Real-Time Dispatch Multi-Interval Optimization

Rahul Kalaskar
Manager, Market Analysis

Guillermo Bautista Alderete
Director, Market Analysis and Forecasting

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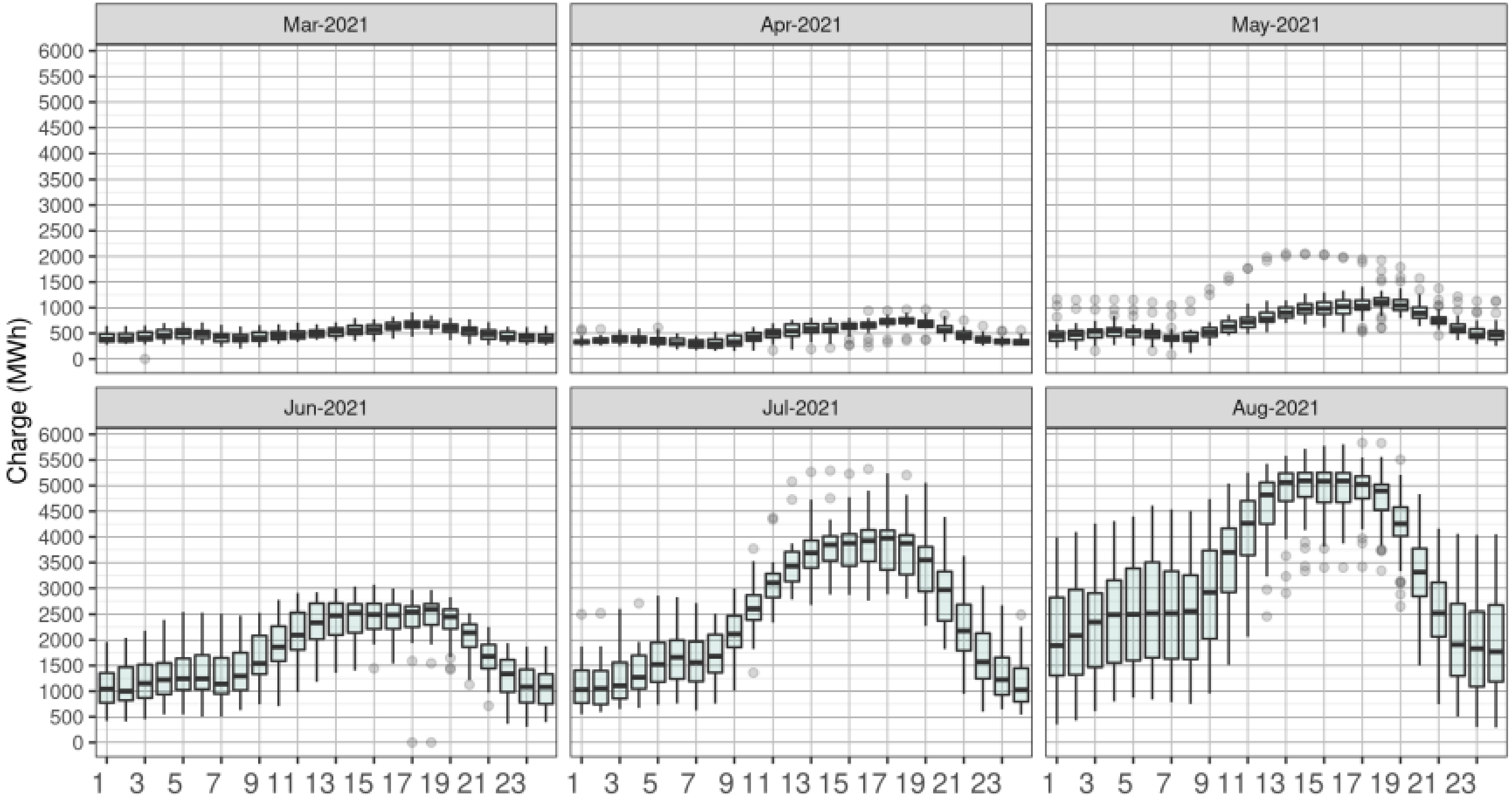
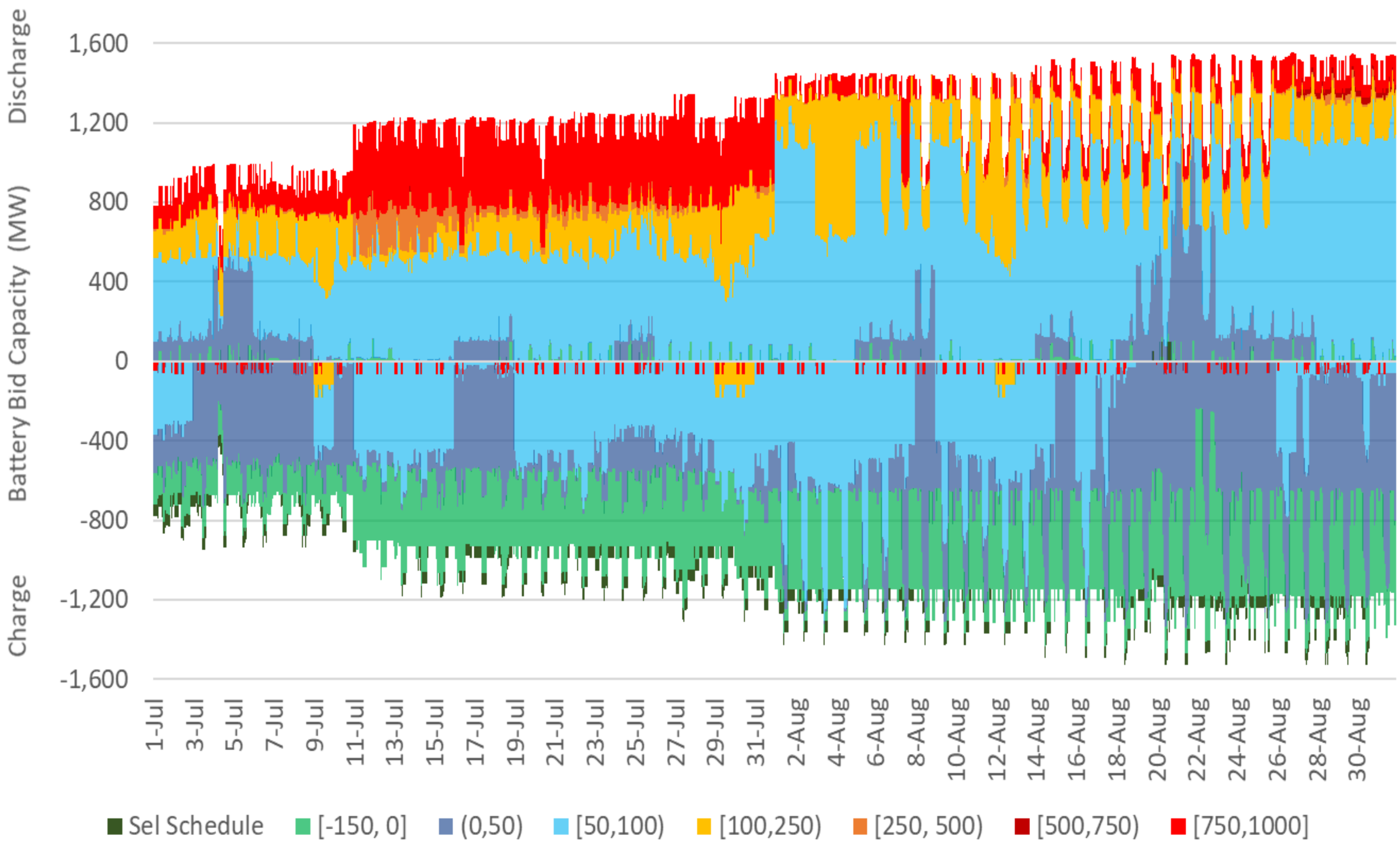
ISO's system has seen a fast growth of storage resources in the last six months



How storage resources economically participate in the ISO's market seems to be evolving –day-ahead bids



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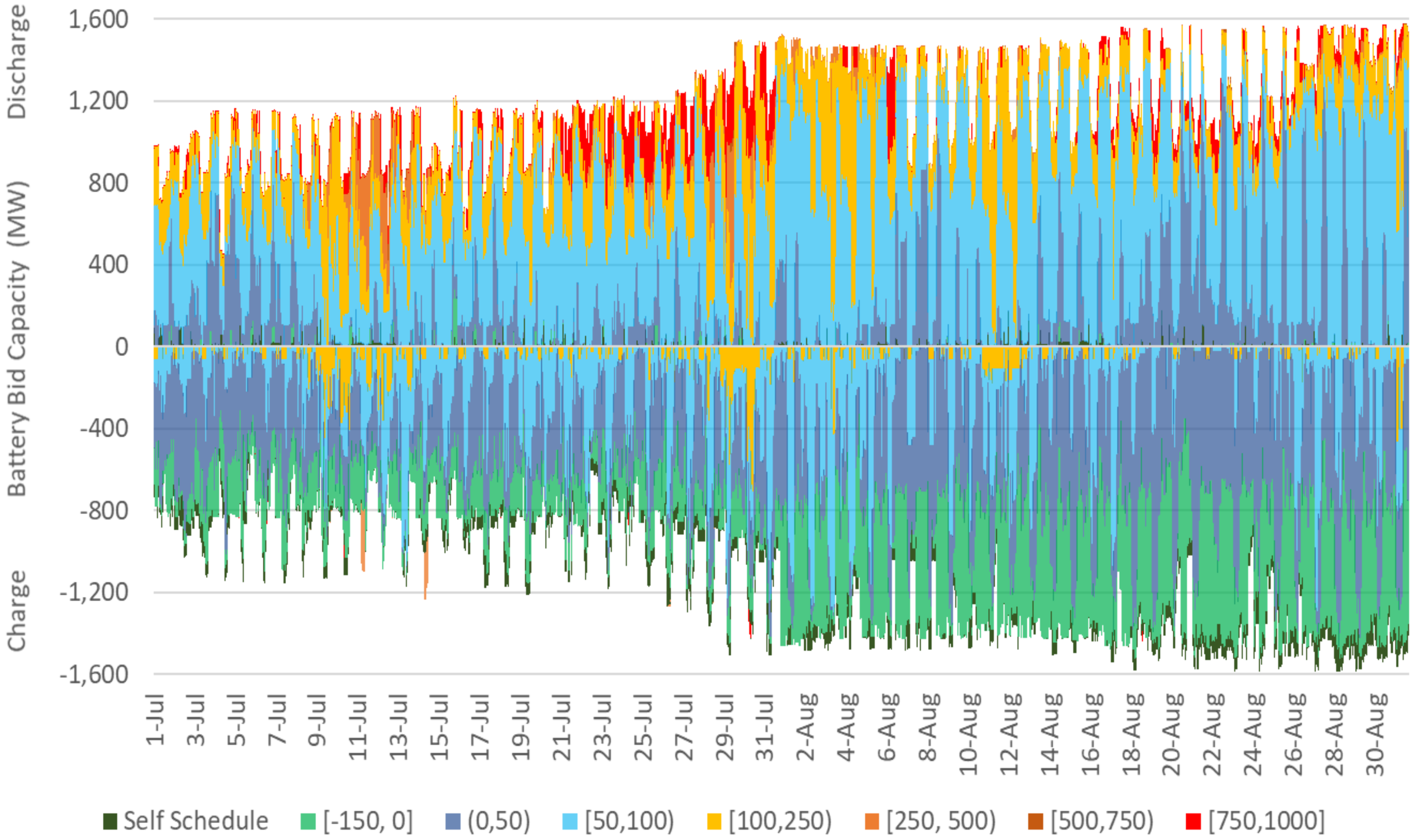
How storage resources economically participate in the ISO's market seems to be evolving -Real-time bids



Real-time economic dispatch

Purpose

Balance supply and demand on a five-minute basis at least cost while respecting all constraints

Market Inputs

- Demand forecast, flexible ramp requirements, resource bids, resource characteristics

Constraints

- Resource: capacity, ramping, temporal
- System: Power balance, ancillary services, flexible ramp
- Security: transmission thermal limits, nomogram constraints

Multi-interval optimization real-time economic dispatch

Minimize Bid-in Costs

$$min \sum_t \sum C(p_{i,t})$$

Optimize over the horizon

S.t.

Power Balance Constraint

$$D_t = \sum_i p_{i,t} + NSI_t$$

Resource Capacity constraint

$$P_{i,t}^{min} < p_{i,t} < P_{i,t}^{max}$$

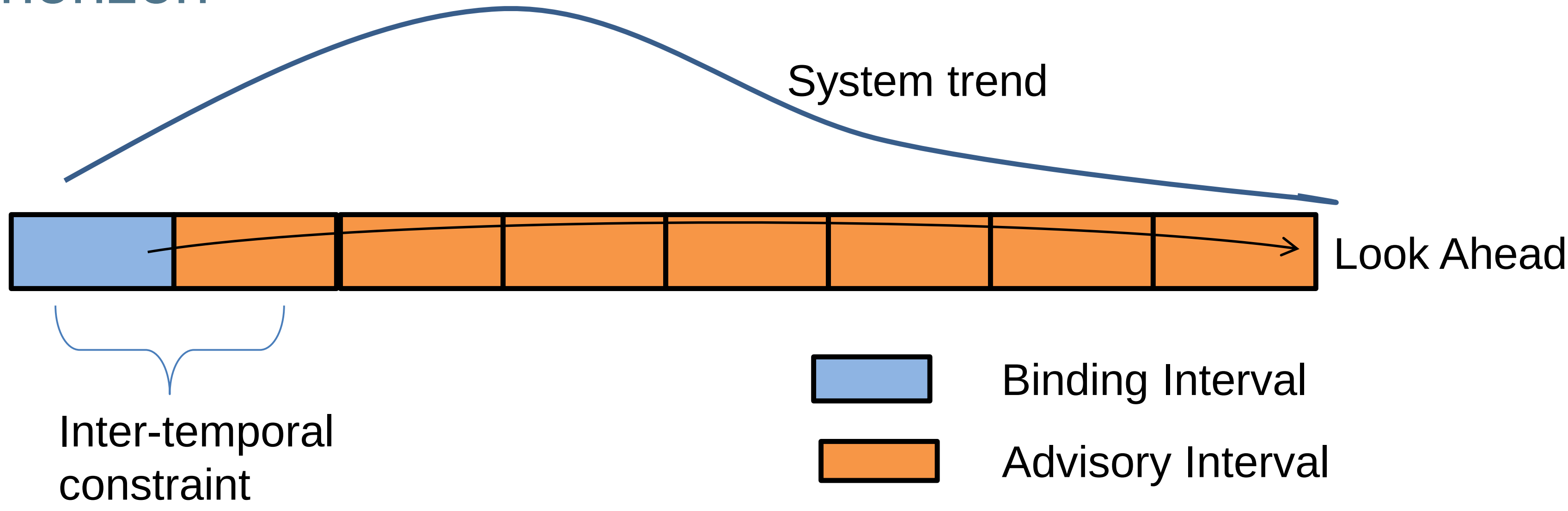
Resource Ramp Constraint

$$RR_{i,t}^{DN} < \underbrace{p_{i,t} - p_{i,t-1}}_{} < RR_{i,t}^{Up}$$

Coupling of adjacent intervals

i 1… N, where N is number of generating units
t Time interval
D demand
p_i power output from generating unit
NSI Net-Schedule Interchange
P_i^{min}, P_i^{max} Min and Max power output of generating unit i
$RR_{(i,t)}^{DN}$ - Ramp rate down
$RR_{(i,t)}^{up}$ - Ramp rate up

Real-time economic dispatch uses a multi-Interval horizon



- Multi-Interval optimization allows real-time market to position resources to handle changes in future horizon
- Inter-temporal constraints links solutions between intervals
- Changes in the horizon may include:
  - Demand changes: demand ramping up or down
  - Supply changes: derates/rerates, ancillary service awards, start-up shut down, renewable production variability
  - Net schedule Interchange: changes in hourly imports/exports

ISO’s model for storage resources

- Resources that can operate in generation or load model with a positive and negative range.
- They can be dispatched to any operating level within their entire capacity
- Can be constrained to charge (consumption) or discharge (generate) in a continuous basis
- Limited energy storage resources is one type of non-generator resource
- Based on an initial state of charge, its consumption or generation is bounded by its max/min storage limit
- They can participate in the energy or ancillary service markets

Non-generating resource model

Non-generating resource (limited energy resource) physical characteristics

- Maximum stored energy (Max SOC)
- Minimum operating limit (Pmin)
- Maximum operating limit (Pmax)
- Ramp rate (up/down)
- Ancillary service capability

Multi-interval real-time economic dispatch

Minimize Bid-Costs

$$min \sum_{i,t} C_{i,t}(p_{i,t})$$

S.t.

Resource Capacity constraint

$$p_{i,t}^{min} < p_{i,t} < p_{i,t}^{max}$$

$$p_{i,t=} p_{i,t}^{+} + p_{i,t}^{-}$$

Resource Capacity plus AS constraint

$$p_{i,t}+Ru_{i,t} + Sr_{i,t} + Nr_{i,t} \leq P_{i,t}^{max}$$

$$P_{i,t}^{min} \leq p_{i,t} - Rd_{i,t}$$

State of Charge Constraint

$$soc_{i,t}^{min} < soc_{i,t} < soc_{i,t}^{max}$$

$$soc_{i,t} = soc_{i,t-1} + \left(p_{i,t}^{+} + \eta_i p_{i,t}^{-}\right) * {}^{DT}/_{T}$$

State of Charge Constraint plus Ancillary Service

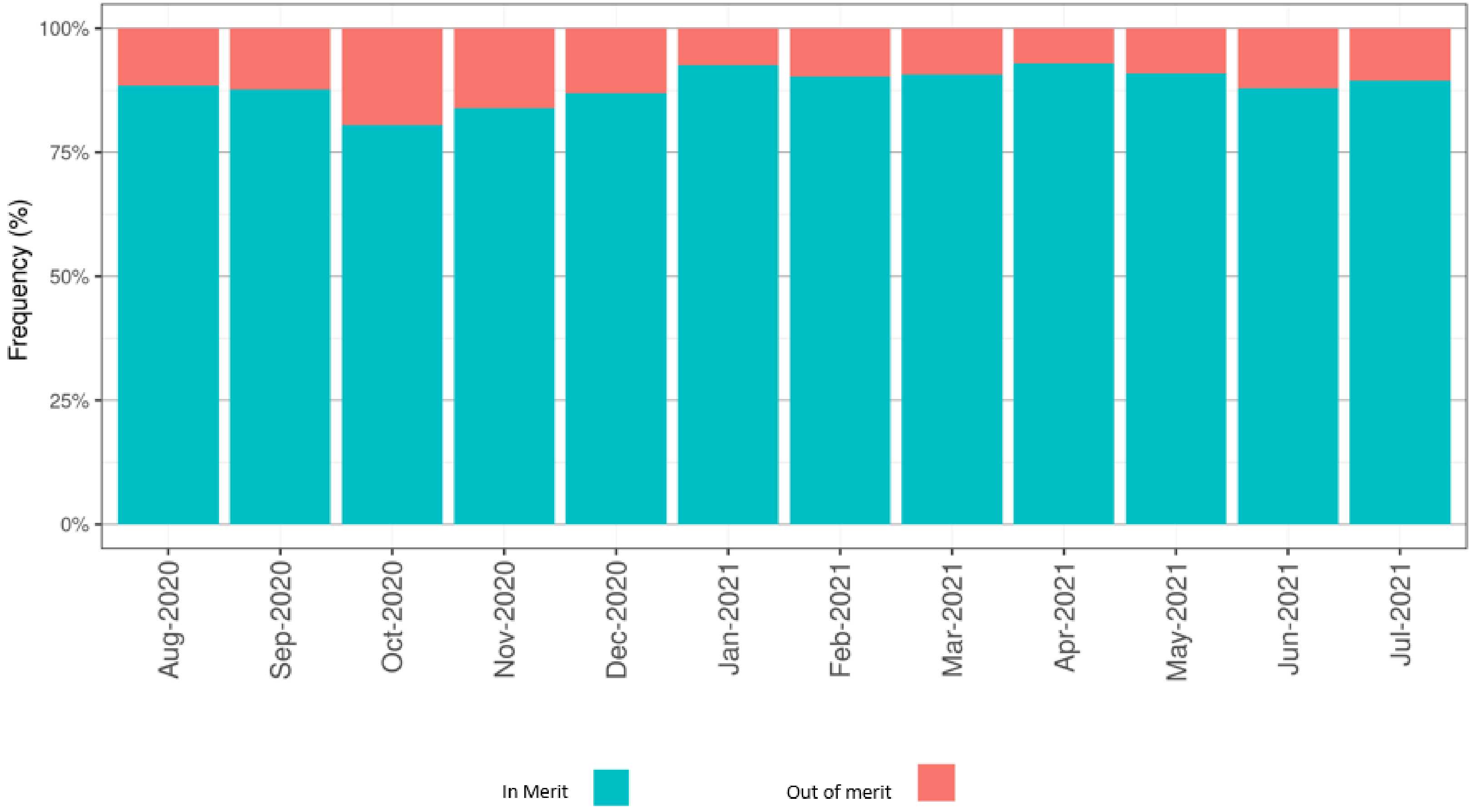
$$soc_{i,t} \geq soc_{i,t}^{min} + \left[Ru_{i,t} + Sr_{i,t} + Nr_{i,t}\right] * {}^{DT}/_{T}$$

Model is simplified to illustrate the concept. Actual implementations may include additional variables and constraints

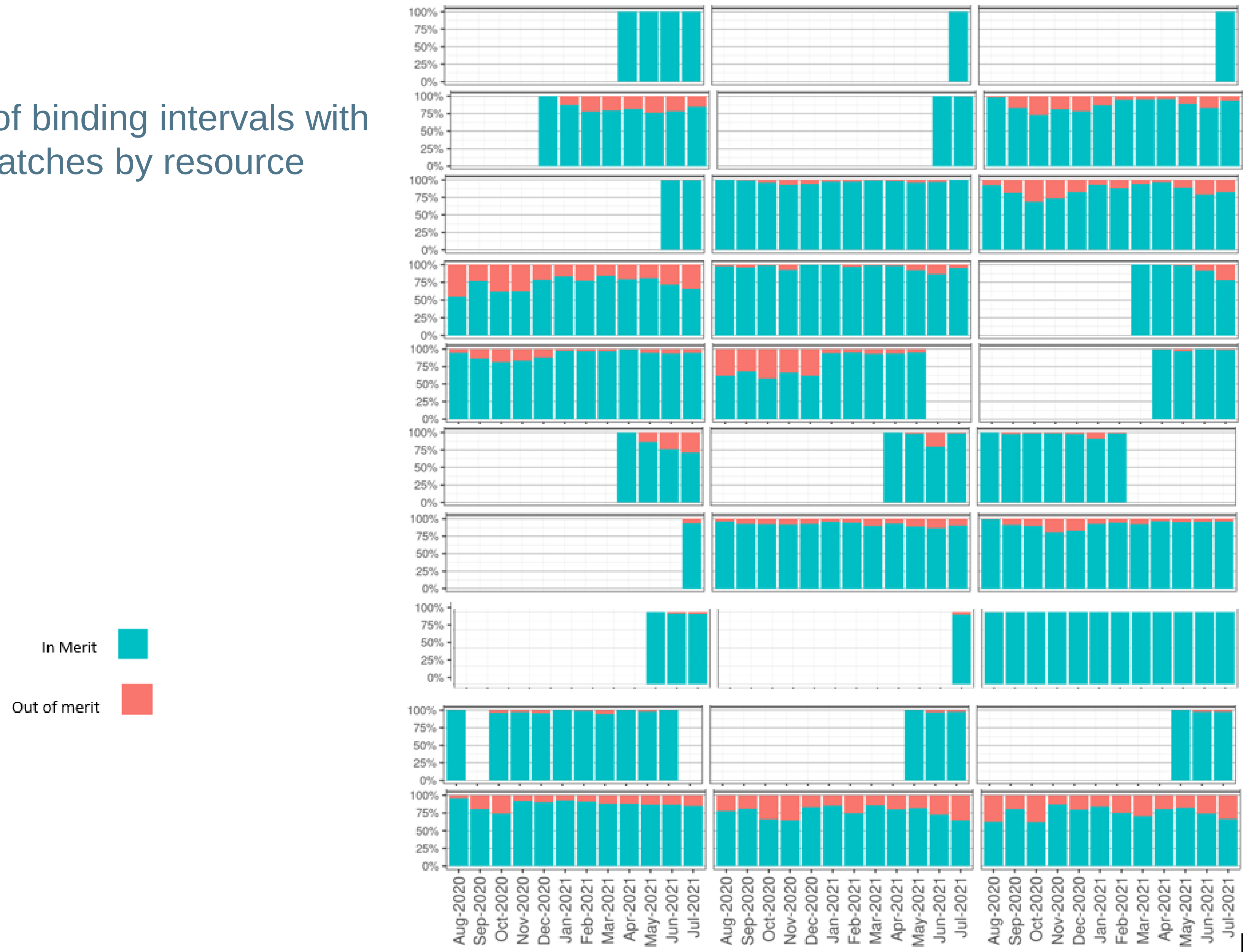
Storage resource awards in binding interval may be uneconomical due to a variety of reasons, including economics, and resource’s capacity and inter-temporal constraints

- Storage resource is charged or discharged in binding interval to support the Ancillary Service awards in either binding or advisory intervals
- Storage resource is charged or discharged in binding interval due to Self-Schedules to charge or discharge in future horizon
- Storage resource is charged or discharged in binding interval to comply with maximum or minimum state of charge in future horizon
- Storage resource is charged or discharged in binding interval due to projected conditions in future horizon
- Additionally, storage resource is charged or discharged due to an exceptional instruction on the resource

Frequency of intervals with dispatches out of merit for all storage resources



Frequency of binding intervals with market dispatches by resource



Scenarios of multi-interval optimization

Scenario I : Real-time dispatch binding interval energy award impacted by regulation up award

Parameter	Value
Regulation Up Award	19.07 MW
Upper Economic Limit	9.87 MW
Resource bid to Charge	9.85 MW@ $28.97/MWh
Resource LMP	$33.78 MW
Resource energy award	-9.2 MW

- Resource receives an uneconomic energy award to charge at 9.2 MW to support the regulation up award of 19.07 MW
- The resource bid to charge is $28.99/MWh while the locational marginal price is $33.87/MWh

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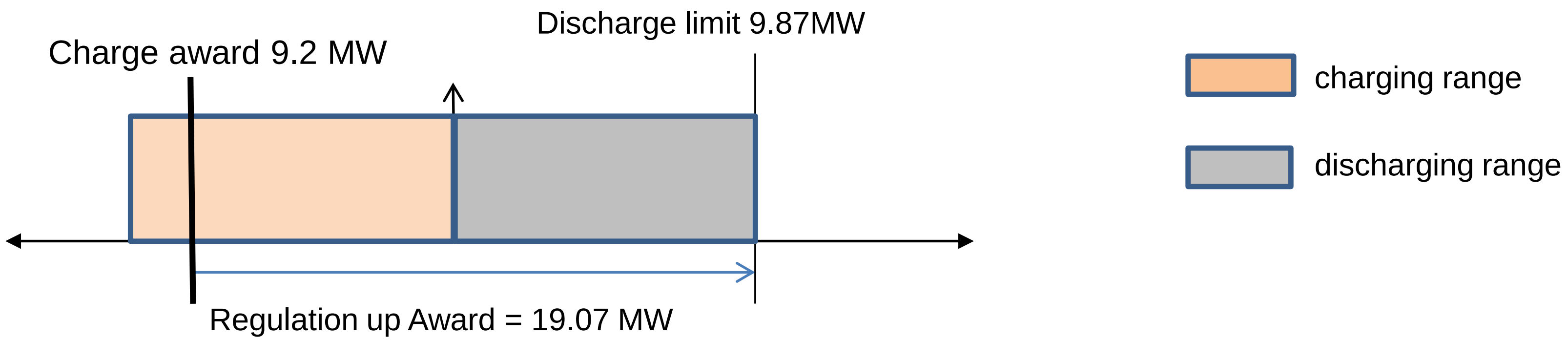
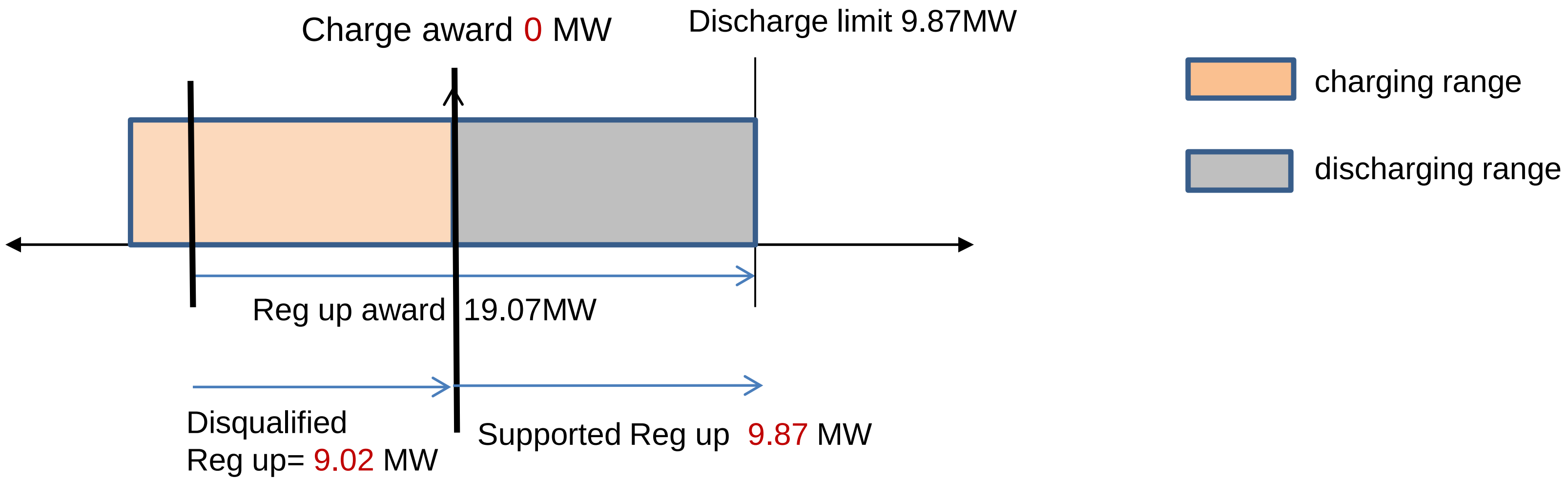
Scenario I: RTD Binding Interval Energy Award Impacted by Regulation Up Award



- Resource receives an energy award to charge at 9.2 MW to support the regulation up award of 19.07 MW
- The resource bid to charge is $28.97/MWh but LMP is $33.87/MWh
- Resource dispatch is uneconomic due to Regulation Up award

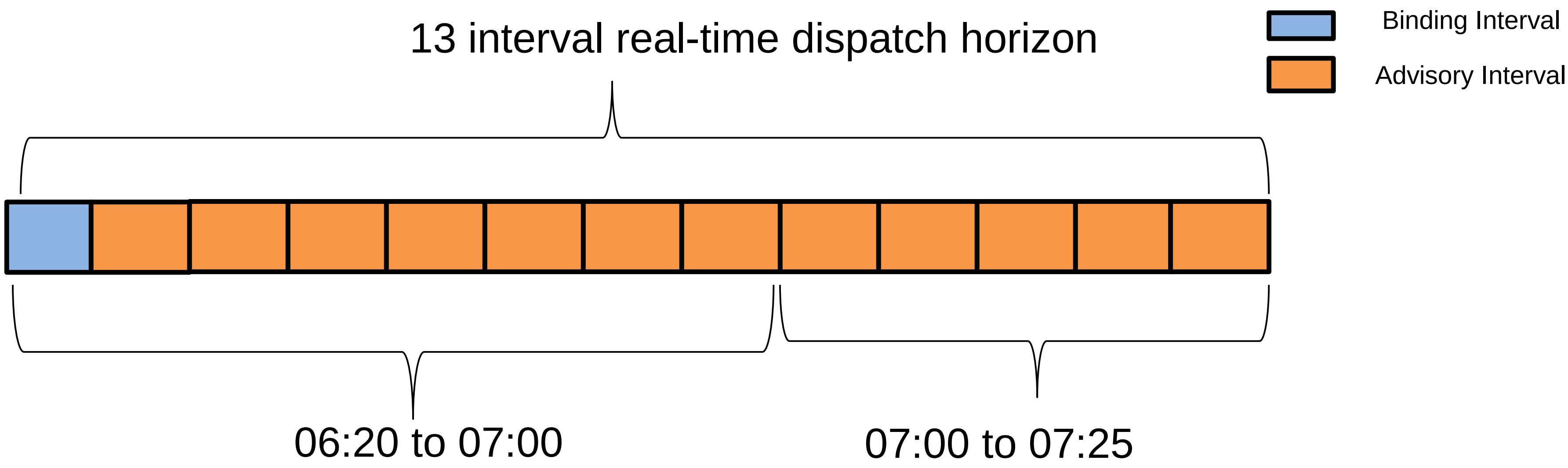
Counterfactual scenario I: If resource is not dispatched uneconomically for energy, it cannot provide its regulation award



Counter-factual:

- If resource is not dispatched uneconomically for energy, it cannot provide its regulation award
- If there is no multi-interval optimization, this type of scenarios will increase because there would not be an opportunity to position resources to this condition in advance

Scenario II : Future interval self-schedule impacts binding interval energy award



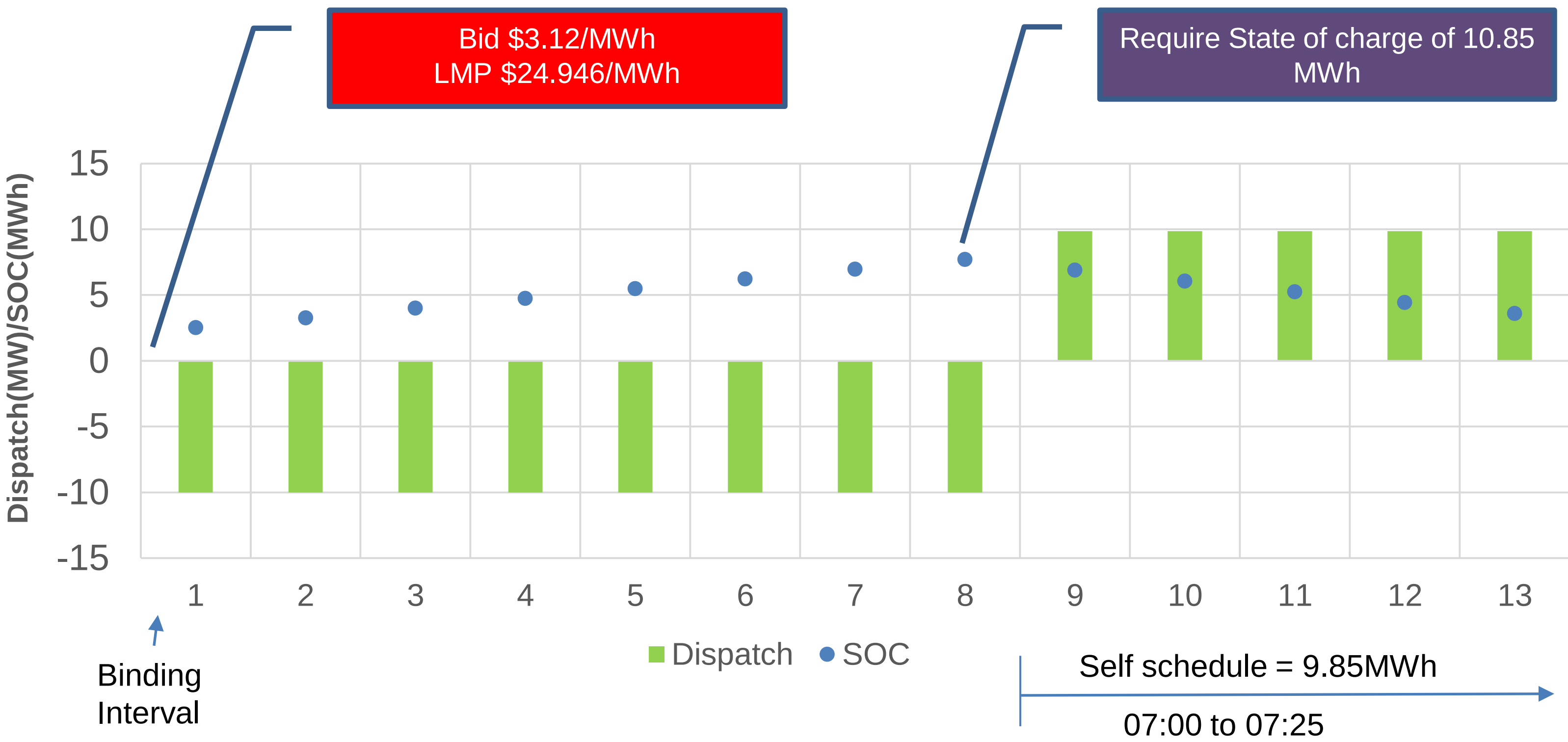
Market inputs

- Resource has self-schedule to discharge at 9.85 MWh from 07:00 to 08:00
- Resource state of charge at 06:15 is 1.77 MWh
- Resource maximum charge capacity – 9.85 MWh
- Resource charging bid - 9.85 MW @ $3.14/MWh
- Resource minimum state of charge is 1 MWh

Resource solution constraint

- Before 7:00, resource needs the state of charge at 9.85 MWh plus 1 MWh of minimum state of charge to ensure it can discharge continuously at 9.85 MW and comply with minimum state of charge

Scenario II: Future interval self-schedule impacts the binding interval energy award



- Resource is charged continuously between Intervals 1 to interval 8 to meet self-schedule to discharge from 7:00 to 8:00 but resource is unable to reach 10.85 MWh
- Resource is charging at 10 MW in binding interval at locational marginal price of $24.9/MWh
- Resource bid in to charge at 10 MW is $3.12; thus, it is dispatched out of merit

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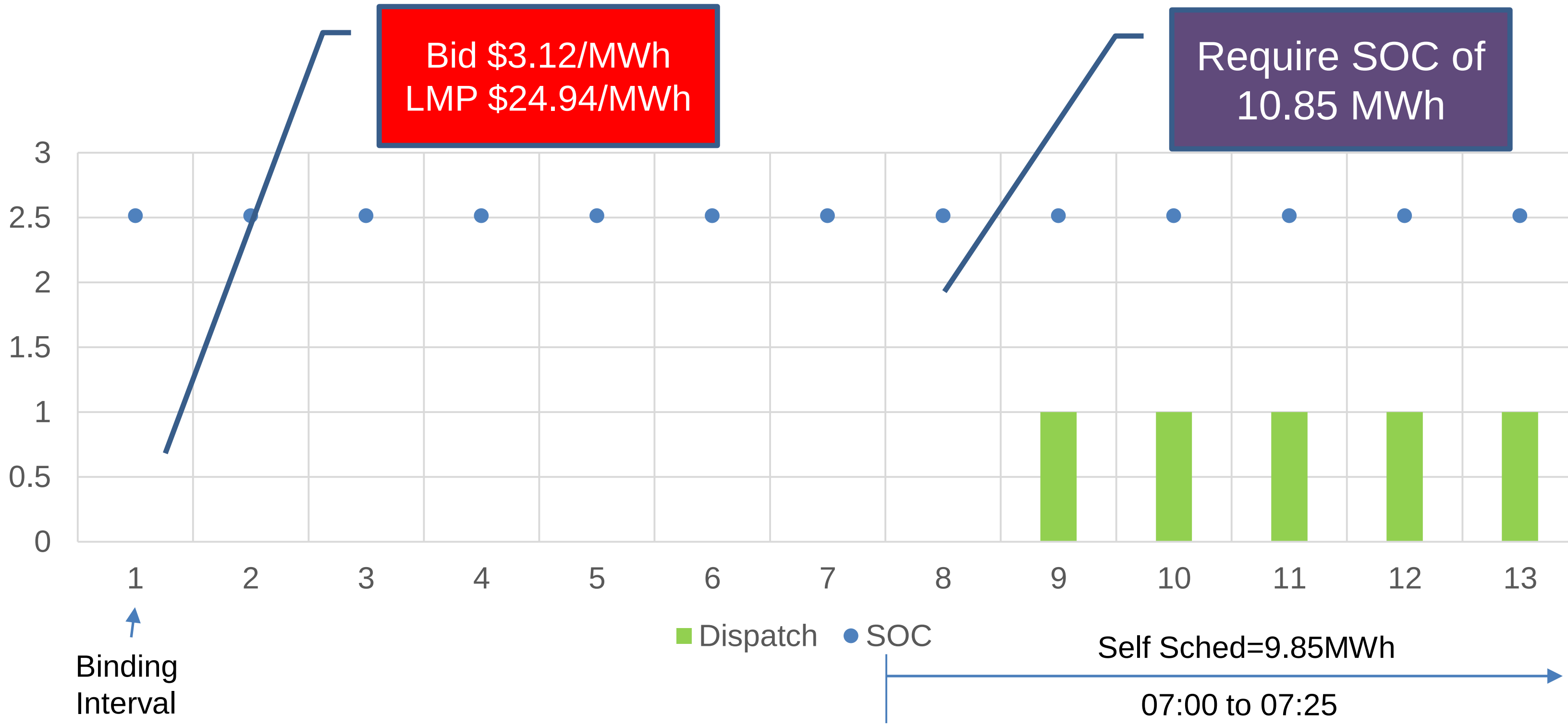
Counterfactual Scenario II: With no multi-interval optimization, market has no mechanism to set resource in advance to meet self schedule



- Based on binding interval price, resource would not be charged in this interval.
- For every interval (1 through 7) that resource is not charged, the resource will not be able to comply with self schedule for an interval of next hour

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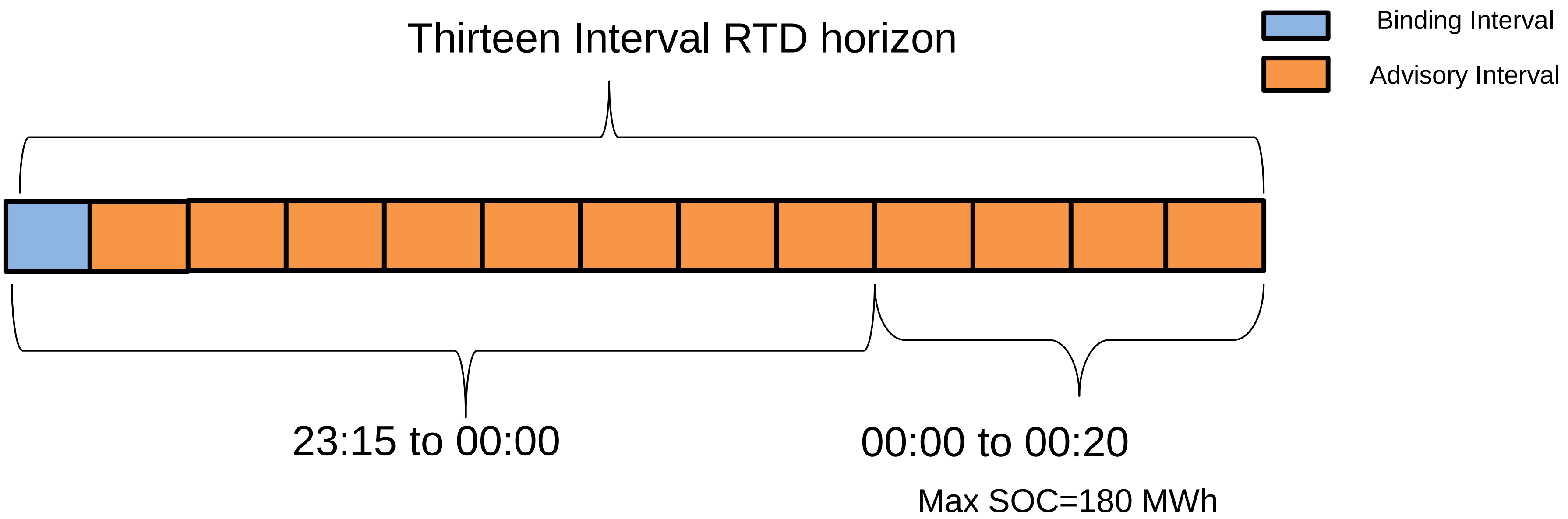
Scenario III: Maximum SOC constraint in future hour impacts binding interval energy award



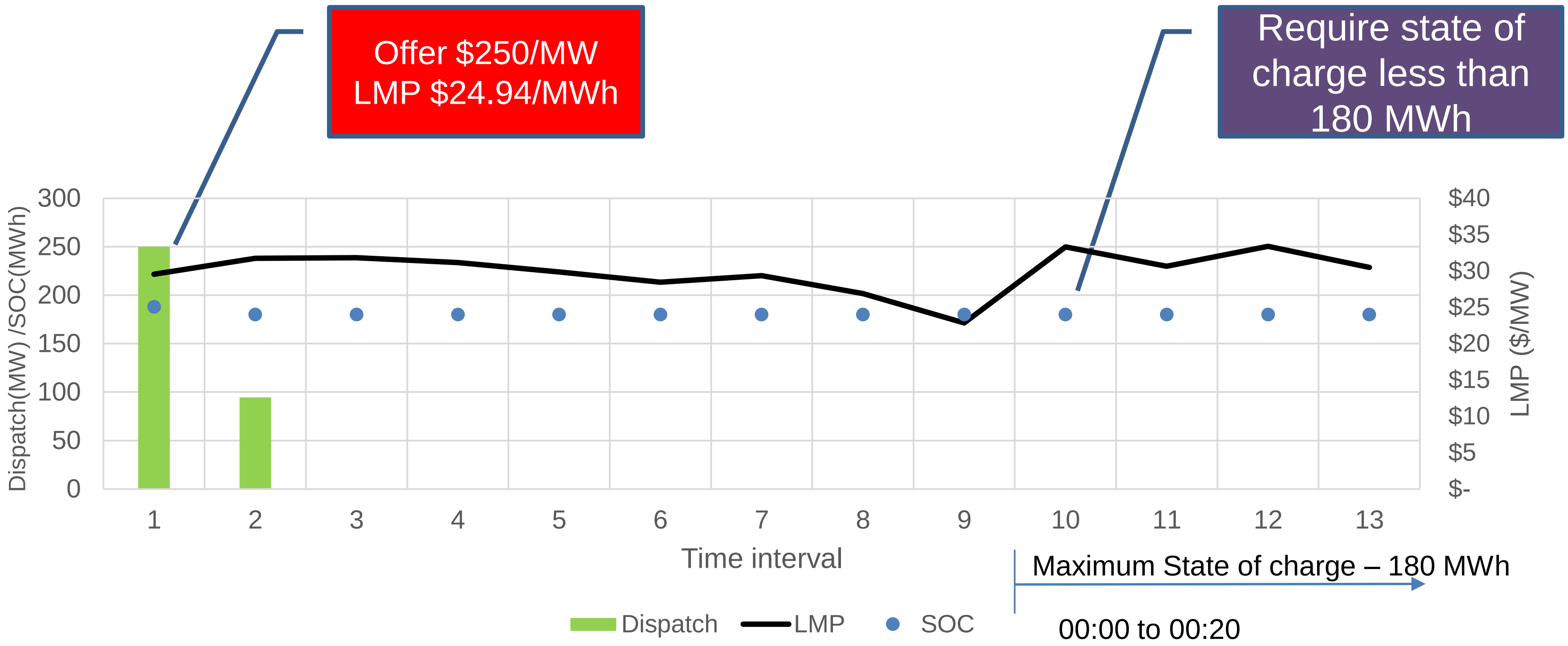
Market Inputs

- Resource bid-in Maximum SOC from 00:00 to 01:00 is 180 MWh
- Resource State of Charge (SOC) at 23:10 is 208.7 MWh
- Resource Discharge bid - 250 MW @$250/MWh

Resource Solution Constraint

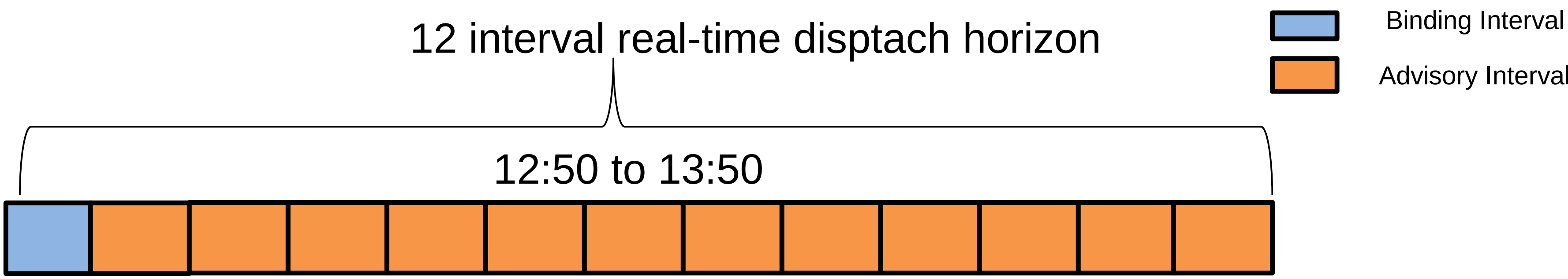
- Resource needs to start discharging to comply with SOC of 180 MWh at 00:00

Scenario III: Future interval maximum State of charge impacts binding interval Energy Award



- Resource is discharged in intervals 1 and 2 to ensure the resource state of charge is not more than 180 MWh at 00:00 based on bid-in maximum state of charge
- Resource locational marginal price in interval 1 is $29.53/MWh and interval 2 is $31.75/MWh
- Resource discharge offer for 250 MW@ $250/MWh and 100 MW@ $100/MWh
- Resource is discharged uneconomically

Scenario IV(a) : Future interval economic conditions impacts binding interval energy award



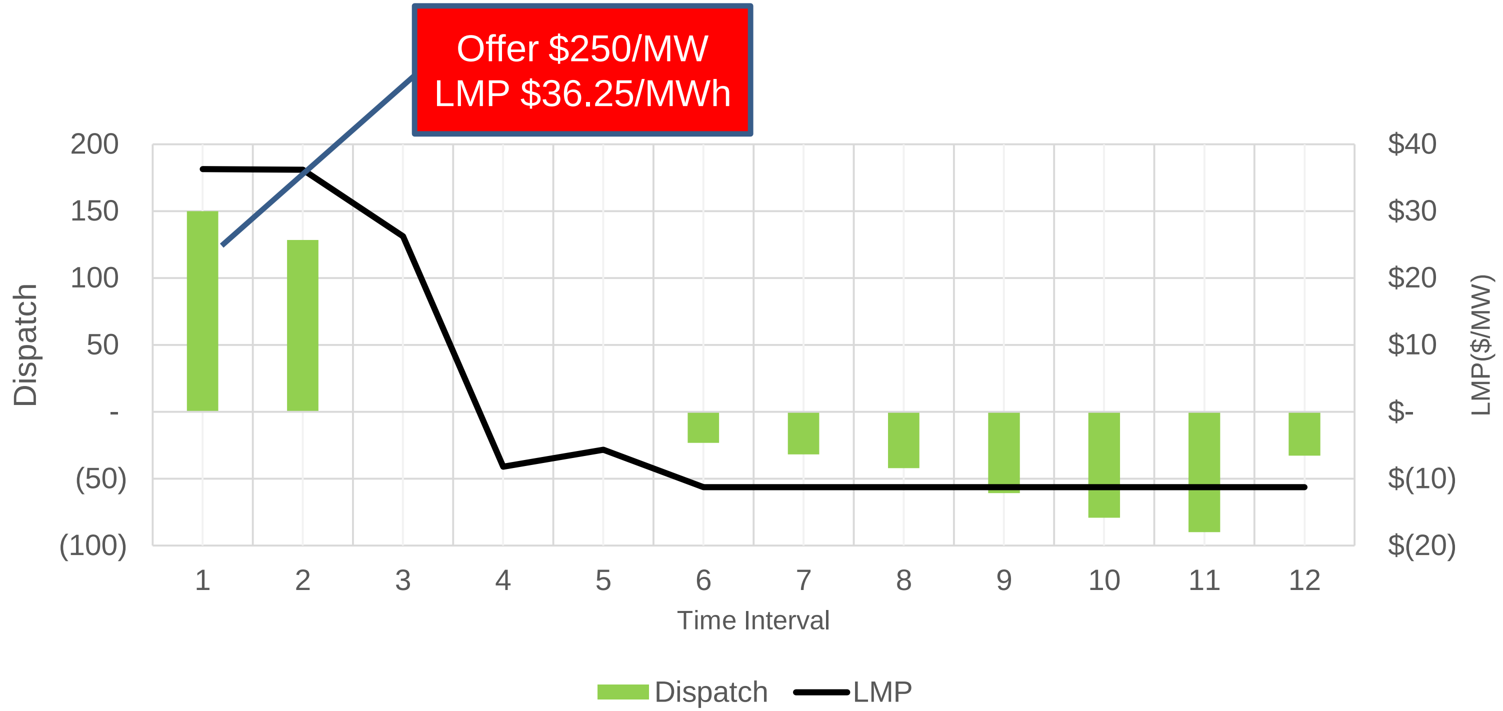
Market inputs

- Resource discharge offer 150MW @ $120/MWh
- Resource charge bid 100 MW @ $60

Resource solution constraint

- Market can minimize overall costs by discharging resource below it offer and charge the resource at price lower than its bid through the whole horizon
- The horizon will factor in projected system conditions for all intervals, not just for binding interval

Scenario IV(a) : Projected system conditions impacts binding interval energy award

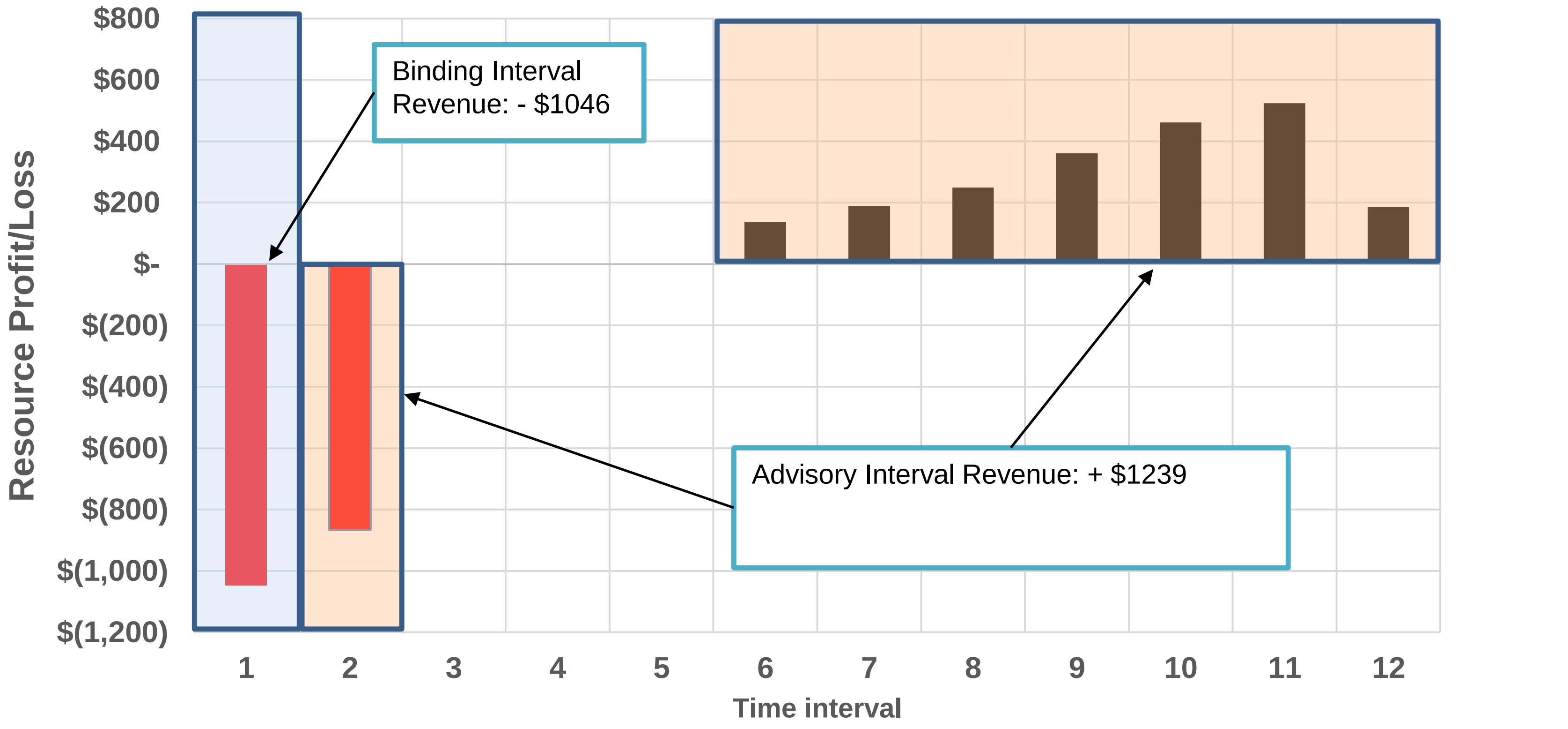


Binding interval – Resource discharged uneconomically at locational marginal price below offer price

Advisory intervals – Resource is charged back at locational marginal prices below bid to charge

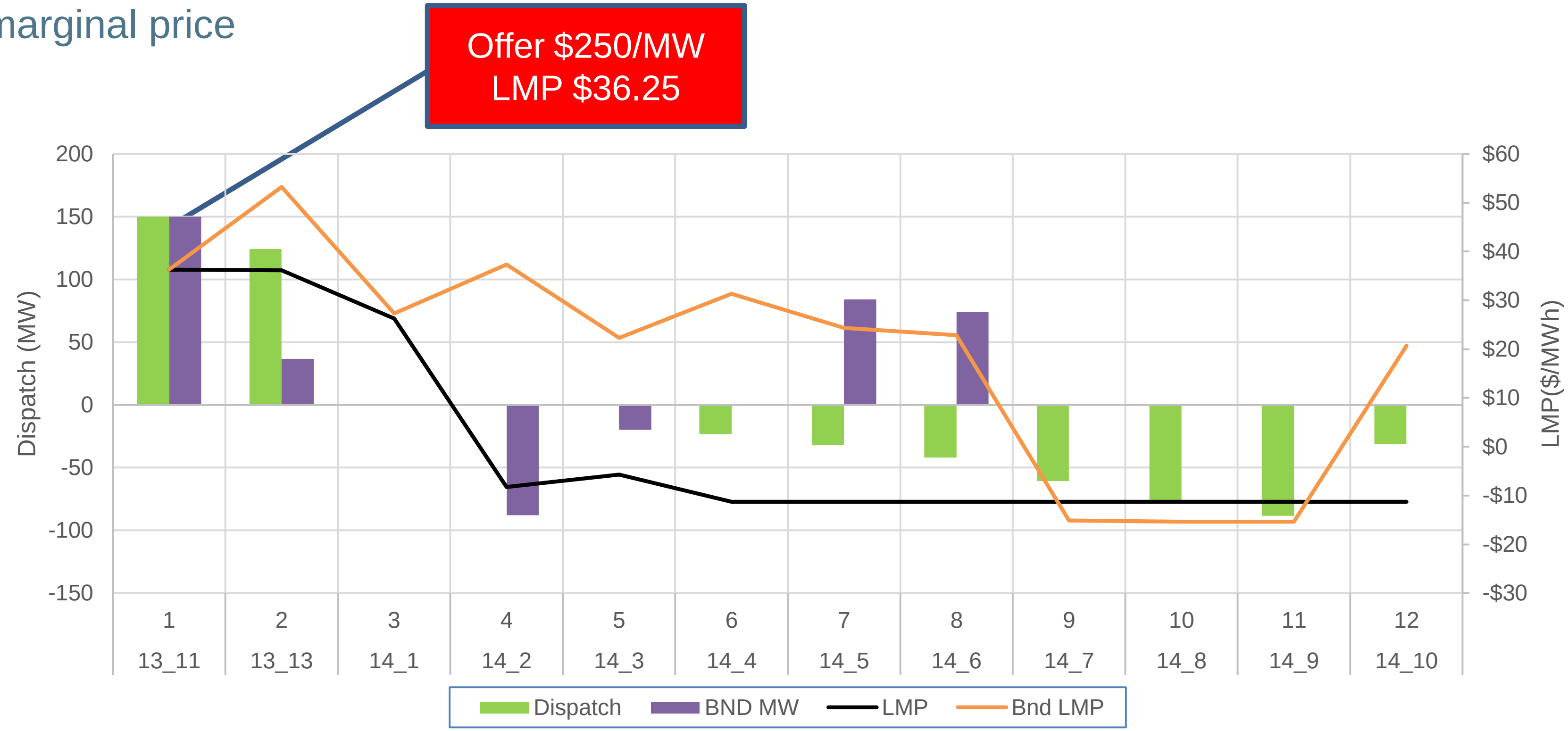
Overall, resource is in the money through the horizon

Scenario IV(a) : Projected system conditions impacts binding interval energy award – revenue



Resource has a positive revenue across all real-time dispatch intervals of $193.02

Scenario IV(a) : Projected system conditions impacts binding interval energy award – with binding MW and Binding locational marginal price



The project dispatch and price from the real-tine dispatch run with start time 13_11 did not materialize in future binding intervals.

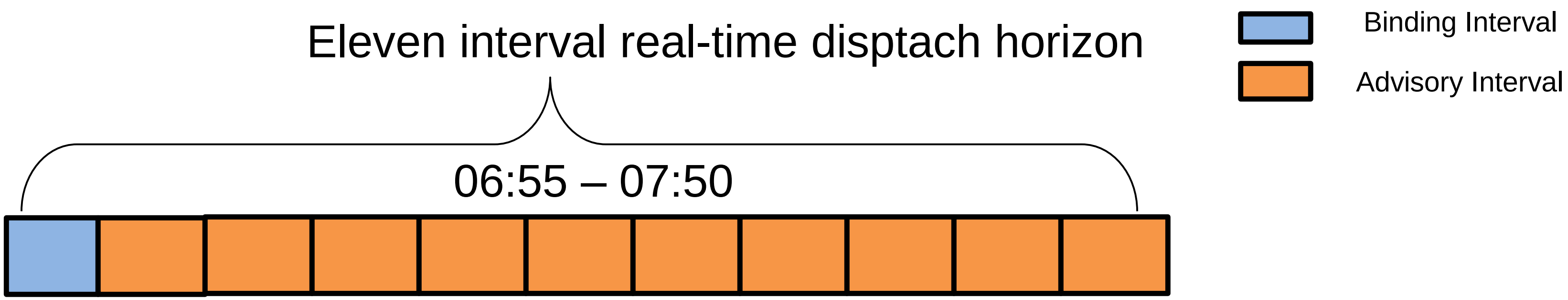
Impact of change in system condition on market solution

- Resource is uneconomically discharged in HE13 Interval 11 and 12 because in advisory intervals for HE 14 it was projected to charge at locational marginal price, lower than the bid price
- The lower locational marginal prices were projected in hour ending 14 due to congestion on the 22192_DOUBLTTP_138_22300_FRIARS _138_BR_1 _1 line
- The projected lower locational marginal price and lower congestion on 22192_DOUBLTTP_138_22300_FRIARS _138_BR_1 _1 constraint did not materialize due to variation in output from solar resources

There are numerous inputs used in the real-time market optimization. Changes in inputs between different real-time market runs can result in different solution.

These inputs include, load and renewable forecast updates, load bias, exceptional dispatches, transmission congestion, intertie changes

Scenario IV(b) : Future interval economic conditions impacts binding interval energy award



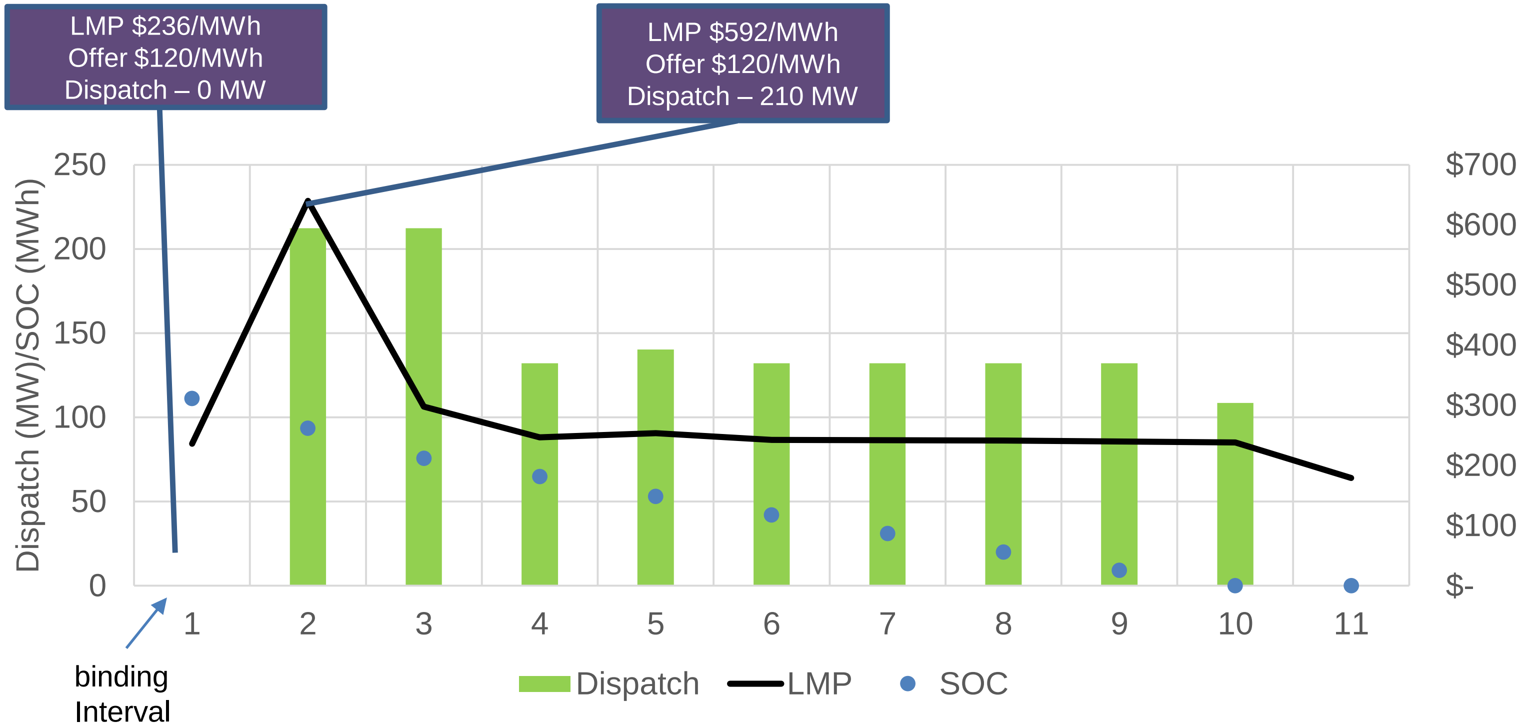
Market inputs

- Resource initial state of charge is 111 MWh
- Resource discharge offers – 132 MW @ $75/MWh, 132 MW-176 MW @ $90/MWh, 176 MW-212 MW @ $120/MWh
- Congestion on MIDWAY-VINCENT 500 kV line and LUGO –VICTORVL 500 kV lines

Resource solution constraint

- There is not sufficient state of charge over the real-time dispatch horizon to further dispatch the resource in all intervals

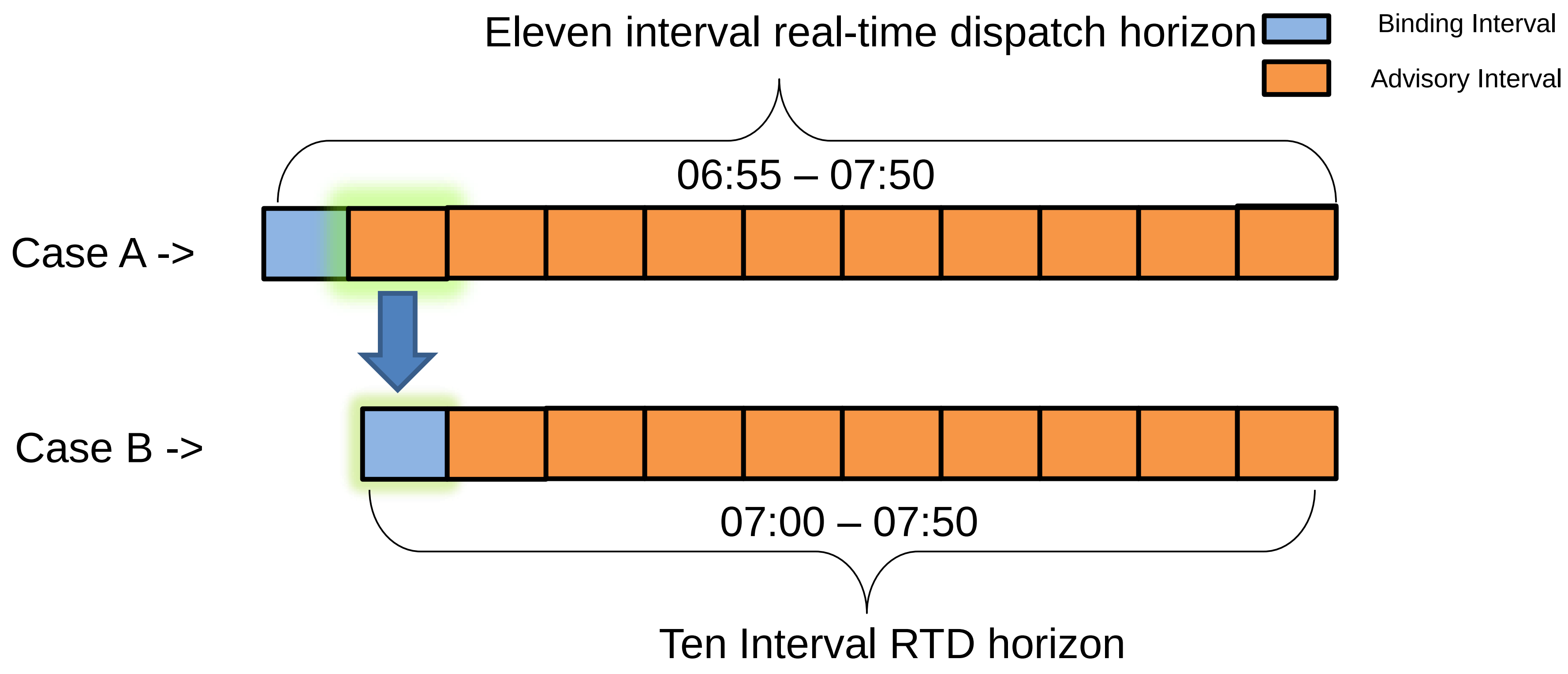
Scenario IV(b) : Future interval economic conditions impacts binding interval energy award



The binding (first) interval locational marginal price is $236/MW but the first advisory (second) interval locational marginal price is $592/MW. These locational marginal prices are mainly driven by congestion.

Due to limited state of charge on the resource, it is dispatched to 0 MW in binding Interval such that resource can be dispatched in advisory intervals and exhaust its state of charge

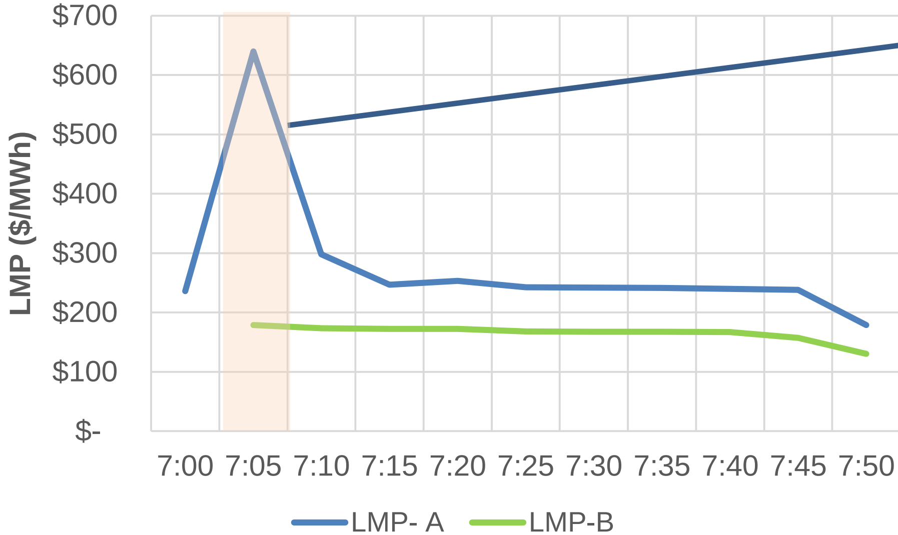
Scenario IV(b) : Future interval economic conditions impacts binding interval energy award



Compare results for 7:00 to 7:05 real-time dispatch interval between case A and case B

- In case A first advisory interval locational marginal price was $592. Did that materialize in case B binding interval ?

Scenario IV(b) : Locational marginal price projected in Case A does not materialize in Case B

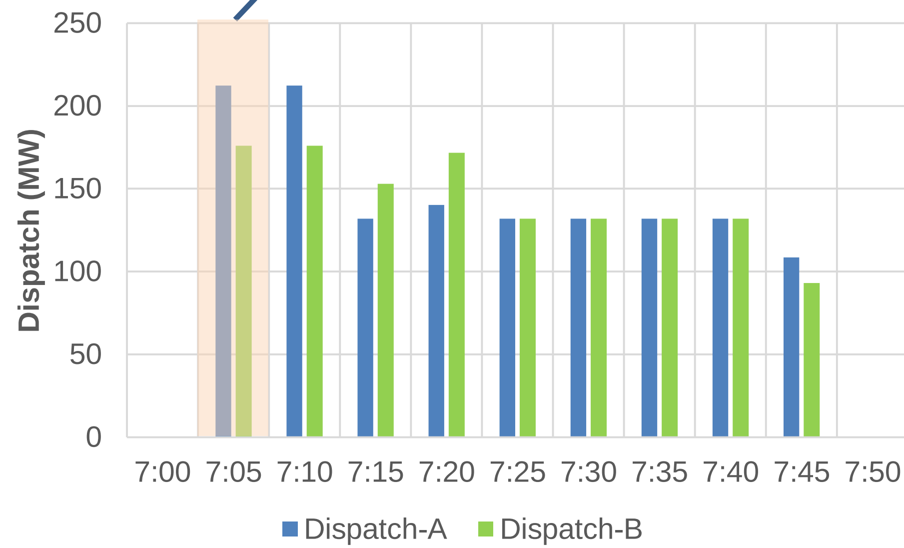


LMP-A - $640
LMP-B - $178

Dispatch-A – 212 MW
Dispatch-B – 176 MW

What changed between these two case?

- Active flow management on Lugo – Victorville 500 kV line resulted in lower level of congestion and drove lower marginal congestion price, resulting in a lower real-time dispatch



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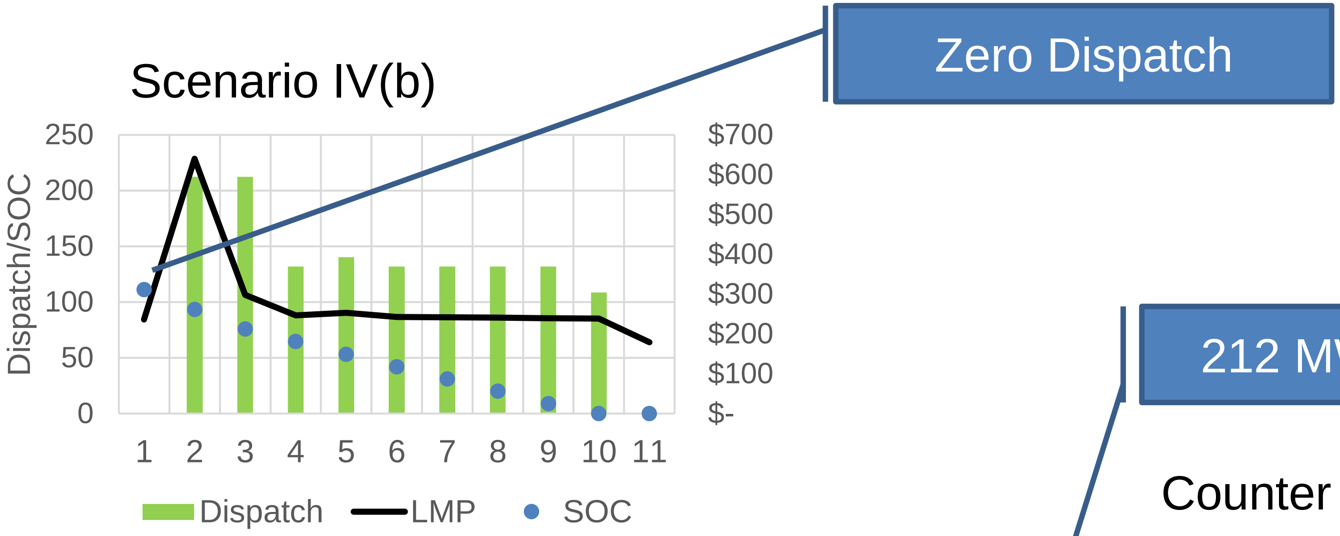
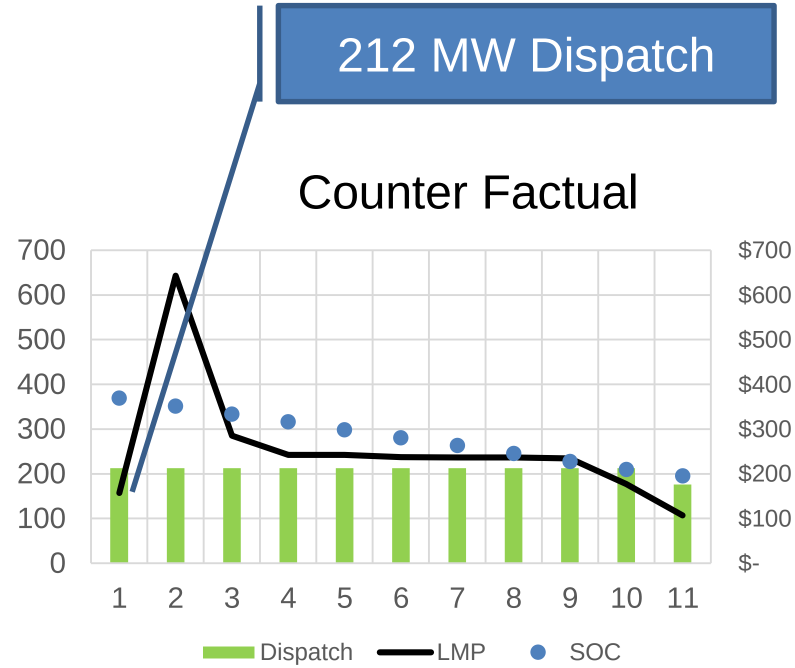
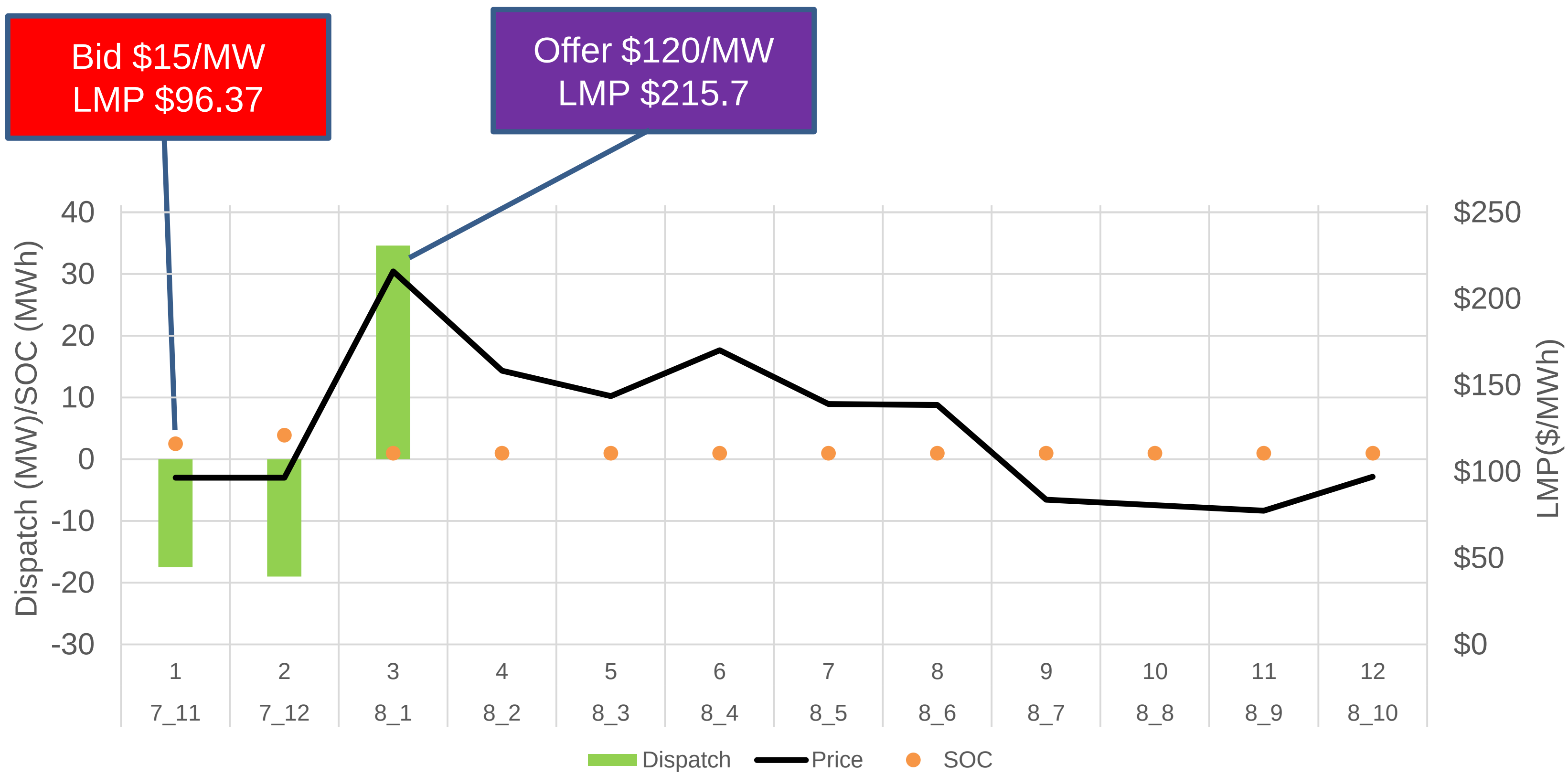
Scenario IV(b) – Counter factual resource dispatch with sufficient state of charge



Resource is dispatched to 212 MW if it was fully charged at 400 MWh



Scenario IV(c) : Future interval economic conditions impacts binding Interval energy award



Binding interval – Resource charged uneconomically at locational marginal price above offer price

Advisory intervals – Resource is discharged back at locational marginal prices above offer to discharge

Overall, resource is in the money through the horizon

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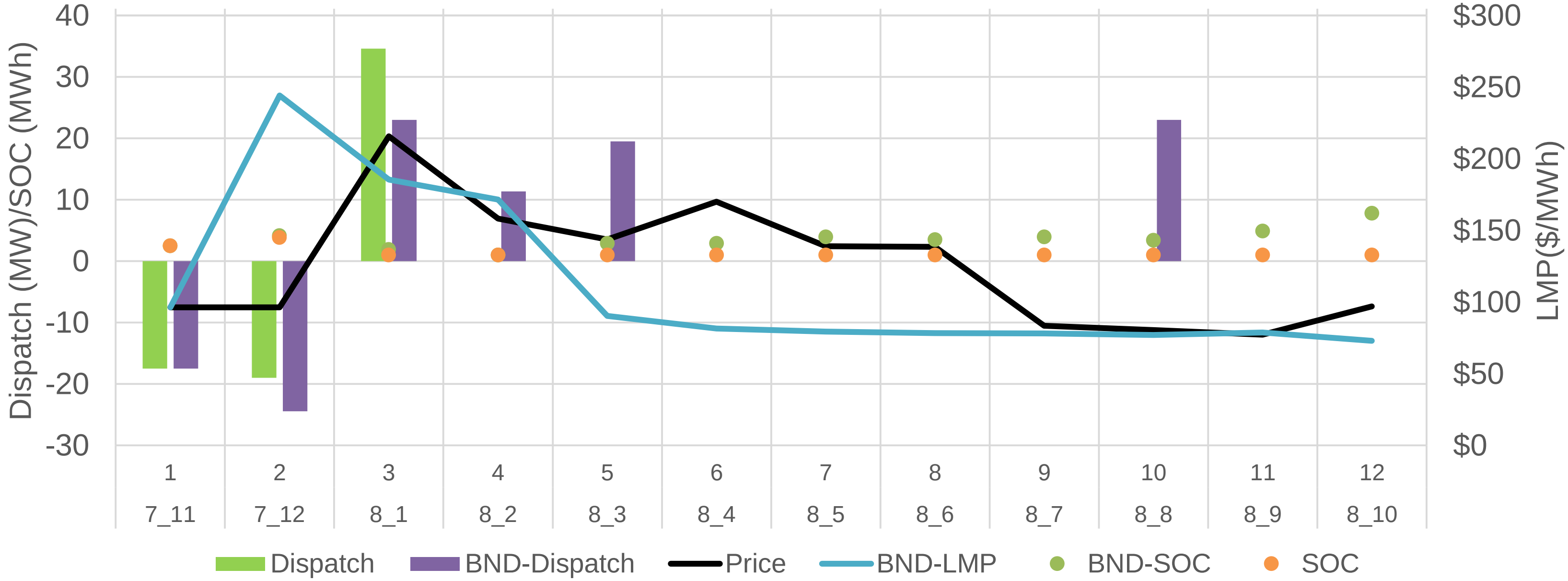
Scenario IV(c) : Future interval economic conditions impacts binding interval energy award- With binding interval information



The Advisory locational marginal prices did not materialize as system conditions changed:
active flow management on Lugo – Victorville 500 kV line resulted in lower level of congestion and drove lower marginal congestion price, resulting in a lower real-time dispatch

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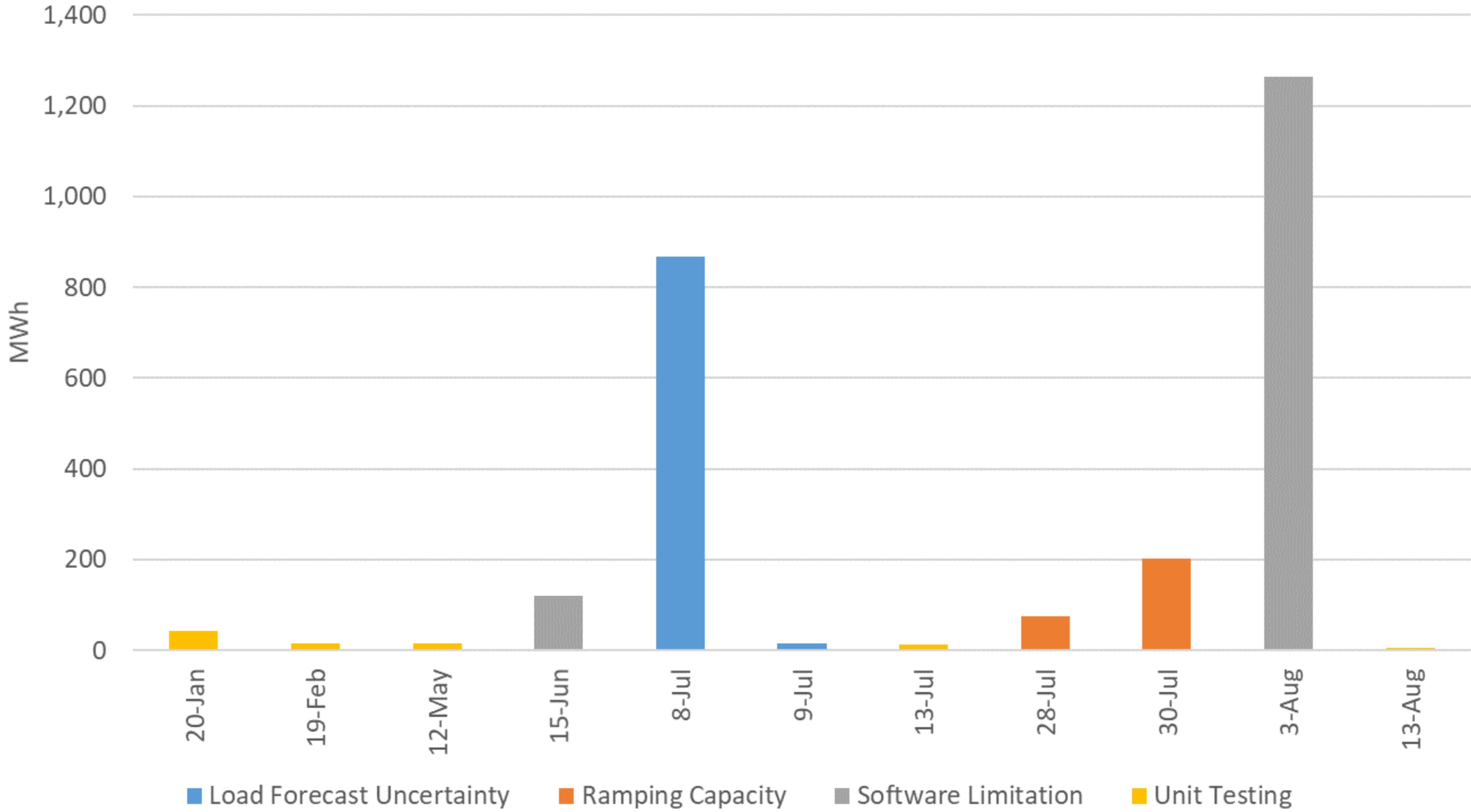
Exceptional dispatch

ISO uses exceptional dispatches to manage real-time load forecast uncertainty

- Thermal resources may be started up before the evening peak or net load peak to manage forecast uncertainties
- Thermal resources may be dispatched at levels that can support fast ramp rates before the evening peak or net load peak to manage forecast uncertainties
- Storage resources may be manually dispatched to maximize its use during net load peak

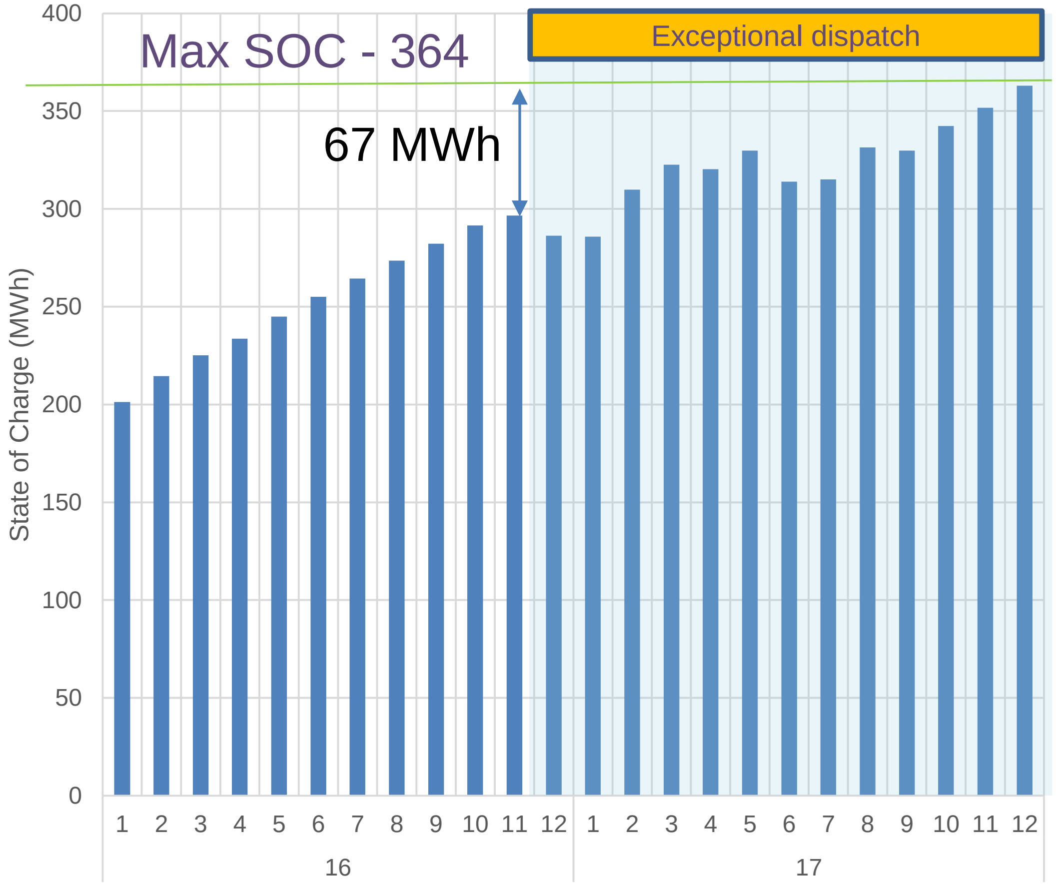
Exceptional dispatches to storage resources have been sporadic in 2021



Exceptional dispatch – storage

- ISO market application currently does not support exceptional dispatch to directly manage state of charge
- Fixed Exceptional dispatch charging instruction are created manually to charge storage resources
- The determination of the fixed exceptional dispatch instruction takes into account:
  - Current state of charge
  - State of charge derate
  - Maximum bid in state of charge
  - Charging efficiency

Exceptional dispatch instruction for a storage resource on July 8, 2021

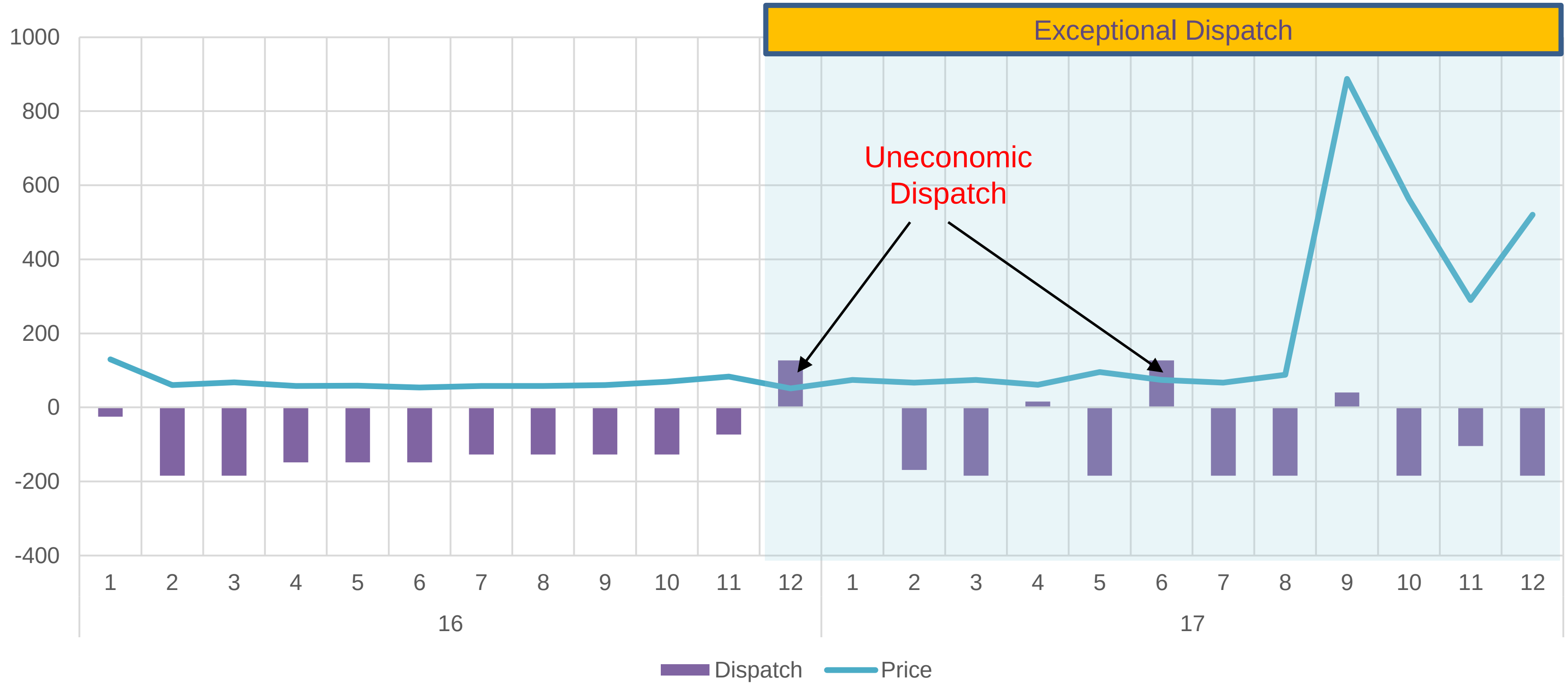


At hour ending 16 interval 11, the initial state of charge was 297 MWh.

The resource maximum bid-in state of charge is 364 MW. The resource charging efficiency is 85%.

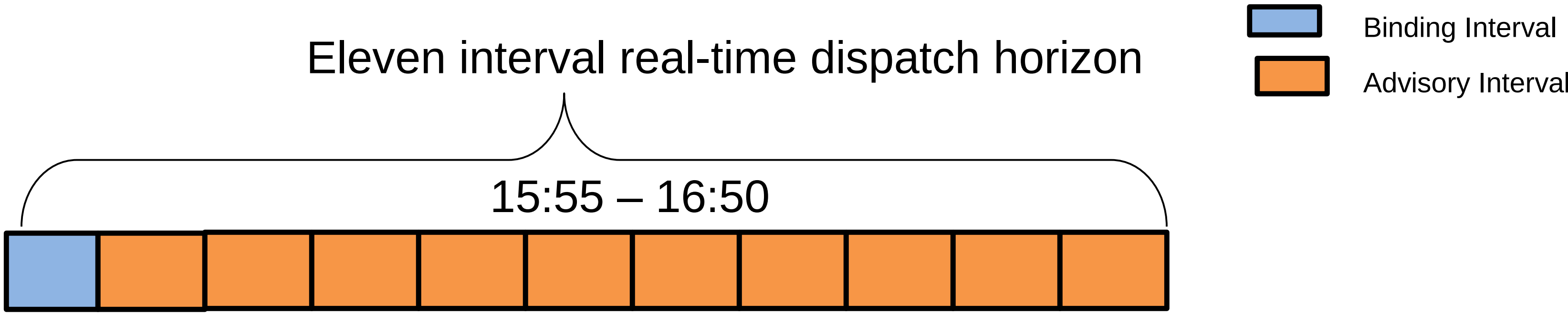
A fixed exceptional dispatch charge instruction of 79 MW for one hour could charge the resource to 364 MWh.

Suboptimal Exceptional dispatch instruction to charge the resource resulted in unexpected outcomes – July 8



A fixed exceptional dispatch Instruction to charge the resource at 184 MW was created instead of a fixed exceptional dispatch to charge at 79 MW. This resulted in unusual market outcome due to a software issue– The resource was discharged uneconomically.

Scenario V: Exceptional dispatch to charge resource results in unexpected discharge



Market inputs

- Resource initial state of charge -297 MWh
- Resource charge bids – 184 MW @ $90/MW
- Resource discharge offers – 127 MW @ $250/MW
- Resource maximum state of charge – 364 MWh

Resource Constraint

- Resource has exceptional dispatch instruction to be charged at 184 MW

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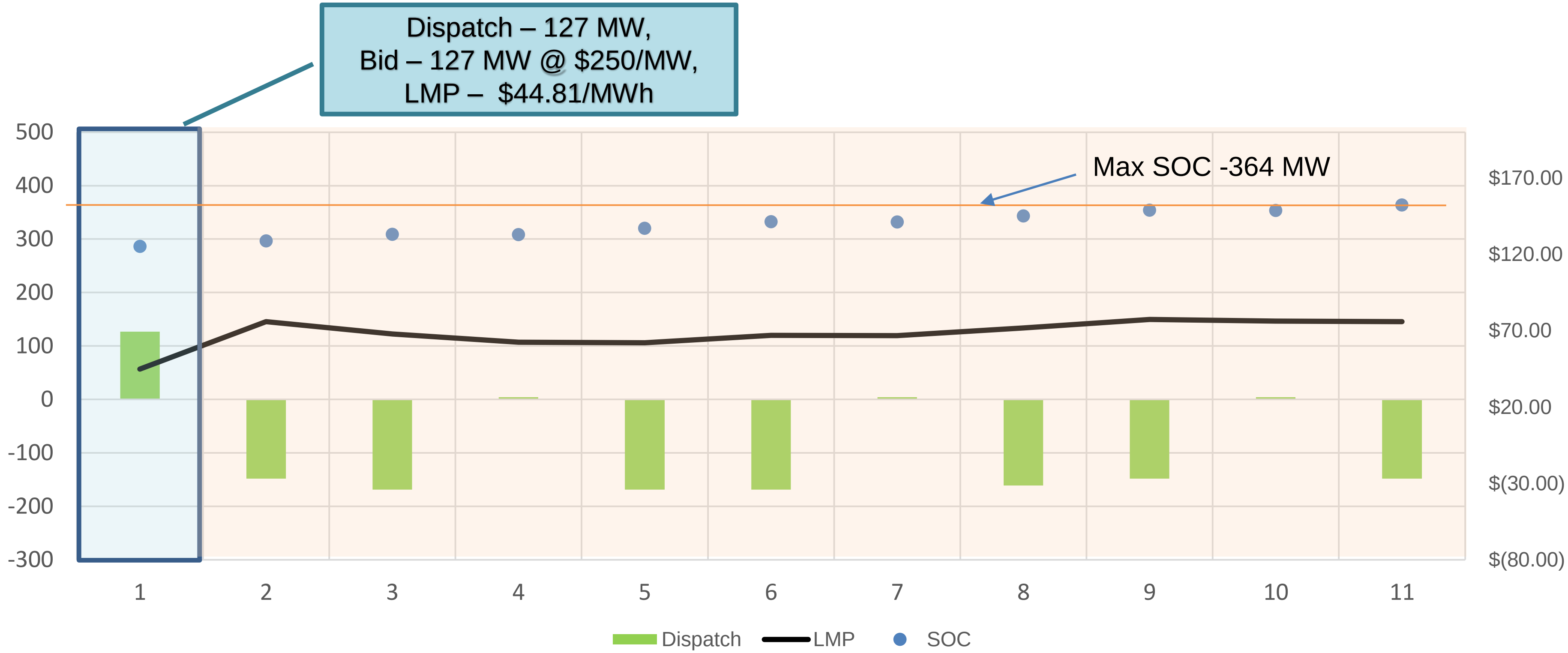
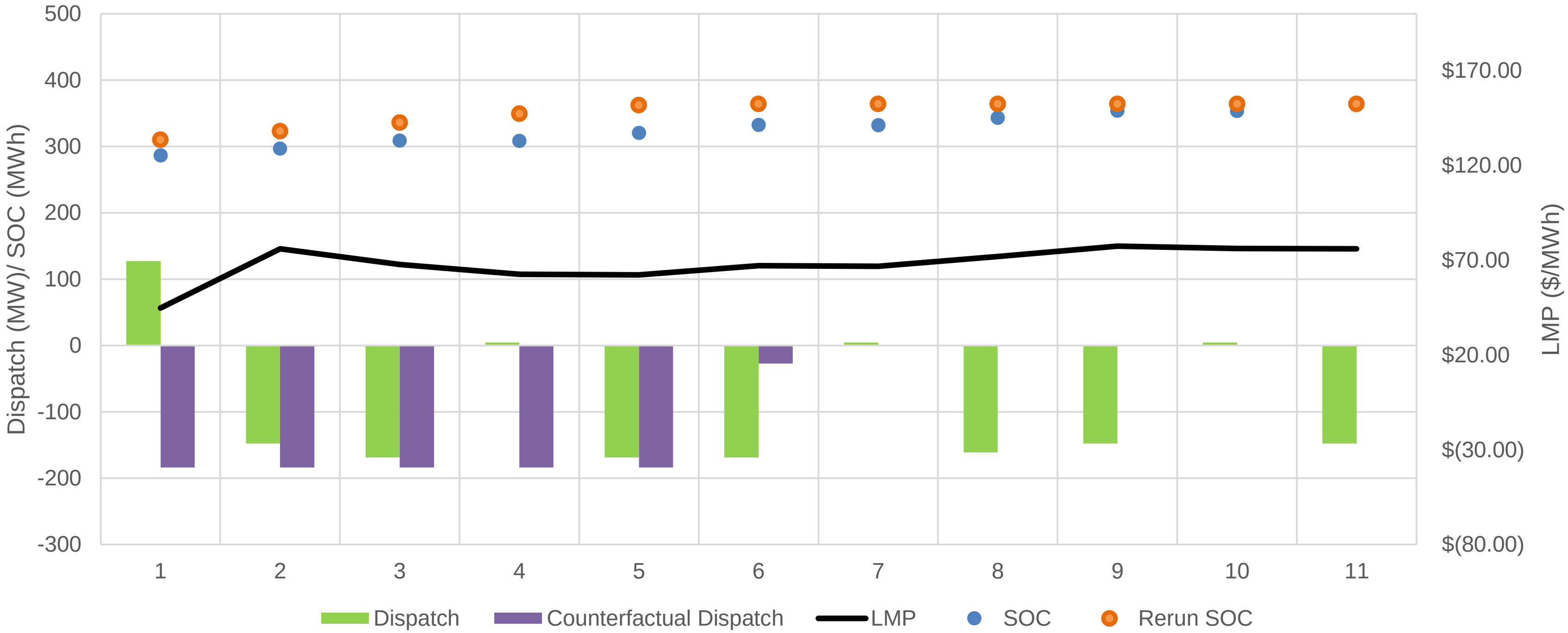
Scenario V: Exceptional Dispatch to charge resource can result in unexpected discharge



Binding Interval LMP is $44.81/MWh whereas its discharge offer is $250. The resource is discharged uneconomically due to a fixed ED to charge the resource at 184 MW instead of 79 MW and a software issue

Scenario V: Exceptional Dispatch to charge resource can result in unexpected discharge



A counterfactual without the software issue results in the resource no longer discharged, as expected.

Closing Remarks

- Multi-interval optimization provides the means to position the system in advance of projected conditions
- Multi-interval optimization may pose challenges for certain dispatches; the lack of multi-interval optimization will pose another type of challenges
- Dynamic system conditions are inherent to the operation of the grid and will impact all resources to a different extent

Notation

i $-$ $Resource\ Index$

$p_{(i,t)} - MW\ output\ of\ storage\ resource$

$p_{(i,t)}^{min} - Minimum\ operating\ limit\ of\ storage\ resource$

$p_{(i,t)}^{max} - Maximum\ operating\ limit\ of\ storage\ resource$

$soc_{(i,t)} - MW\ output\ of\ storage\ resource$

$soc_{(i,t)}^{min} - Upper\ charging\ limit$

$soc_{(i,t)}^{max} - Lower\ charging\ limit$

$Ru_{(i,t)} - Regulation\ Up\ Award$

$Rd_{(i,t)} - Regulation\ Down\ Award$

$Sr_{(i,t)} - Spinning\ Resource\ Award$

$\eta - Charging\ Efficency$

DT- length of time interval

T – length of one interval