in a later interval.
 - **Short-Run Decisions vs. Long-Run Optimal Dispatch:** PJM's economic dispatch optimizes over the short run (on hourly basis in DA and 5-minute basis in RT). Energy-limited ESRs will not be dispatched optimally over long run unless allowed to reflect opportunity cost of short-run actions in their offers
- **Opportunity cost is not reflected in cost offers today**

	CAISO	NYISO	MISO	PJM
Allows Inter-hour Opp Costs?	✓	✓	✓	✗

This is a reliability issue.

If PJM is relying on a large battery fleet for resource adequacy, cost offers that do not recognize opportunity cost may result in premature dispatch of this resource, leaving the RTO with fewer MW in tight system conditions.

- The RT cost offer cap calculated as the maximum of the battery's incremental energy cost and its opportunity cost, capped at \$2,000.

Cost Offer Cap = Max(Incremental Energy Cost, Opportunity Cost), capped at \$2,000

Incremental Energy Cost

Charging Cost + VOM
Adder

where:

Charging Cost = Average
of N* lowest DA LMPs at
applicable pnode/
Efficiency Factor

Opportunity Cost

Maximum DA LMP at
applicable pnode

* N = battery duration

Opportunity Cost

Maximum DA LMP at
applicable pnode

- DA LMPs are a good proxy for RT prices, and their use strikes the right balance between simplicity and accuracy.
- The use of the max DA LMP is sensible because the calculation serves as a cap on the cost-based offer, rather than a default value inserted by the RTO. Market participants may submit values that are below this cap.
 - Because batteries derive revenue from energy arbitrage, they have an incentive to submit lower cost-based offers if necessary to clear during the highest-priced hours.
- Meanwhile, reliance on the max DA LMP as the opportunity cost offers sufficient protection from premature RT dispatch and protects PJM from entering tight operating conditions with a depleted battery fleet

- Because RT prices may deviate from DA prices, an opportunity cost adjustment may be warranted.
- The following adjustments may be reasonable to prevent premature dispatch:
 - **Multiplier:** A multiplier on the opportunity cost that reflects deviations between RT and DA LMPs under tight system conditions.
 - **Emergency Conditions Trigger:** Opportunity cost may be permitted to go higher, up to \$2,000 under specific emergency conditions (e.g., at least an EEA1/Max Gen Alert)
 - **RT Price Trigger:** Opportunity cost may be adjusted in RT if prices are sufficiently higher than the max DA price.
- Specific conditions and adjustment rules would need to be developed if any of the above are to be adopted.
- Interplay between any new adjustment and the existing limited 10% cost offer adder should be considered.

Simulation Setup

The simulations compare ESR schedules from single interval optimization with two types of cost offers with an “optimal” schedule from multi-interval optimization in two zones during hot weather and cold weather events

ESR Parameters

Duration	Discharge ECOMAX	Charge ECOMIN	Discharge Efficiency	Charge Efficiency
4 hr. Full Discharge	100 MW	-100 MW	100%	80%

Two LMP Zones

Dominion and COMED: Chosen due to high potential for ESR integration and distinct congestion patterns. ESR dispatch utilizes aggregate zonal RT LMP trajectories

Scenarios

- 1. Multi-Interval “Optimal” Schedule:** Optimized over 24-hour rolling windows
- 2. Single Interval Charging Cost Offer Cap:** Single interval dispatch based on cost offer. The ESR can offer to its charging cost over a 48-hour lookback (+ 10% adder)
- 3. Single Interval Opportunity Cost Offer with Max DA LMP Cap:** Single interval dispatch based on cost offer capped at maximum DA LMP

Extended Hot and Cold Weather Events in 2026

- Around Winter Storm Fern: Jan 24 through Feb 1, 2026
- Around Summer Heatwave: June 29 through July 4, 2026

Simulation 1: Multi-Interval Optimal Dispatch (Benchmark)

Objective

Maximize utility (based on product of Power output and RT LMP) over a 24-hour rolling window with 1-hour shifts between windows

Constraints

- **SOC Dynamics:** The evolution of SOC for each 5-min interval is modeled as a linear equation
- **SOC Limits:** For each interval, SOC should be between min (0%) & max (100%)
- **Charge and Discharge Limits:** For each interval, Power output should be between charge ECOMIN and discharge ECOMAX
- **Cycling Limits:** Number of transitions between charging and discharging in any window should not exceed the window length divided by the ESR duration
- **Initial conditions on SOC and Power are known**

Idealized Optimal Trajectories to Provide a Benchmark

- For each window, the price trajectory is known (**perfect foresight of exogeneous price**)
- From each window, the optimal SOC and Power schedule for the first hour is used
- Continuity between subsequent windows maintained via initial conditions on SOC & Power
- The optimization is only performed over RT LMP (& not DA LMP) under the assumption that RT LMP is the best representation of real-time system conditions

Simulation 2: Dispatch based on “Charging Cost” Cost Offer

Objective

Maximize utility — product of Power output and difference between RT LMP and cost offer — over a single interval using cost offer capped at *adjusted* charging cost

Constraints

- **SOC Limits:** For each interval, SOC should be between min (0%) & max SOC (100%)
- **Charge and Discharge Limits:** For each interval, Power output should be between charge ECOMIN and discharge ECOMAX

Cost Offer Determination

- For each operating hour, the charging cost is the realized cost to charge over a 48-hour lookback window, ending two hours prior to the operating hour, normalized per unit MWh considering ESR efficiency. A 10% adder is applied per Manual 15, Section 2.9
- An ESR with a noisy price forecast (modeled as Gaussian noise with increasing variance over each 24-hour window) can estimate a desired schedule
- For each interval in which the ESR wishes to discharge based on noisy price forecasts, a very low (negative) cost offer is submitted
- For each interval in which the ESR wishes to charge, the offer is at the cost offer cap

This simulates dispatch under an approximation of the status quo cost offer methodology.

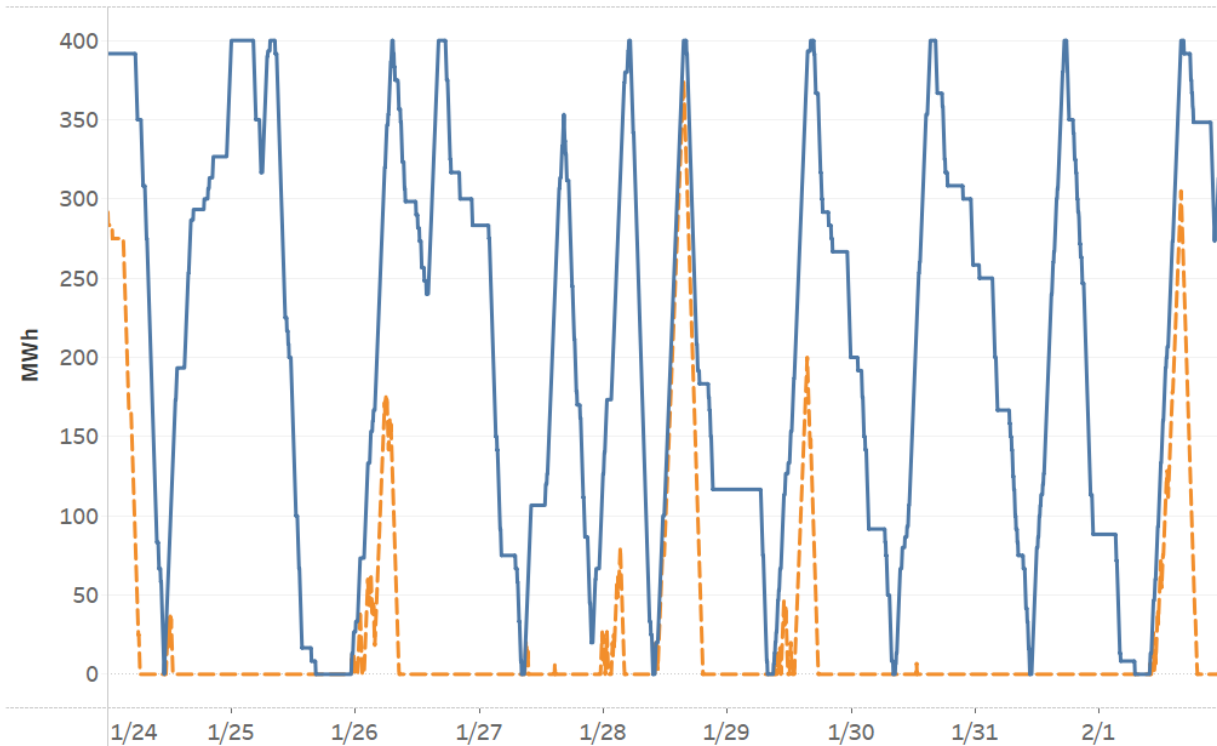
Simulation 3: Dispatch under Max DA LMP “Opportunity Cost”

Objective	Maximize utility — product of Power output and difference between RT LMP and cost offer — over a single interval using cost offer capped at max DA LMP
Constraints	• SOC Limits: For each interval, SOC should be between min (0%) & max SOC (100%) • Charge and Discharge Limits: For each interval, Power output should be between charge ECOMIN and discharge ECOMAX
Cost Offer Determination	• An ESR with a noisy price forecast (modeled as Gaussian noise with increasing variance over each 24-hour window) can estimate a desired schedule • For each interval in which the ESR wishes to discharge based on noisy price forecasts, a very low (negative) cost offer is submitted • For each interval in which the ESR wishes to charge, the offer is at the cost offer cap • For the remaining intervals, the ESR will try to maintain SOC, effectuated by an offer curve at 0 MW over the range of expected RT LMP, with a cap of max DA LMP

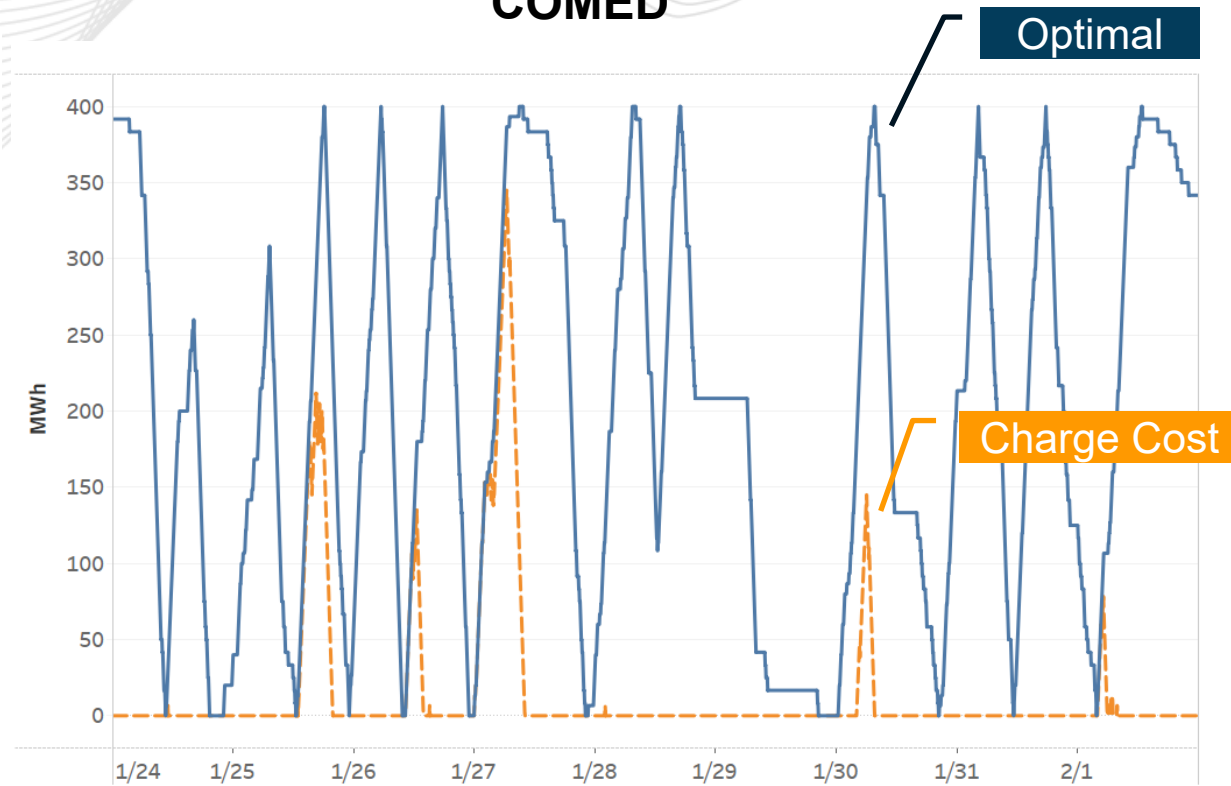
This simulates dispatch under the RT opportunity cost methodology put forward by PJM.

Simulation Results: Winter Storm Fern

DOM

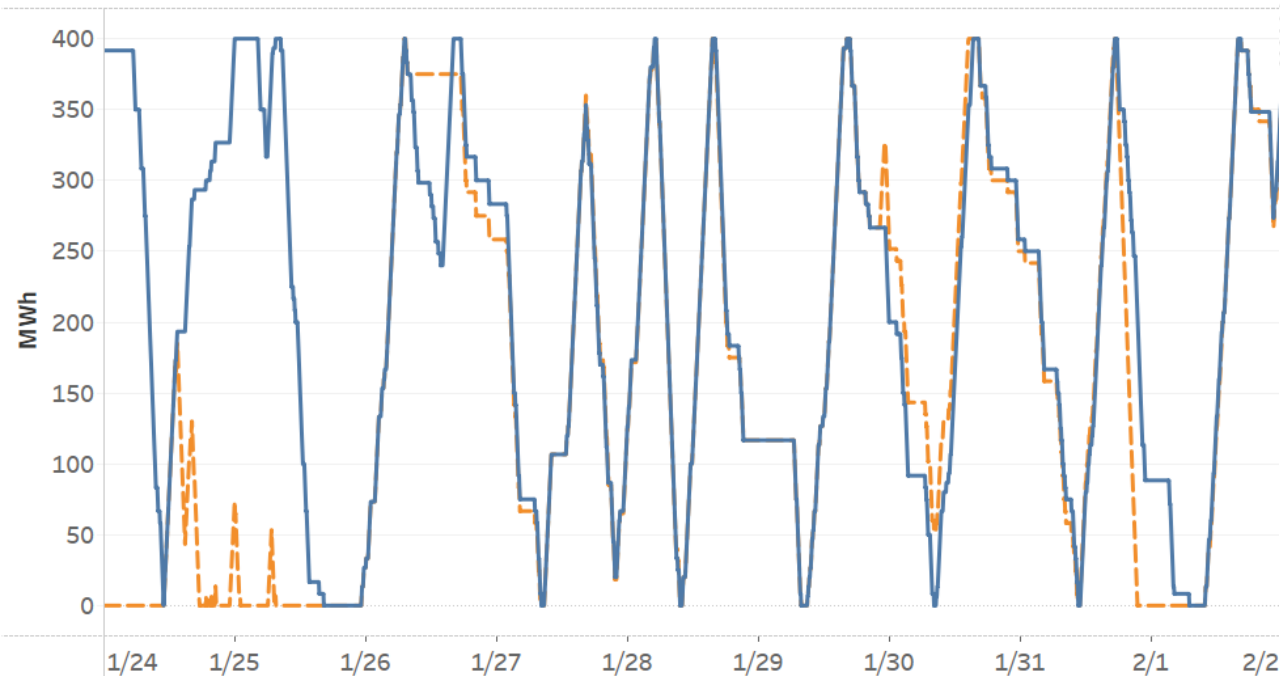


COMED

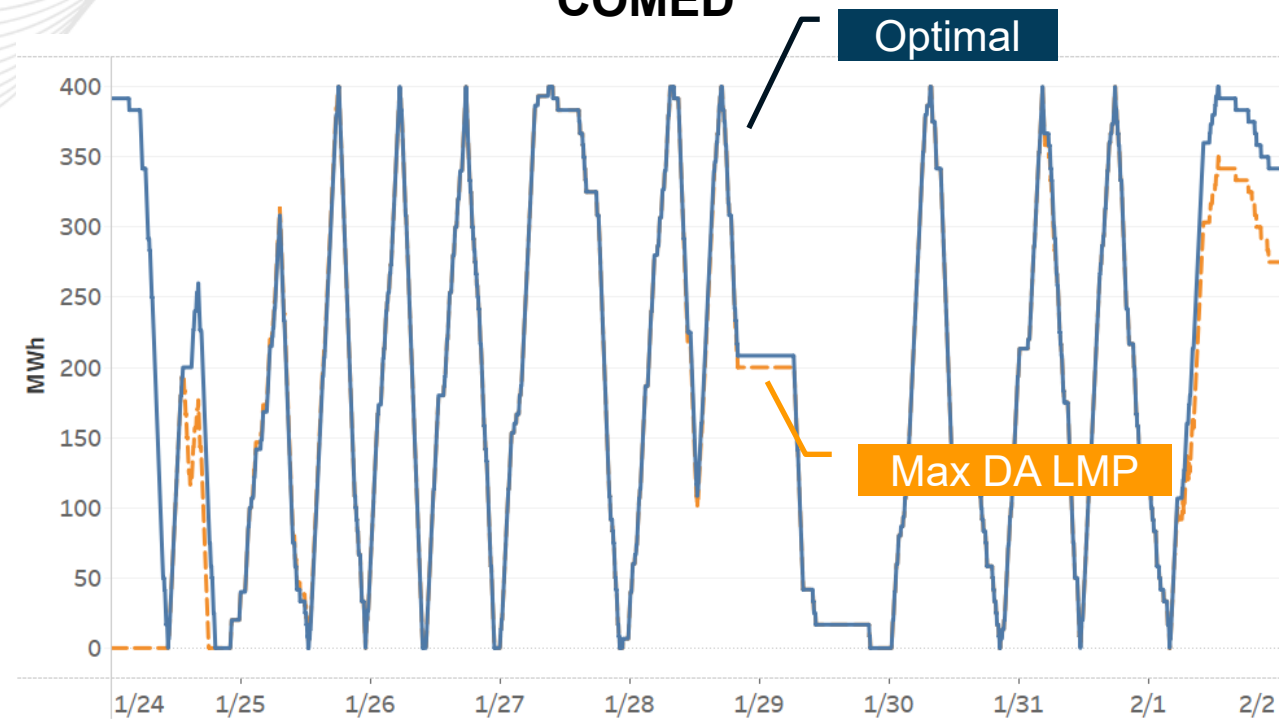


The use of historic charging cost as the sole basis for the cost offer is wholly misaligned with the Optimal SOC trajectory in both DOM & COMED. This renders the ESR unavailable during the times of highest need.

DOM



COMED

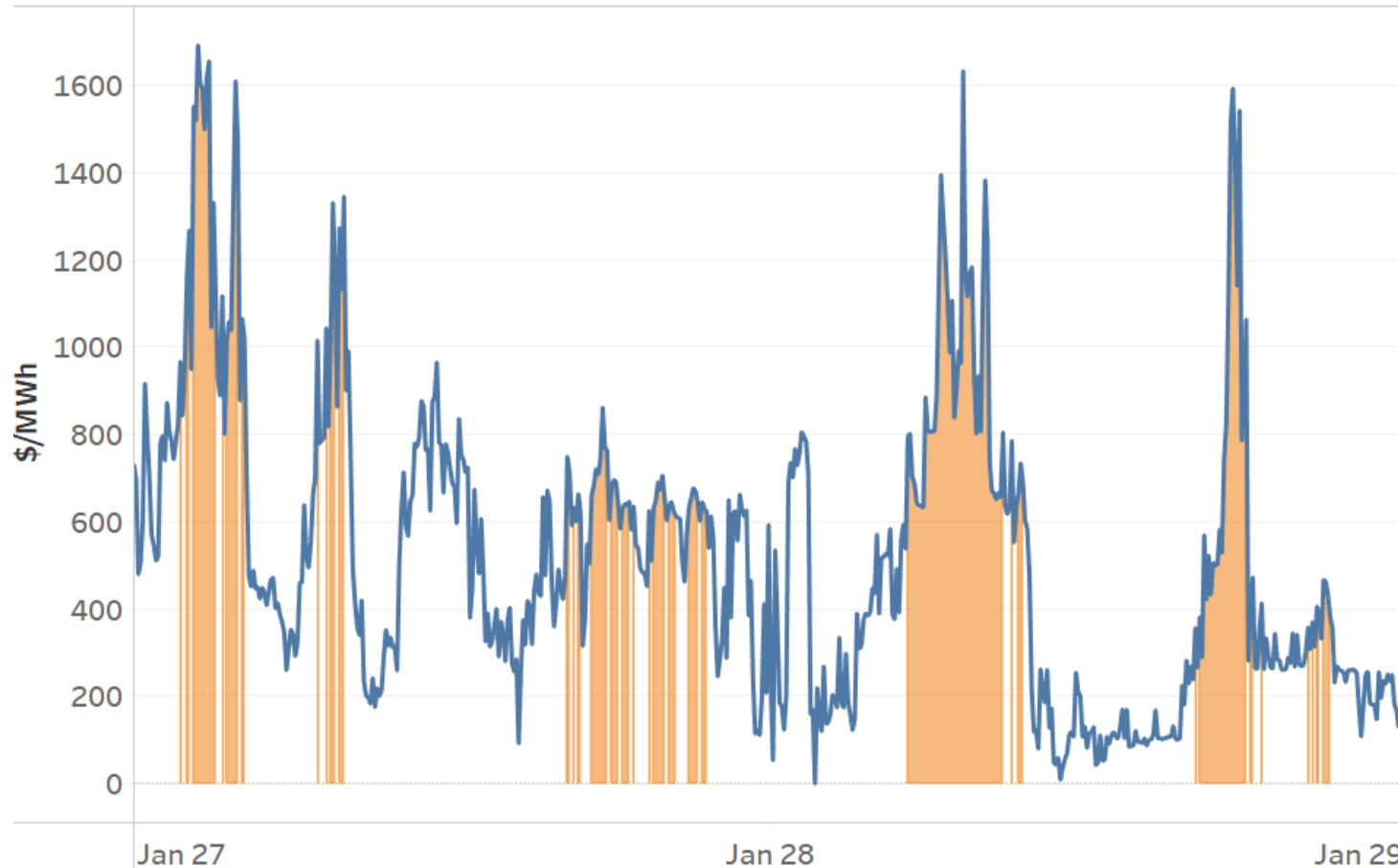


Accounting for opportunity cost capped at max DA LMP in the cost offer better aligns the single interval dispatch with the optimal SOC trajectory. However, the max DA LMP cap is still not sufficient on 1/24-1/25 and 2/1 in DOM.



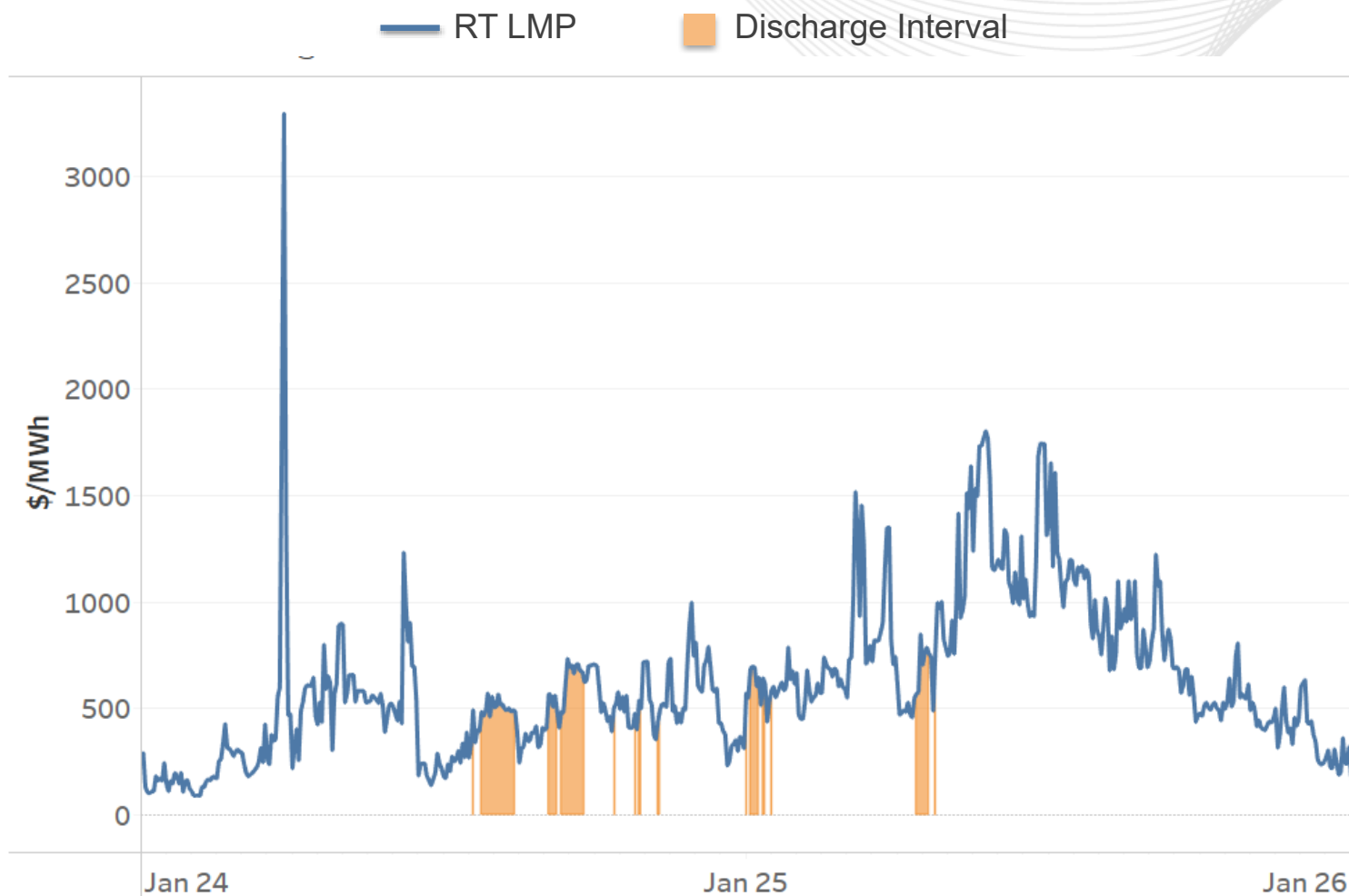
Discharge Under OC Cap of Max DA LMP (DOM, Jan 27 & 28)

— RT LMP ■ Discharge Interval



During the coldest days in Winter Storm Fern, offers reflecting an opportunity cost capped at max DA LMP ensured that the battery discharged during the hours in which the grid was most constrained, as represented through RT LMP.

Discharge Under OC Cap of Max DA LMP (DOM, Jan 24 & 25)

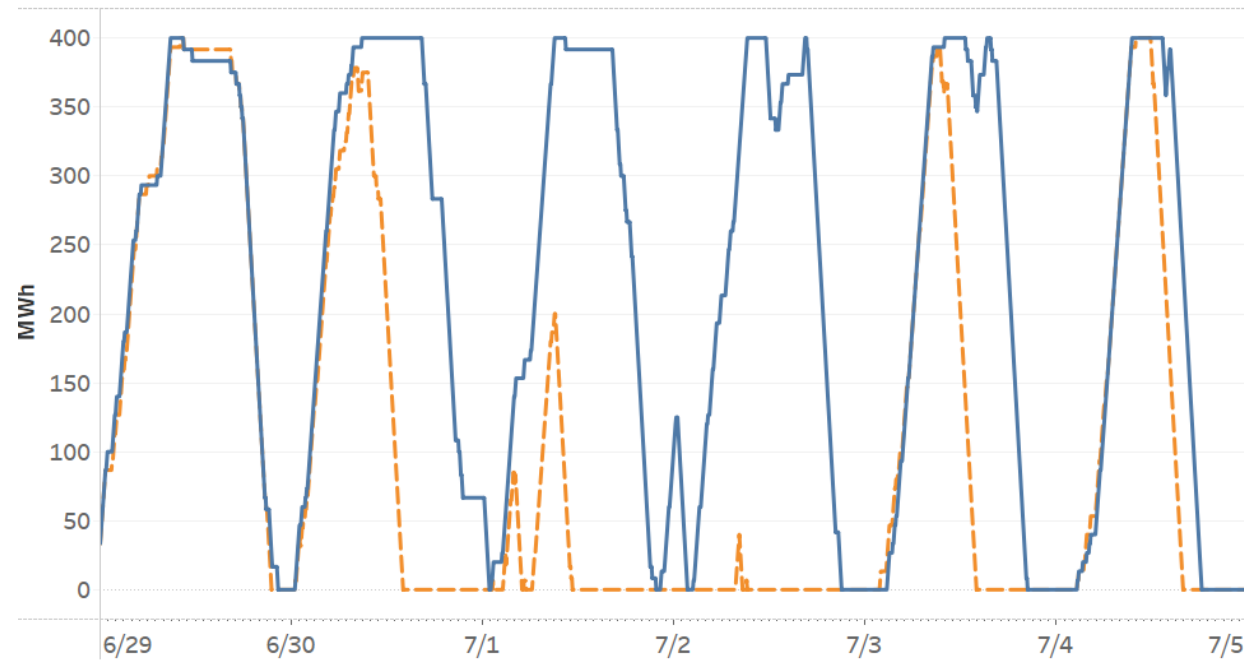


On Jan 24-25, 2026, the RT LMP in DOM was above the max DA LMP for an extended period. Consequently, with a cost offer capped at max DA LMP, an ESR operating in continuous mode and with a depleted SOC at the start of Jan 24 is dispatched prematurely and runs out of SOC prior to the highest RT LMP intervals, thereby not being able to discharge during the hours in which the grid is most constrained.

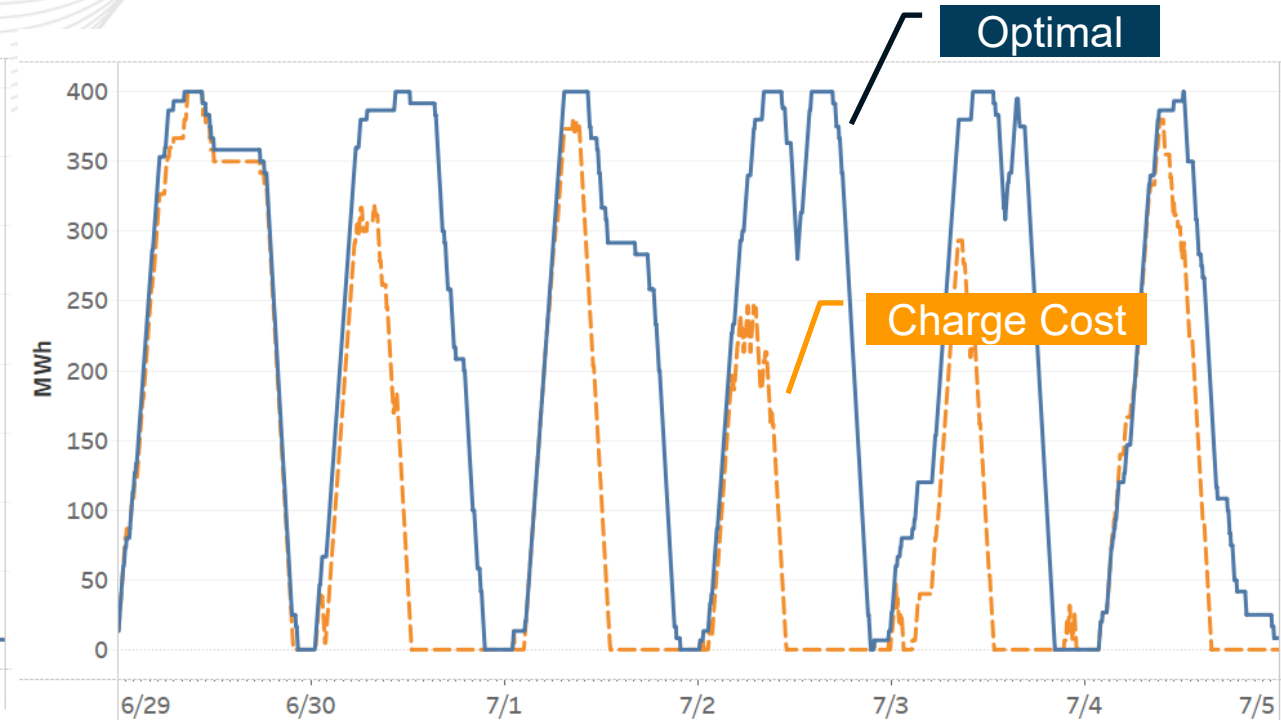
Simulation Results: July 2026 Heatwave

Optimal vs. Status Quo (Charging Cost) SOC – Heatwave

DOM



COMED



In both DOM and COMED, the use of historic charging cost as the sole basis for the cost offer leaves the battery depleted and unavailable during the hours of highest need on some key dates, including 7/2.

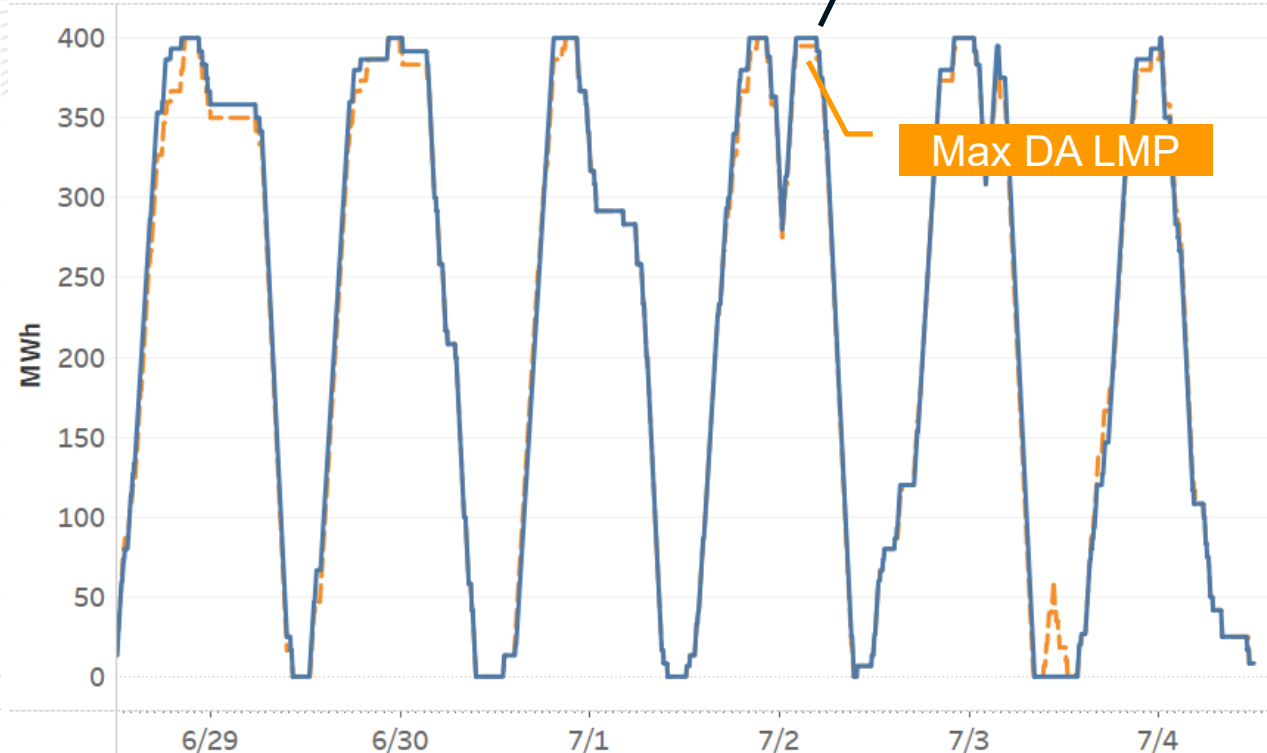
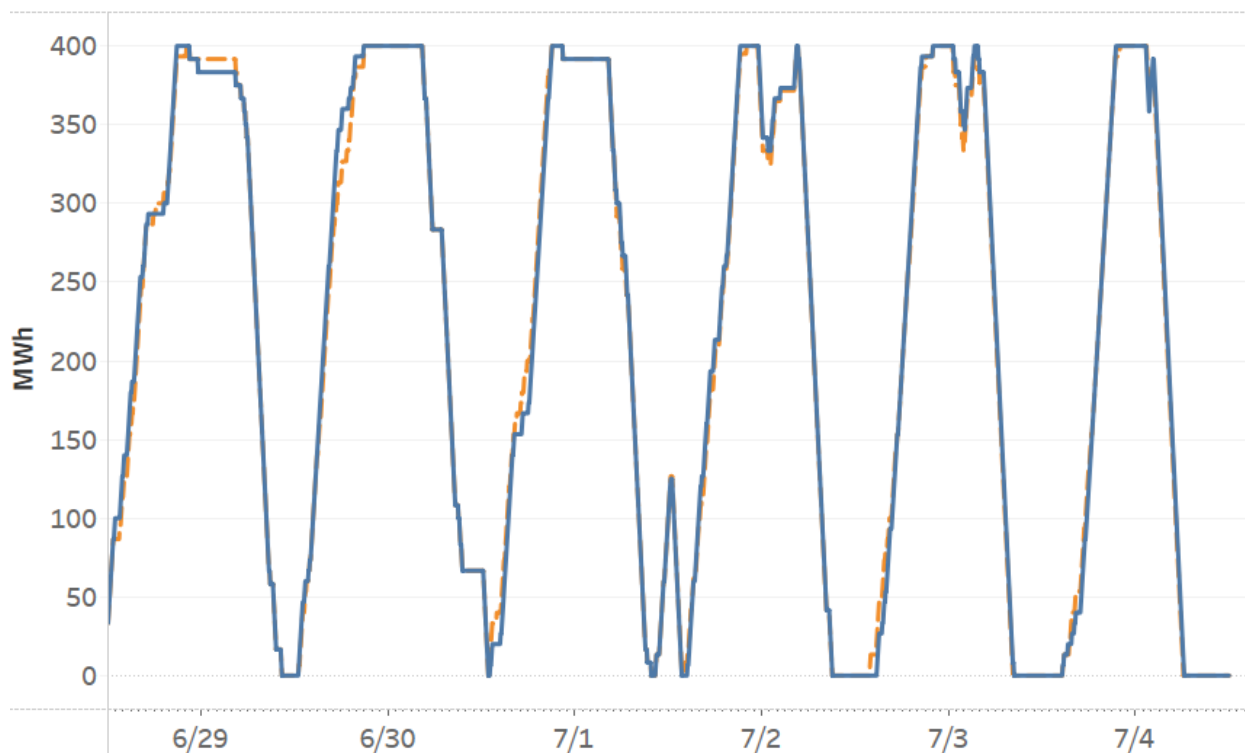
Optimal vs. Opp. Cost (Max DA LMP) SOC – Heatwave

DOM

COMED

Optimal

Max DA LMP

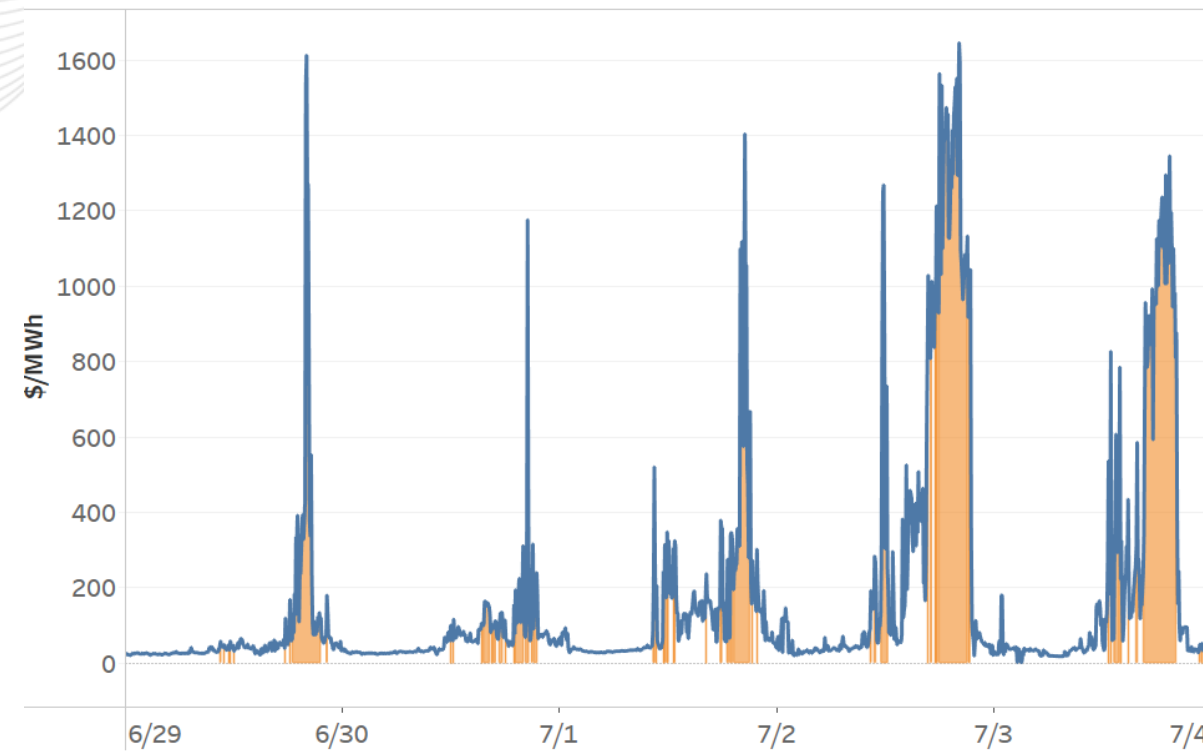
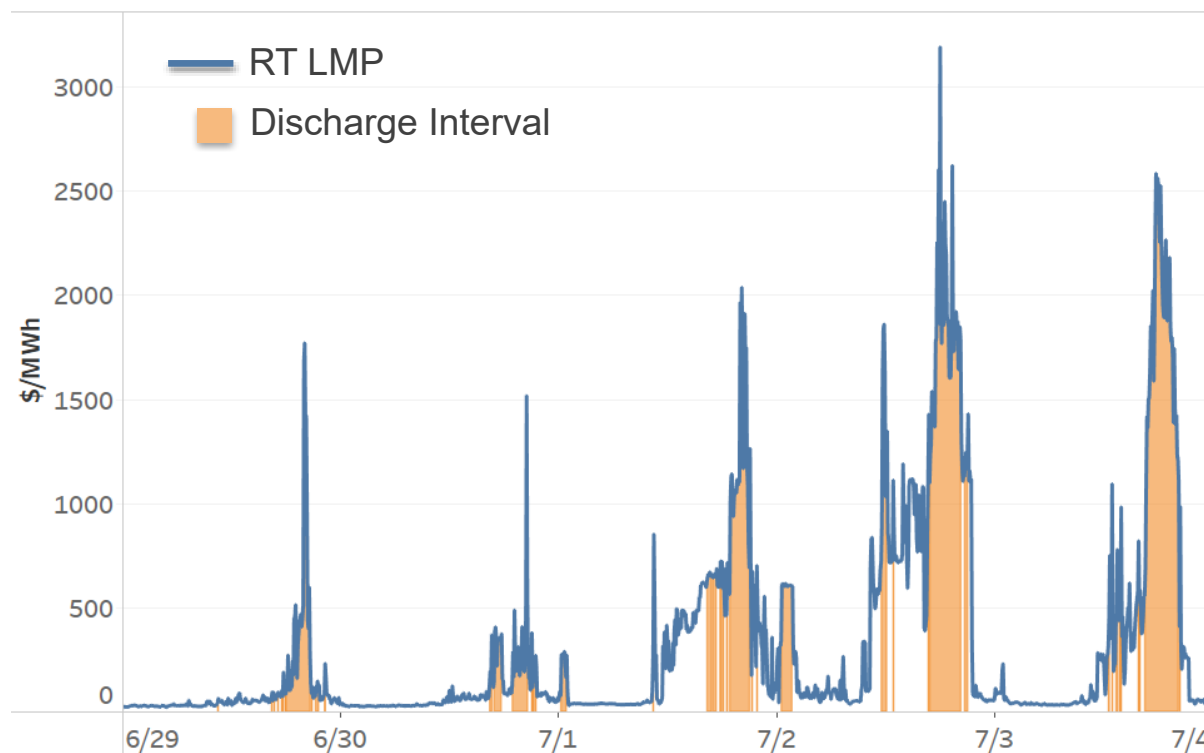


In both DOM and COMED, accounting for opportunity cost capped at max DA LMP in the cost offer ensures near perfect alignment between the single interval dispatch and the optimal SOC trajectory during the heatwave

Discharge Under OC Cap at Max DA LMP

DOM

COMED



Representation of opportunity costs capped at max DA LMP ensures that ESRs discharge during the highest RT LMP hours (proxy for tightest constrained grid conditions) in both Dominion and COMED

Representation of Opportunity Costs in ESR offers leads to better alignment between ESR dispatch and grid reliability needs and improves market efficiency. The simulations demonstrate that including opportunity costs enables ESRs to schedule themselves optimally and ensure that they are available for dispatch during tight grid conditions. The status quo charging cost methodology fails during such times.

OC Cap at Max DA LMP

The opportunity cost in the Real-Time Market capped at the maximum LMP from the day-ahead market has remarkable performance during the July 2026 heatwave for LMPs in the Dominion and COMED zones. However, the ESR is forced off the optimal schedule under this cap in Dominion on Jan 24-25 and Feb 1. The status quo cost offer is wholly insufficient during both events.

Potential OC Cap Adjustments

When RT conditions vary substantially from DA leading to an extended period during which RT LMPs exceed DA LMP, a multiplier on the max DA LMP, or a trigger to a higher cap, can prevent sub-optimal dispatch.

SOC Management

Accounting for SOC constraints for both energy and reserve assignments for ESRs in the Energy & Ancillary Services Markets ensures feasible dispatch aligned with grid reliability needs.

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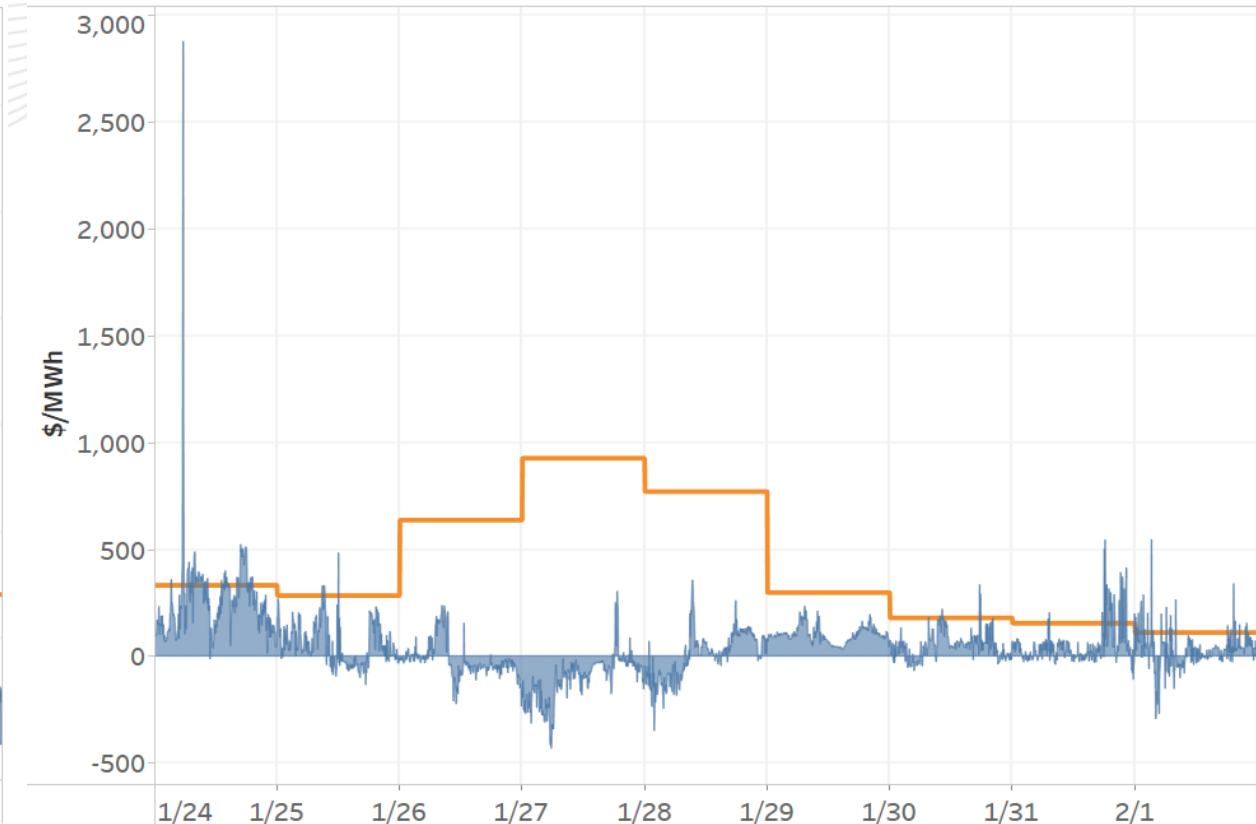
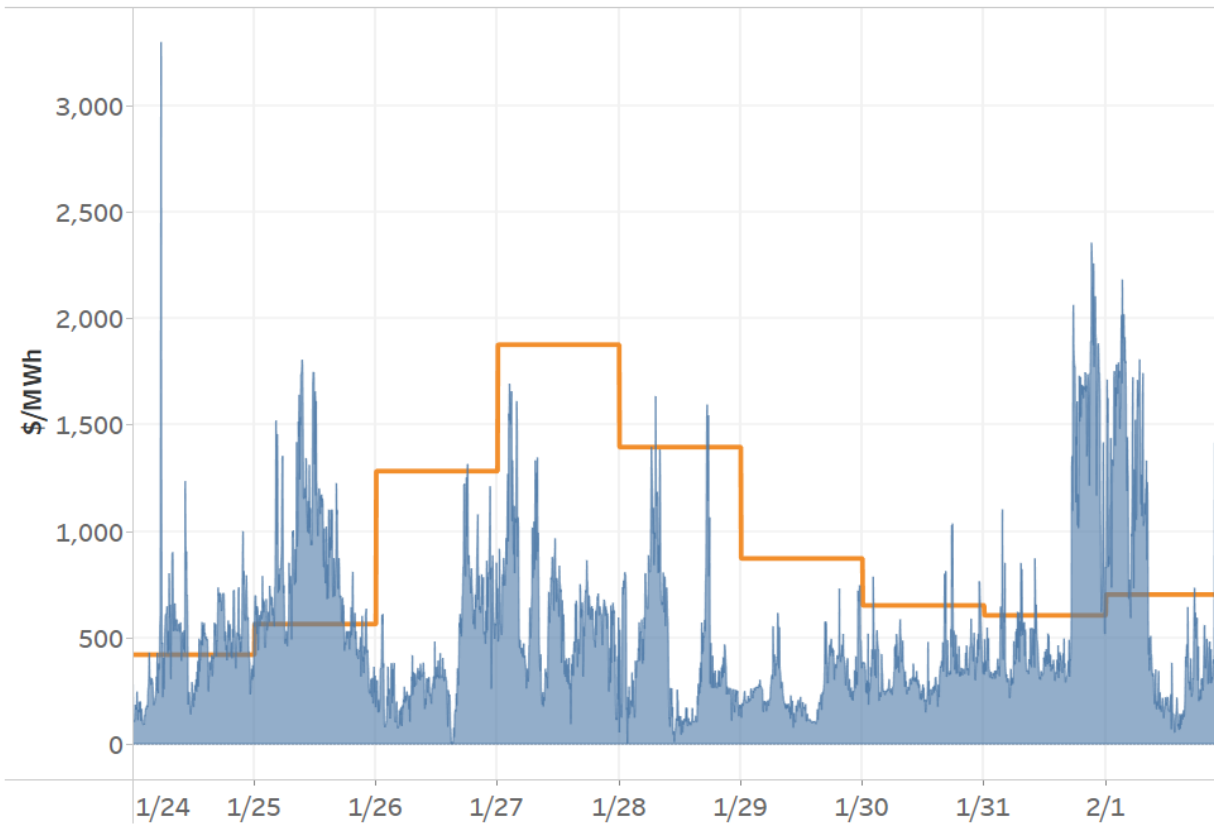


Appendix

RT LMP vs. Max DA LMP — Winter Storm Fern

DOM

COMED



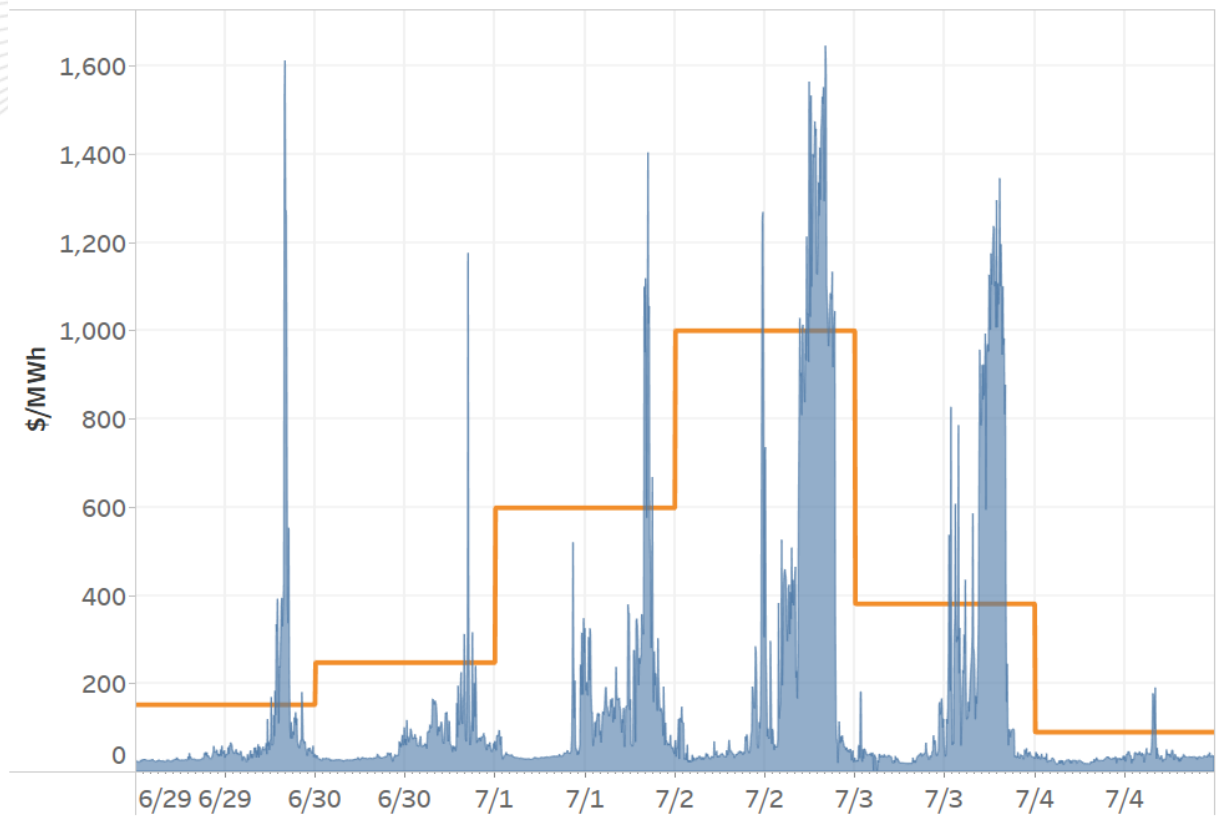
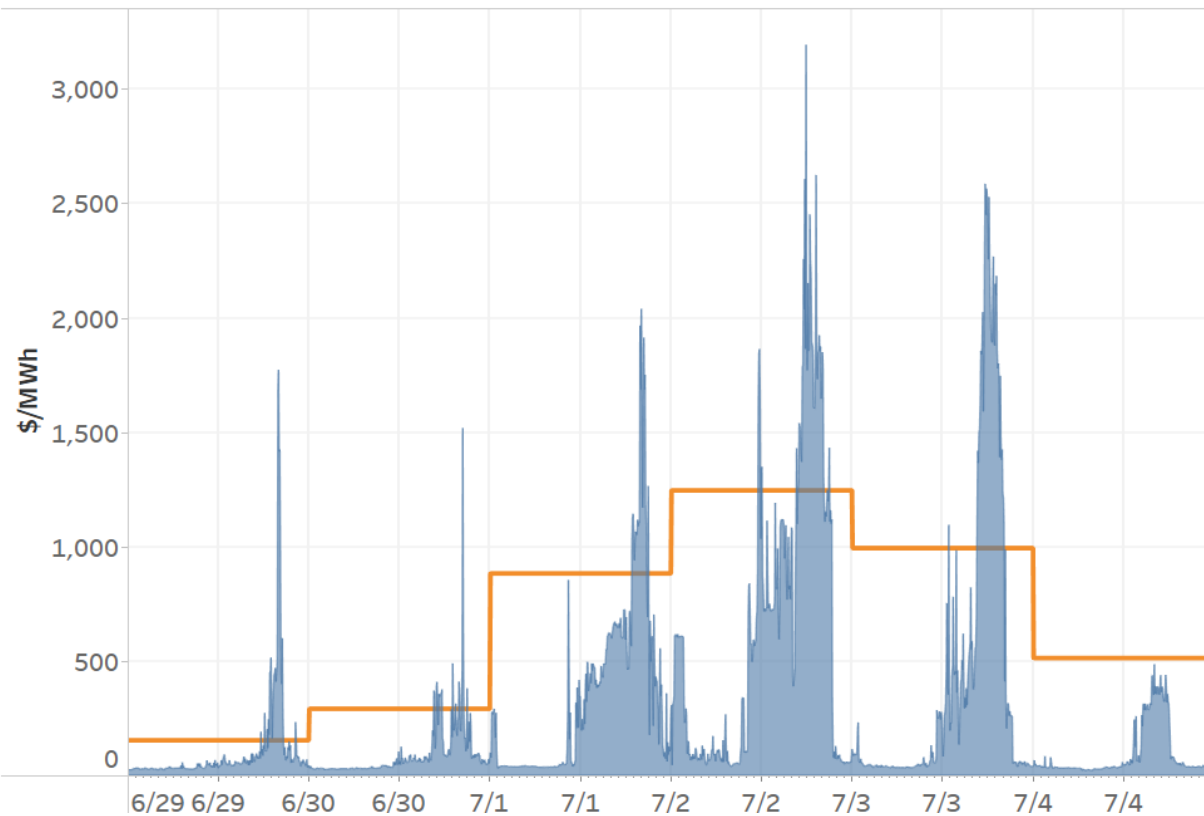
Dominion had extended periods of time with RT LMP exceeding max DA LMP.
Max DA LMP was above RT LMP for most intervals in COMED.

■ RT LMP
■ Max DA LMP

RT LMP vs. Max DA LMP – Summer Heatwave

DOM

COMED



In general, during the heatwave, the RT LMPs only exceeded max DA LMP for less than 4 hours per day (ESR duration) in both DOM and COMED

■ RT LMP
■ Max DA LMP