Grid Operational Impacts of Widespread Storage Deployment

Session 3: Planning and Deployment Implications with Storage and IBRs

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ESIG Fall Technical Workshop
October 25, 2022

Participation Model Objectives

- Primary objective: *Allow for greatest flexibility in participation options where possible, noting different perspectives of different market participants who may prefer different models*
  - Subject to **reliability** and the changing impact when **large amounts** and **multiple configurations** of these resources integrate
  - Subject to **costs** of implementation, and in some cases **solve time impacts**
- Granular models tend to provide **theoretical efficiency gains**, but they also add complexity to the market clearing software, and they may not be desired by all participants.
- **Regional differences** in systems, priorities, and existing market designs are important considerations

Standalone Electric Storage Resource Participation Models

Timeline of O841 compliance filings

2019

Dec 3: CAISO compliance filing effective

Dec 3: PJM compliance filing effective for *majority* of O841 aspects

2020

Aug 26: NYISO compliance filing effective

2021

Mar 1: ISO-NE compliance filing effective for *majority* of O841 aspects

Aug 5: SPP compliance filing effective

2022

Jun 6: MISO compliance filing effective

2024

Mar 31: PJM compliance filing effective for SOC consideration

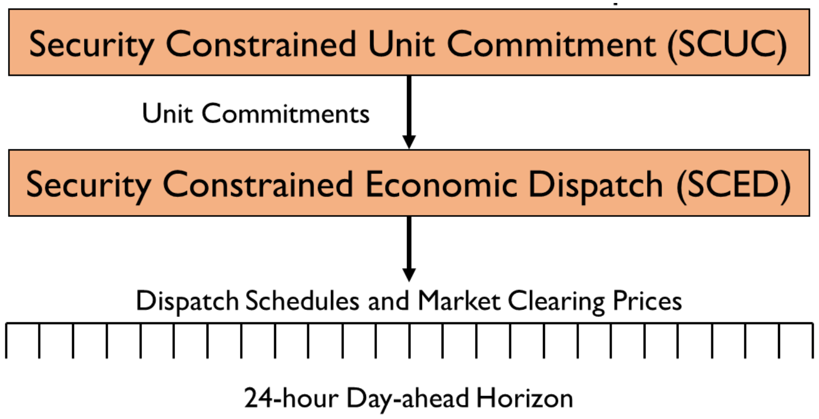
2026

Jan 1: ISO-NE compliance filing effective for DAM

Dec 3, 2018: Deadline for ISOs/RTOs to file compliance plans
Dec 3, 2019: Implementation deadline

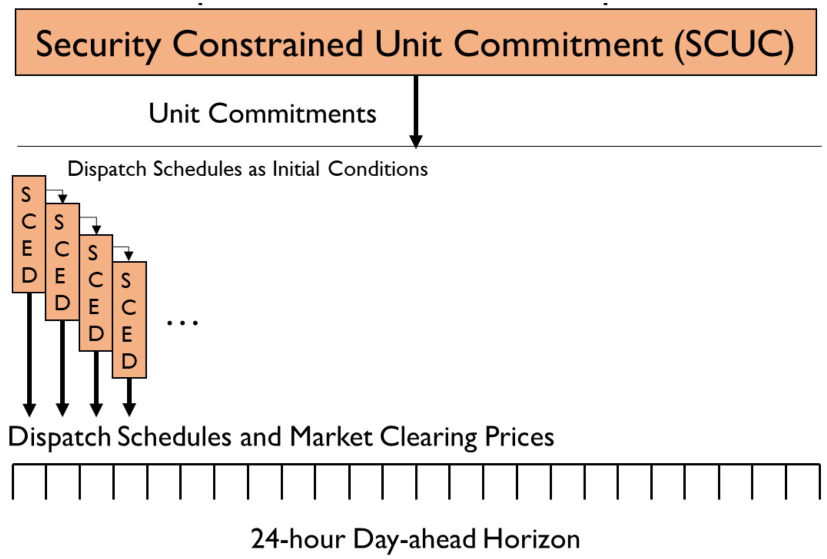
Market Clearing Software Differences

ISO-SOC-Management Simultaneous SCED Approach



- **RTO/ISO**: CAISO, NYISO
- **DASCED Objective**: Maximizes social welfare / minimizes total system operating costs over the entire DA operating horizon (i.e., 24-hours)
- Previous hour's SOC and dispatch schedules (charge, discharge decisions) are variables in the SOC and ramp rate constraints (impacts dispatch/LMP calculations)

SOC-Management-Lite Sequential SCED Approach



- **RTO/ISO**: SPP, ISO-NE, MISO, PJM
- **DASCED Objective**: Maximizes social welfare / minimizes total system operating costs for each DA time period or market interval individually (i.e., 1-hour)
- Previous hour's SOC and dispatch schedules (charge, discharge decisions) are parameters in SOC and ramp rate constraints (impacts dispatch/LMP calculations)

*PJM uses a separate software program, referred to as pumped hydro optimizer, for determining pumped storage hydro (PSH) schedules

State of Charge Management: Options

Self-Schedule

- ESR self-dispatches its output and is insensitive to price.

Allowed by all ISOs/RTOs

Self-SOC-Management

- ESR provides an offer curve analogous to traditional resources.
- ESRs can set offers to ensure desired and feasible SOC.
- ISO schedules without SOC consideration

CAISO, NYISO ESRs, NYISO PSH units

SOC-Management-Lite

- ESR provides an offer curve.
- ISO does not schedule ESR if it would lead to infeasible SOC.
- Schedules are not optimized across time to optimize ESR schedules.

SPP, ISO-NE, MISO, PJM

ISO-SOC-Management

- ESR may or may not provide an offer curve.
- ISO ensures SOC feasibility and optimizes ESR schedules across time to minimize cost.

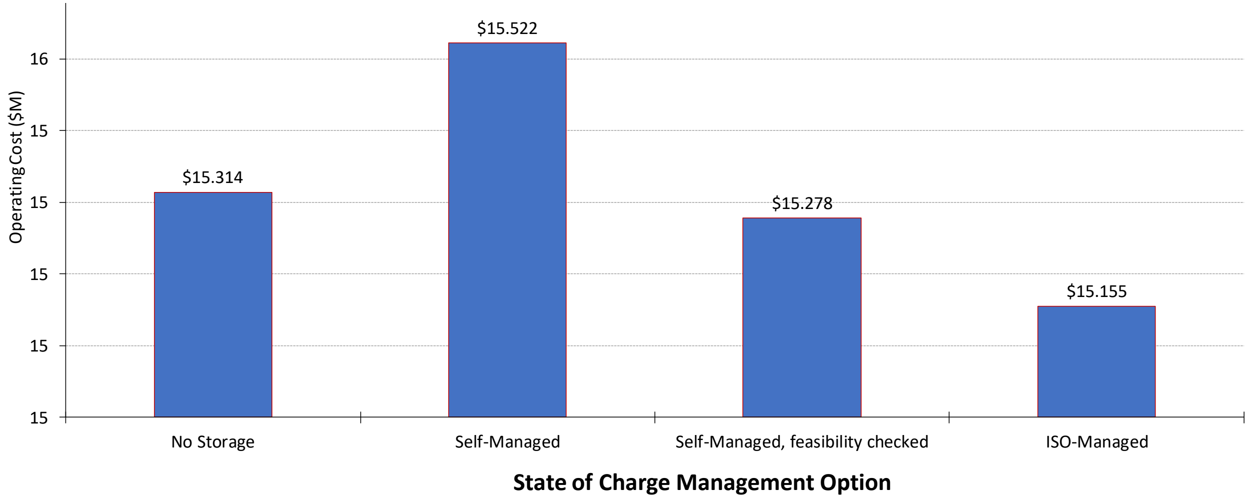
CAISO, NYISO ESRs, PJM PSH units

→ ISO Scheduling Responsibility / Theoretical Economic Efficiency and Reliability Benefits / Complexity

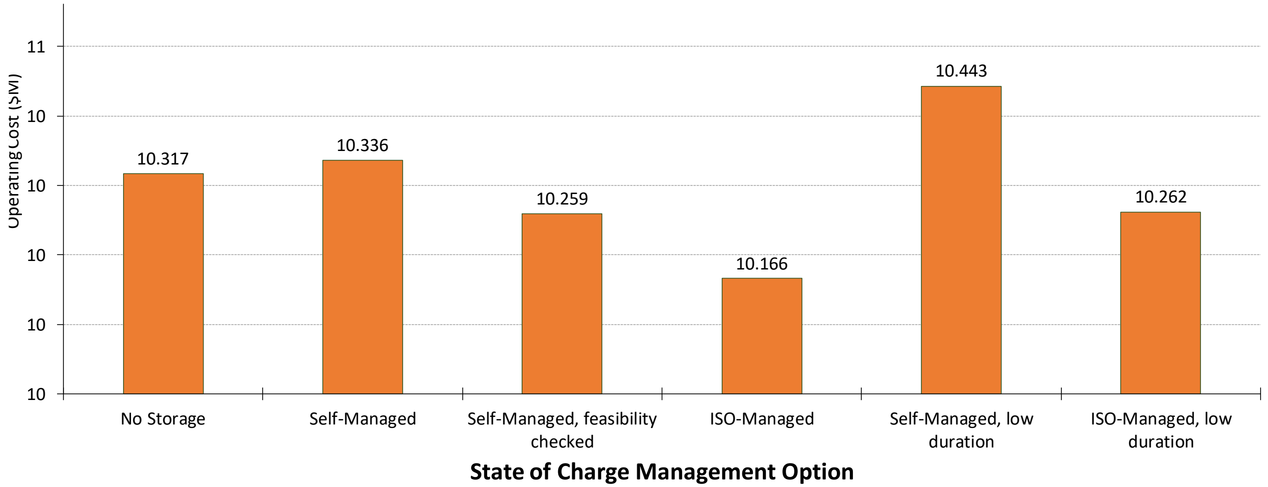
← ESR Asset Owner Participation Responsibility and Flexibility / Computational Efficiency

Operation and Market design

Low Renewable Scenario



High Renewable Scenario



- ✓ Self-management found to ***increase*** costs when storage deployed
- ✓ ***Greatest*** cost reduction and profits observed when ISO manages state of charge and optimizes to lower costs
- ✓ Self-management still benefits efficiency if feasibility checked, allowing ***greater flexibility*** for participant
- ✓ Challenges may be ***exacerbated*** by duration of storage, amount of storage, and amount of renewables

E. Ela, N. Singhal, *Integrating Electric Storage Resources into Electricity Market Operations: Evaluation of State of Charge Management Options,* EPRI, Palo Alto, CA: 2019. 3002013868.

The way electric storage is operated and how it participates within the market may have a substantial impact on the magnitude of benefits it provides to the system.

Hybrid Resource Participation Models

Nikita Singhal, Rajni Kant Bansal, Erik Ela, EPRI
Julie Mulvaney-Kemp, Miguel Heleno, LBNL

This presentation is, in part, supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy

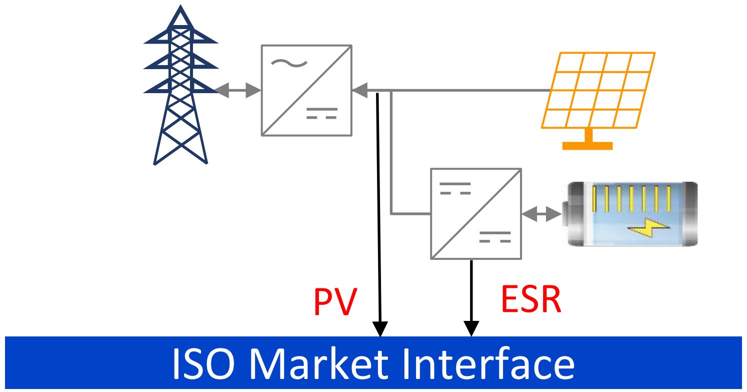
Exploring Hybrid Resource Participation Models

- Project Motivation
  - Hybrid/co-located resources are on the rise, especially in U.S. market regions
  - Uncertainty around efficient and reliable ways to operate these resources
  - Uncertain impacts when high levels of hybrids are present
- Project Goals
  - Provide industry with metrics that quantify advantages and disadvantages of different participation options using realistic power market simulations
  - Identify general implications on reliability, economic efficiency, and asset profitability of high penetrations of hybrids
  - Make recommendations for further examination

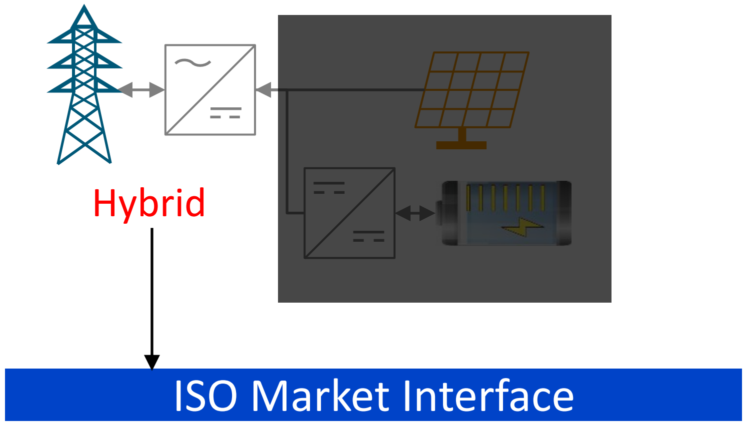
EPRI Proposed Market Modeling Options

Option A: 2R ISO-Managed *Co-located* Model

Separately represent each resource, with minimal changes to existing market designs



Option B: 1R Self-Managed *Hybrid* Model



Single offers and operating parameters allows participant bidding strategy flexibility

Option C: 1R ISO-Managed-Feasibility *Hybrid* Model

Add telemetry requirements to allow ISO to limit infeasible schedules during critical times

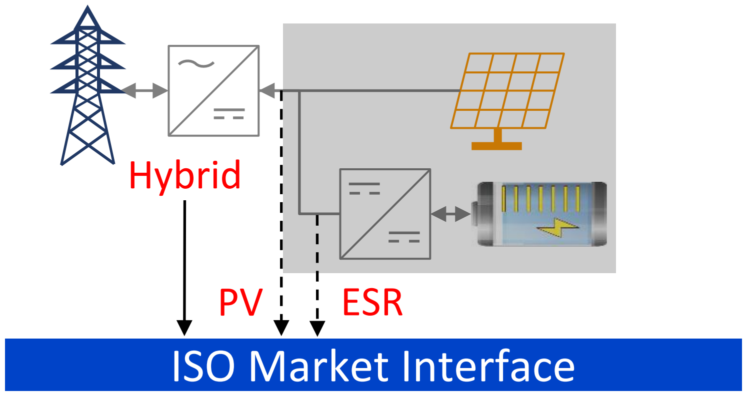
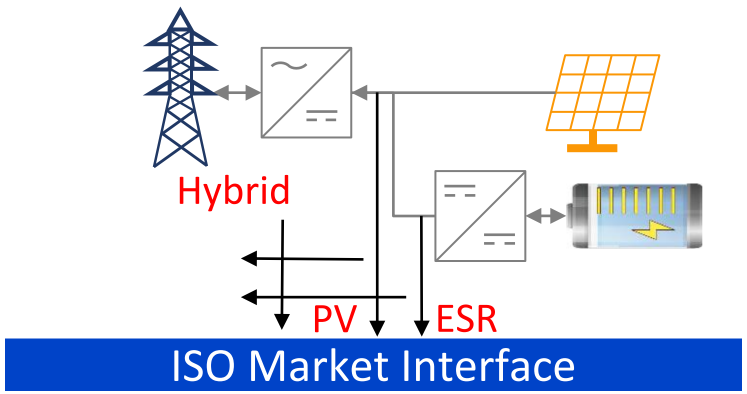


*figure illustrates dc-coupled strategy for demonstration purposes

Option D: 2R Linked *Co-located* Model



Add linking constraint to increase ISO's and asset's ability to operate and represent the resource's dependencies

RTO/ISO Hybrid Resource Market Design Proposals

Market Design Aspect	NYISO	PJM	SPP	ISO-NE	MISO	CAISO
Participation Model	❖ Most entities are proposing two separate participation modeling options: Co-located (2R; two separate independent resources model) and hybrid (1R, single integrated resource model)					
	2R: CSR (IPR, ESR) CSR scheduling constraints; Wind or Solar Output Limit flag allocated to co-located IPR (if CSR schedules ~90% of CSR Injection Scheduling Limit). **1R**: HSR (ongoing developments)	**2R** **1R**: adopt larger parent fuel-type model in the interim *Future*: ESR (fully applicable to open-loop hybrids; partially applicable to closed-loop hybrids) ✓ Solar-Battery Hybrids: ESR (except add solar-only mode, delete non-energy Regulation & reserves modes, closed-loop model lacks negative MW functions)	**2R**: owner to ensure Order 845 appropriately accounted for; **1R** (HSMR): currently (Generating Unit, Plant), considering MSR, but 2R EMS (reliability) Model. If HSMR not registered as MSR and its ESR component is capable of charging from the grid, then provision to include withdrawn energy in a load settlement location.	• **2R**: ✓ VER: SOR, non-dispatchable generator, DNE dispatchable generator ✓ Battery: SOR, CSF • **1R**: SOR, CSF (preferred by ISONE), Intermittent Generator	• **2R** • **1R**: Generation Resource, DIR, or SER Type II/ESR • **ECC** (in the 5y horizon)	**2R** (co-located resource): ACC (master, subordinate); ESR allowed to deviate from dispatch instruction & reduce output under certain conditions; ISO may curtail EIR based on its bid curves or operating needs **1R** (hybrid resource): NGR

AS: Ancillary Service; **ACC**: Aggregate Capability Constraint; **ATRR**: Alternative Technology Regulation Resource; **BSF**: Binary Storage Facility; **CSF**: Continuous Storage Facility; **CSR**: Co-located Storage Resources; **DAM**: Day-ahead Market; **DARD**: Dispatchable Asset Related Demand; **DIR**: Dispatchable Intermittent Resource; **DNE**: Do-Not-Exceed; **ECC**: Enhanced Combined Cycle; **EIR**: Eligible Intermittent Resource; **ELR**: Energy Limited Resource; **EMS**: Energy Management System; **ESF**: Energy Storage Facility; **ESR**: Electric Storage Resource; **HSL**: High Sustained Limit; **HSMR**: Hybrid Storage Market Resource; **HSR**: Hybrid Storage Resource; **IPR**: Intermittent Power Resource; **MSR**: Market Storage Resource; **NGR**: Non-Generator Resource; **POI**: Point of Interconnection; **PSH**: Pumped Storage Hydro; **RA**: Resource Adequacy; **RTM**: Real-time Market; **SER**: Storage Energy Resource; **SOC**: State of Charge; **SOCM**: SOC Management; **SOR**: Settlement Only Resource; **VER**: Variable Energy Resource

[1] Participation Options and Designs for Emerging Technologies in Electricity Markets*: 2021 Update on Storage, Hybrid Storage, and DER Aggregations.* EPRI, Palo Alto, CA: 2021. 3002021948.

Case Studies: Introduction

- Goal
  - Evaluate the key differences that alternative market designs for hybrid resources have on key metrics through modeling, simulation and analysis, while focusing impacts on day-ahead (DA) and real-time (RT) energy
    - Economic efficiency (operating costs/societal welfare)
    - Profits and incentives (individual resource/aggregate profits, revenue adequacy)
      - Day-ahead revenue, real-time revenue, two-settlement profit
    - Reliability of the system (power imbalances, reserve shortages)
    - Computational efficiency
  - Other anticipated impacts such as price setting, market settlements, make-whole payments, and market mitigation are out of scope for this specific study.

Bidding module: High-level overview

Stochastic variable modeling

1. Inputs
- Historical data related to renewable generation production and day-ahead market prices
- Define number of scenarios for each uncertainty source

2. Build Time-series

3. Scenario Generation

Optimization problem

Obj. Function: Max. [Expected Profit]

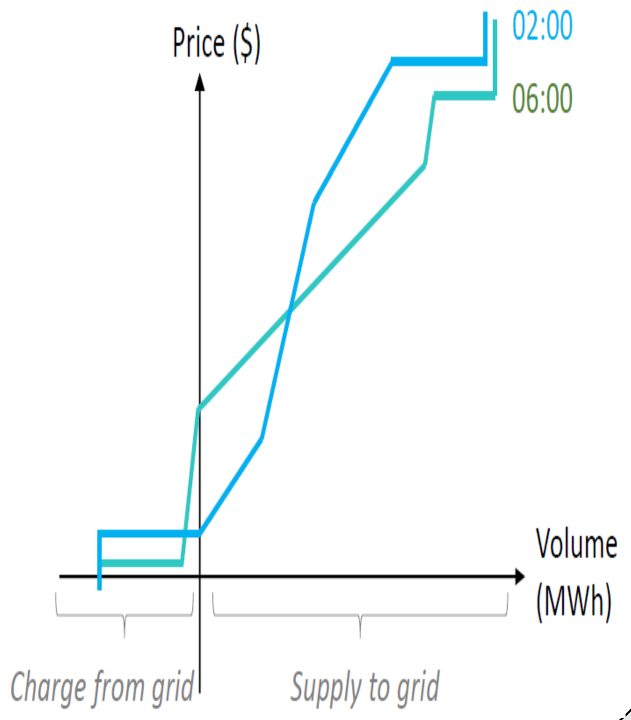
Subject to:

- CVaR constraints
- ESR operational constraints
- VRE operational constraints
- Offer/bid curve constraints

Apply Heuristics

Resource parameters

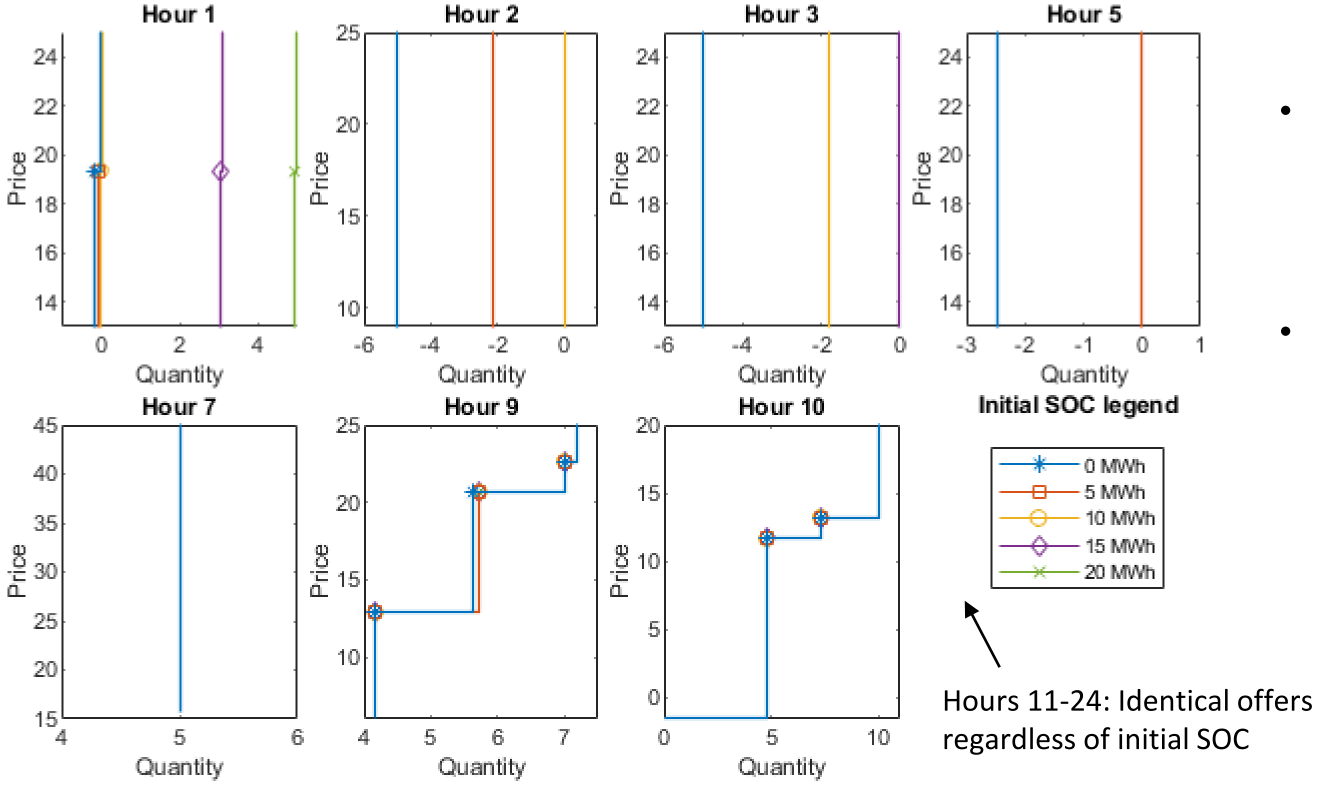
Output



*collaboration b/w LBNL and EPRI

Bids are sensitive to the day's initial state-of-charge…

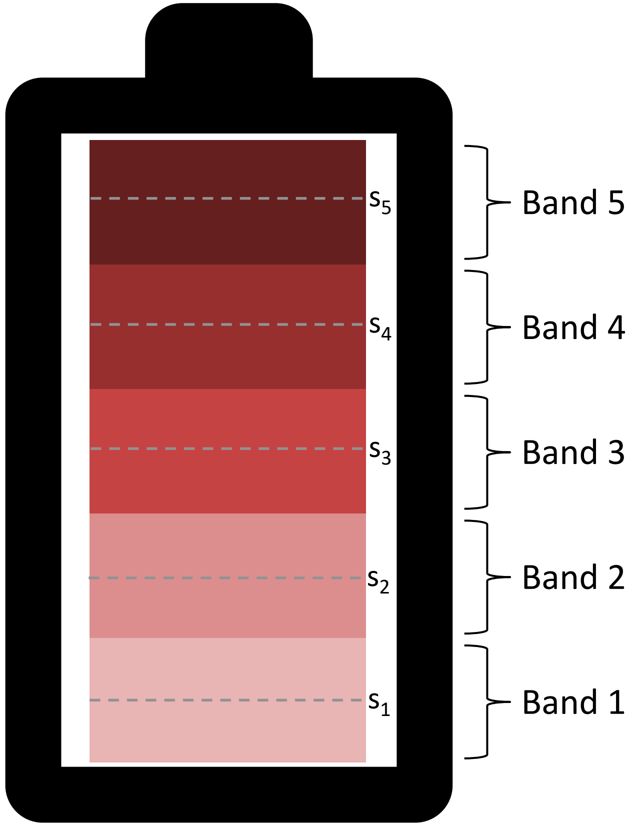
Example:



- A large initial SOC allows the hybrid to deliver power in hour 1 and then remain idle until delivering again during morning peak price hours.
- Meanwhile, hybrids with small initial SOC charge from the grid (negative quantity bids) during low-price morning hours (e.g., hour 2).

…but PCM runs requires months of bids to be submitted at once. What initial state-of-charge should the bids for day 42 be based on, given the uncertainty in generation and dispatch on days 1-41?

Solution: Create several sets of offers for each day corresponding to different initial SOC conditions



Methodology for creating bids for each day:

- Compute 24 hourly bids based on the state-of-charge at the start of hour 1 being s_1. This is Bid Set 1.
- Compute 24 hourly bids based on the state-of-charge at the start of hour 1 being s_2. This is Bid Set 2.
- …
- Compute 24 hourly bids based on the state-of-charge at the start of hour 1 being s_5. This is Bid Set 5.
- The price scenarios, generation scenarios, and all other parameters (aside from initial SOC) are identical across these computations.

Methodology for selecting which bid set to use in the day-ahead market:

- At noon the prior day, PSO projects what the initial SOC will be based on current SOC and cleared bids for the next 12 hours.
- If this projection is in Band X, then Bid Set X is used in the market simulation and all other bid sets are ignored.

Case Studies: Simulation Tool

- Market clearing software simulation tool: Power System Optimizer by Polaris

Power System
Optimizer

- Initial assumptions
  - **Day-ahead market**: Modeled market structure includes DA SCUC and DA SCED
    - Commit long-start resources, schedule hybrids, uses DA forecasts
  - **Real-time operation**: Modeled market structure includes RT SCUC and RT SCED.
    - Accommodates imbalance, commits quick starts, dispatches resources, hybrids follow one of two options
    - Additional scheduling modifications to accommodate real-time operations
  - **Ancillary services market**: Excludes A/S provision from hybrid storage
  - **Power system test case**: Zonal New York Bulk Power System (NY BPS)
- Planned multi-cycle simulation approach

DA SCUC: Day-ahead Security Constrained Unit Commitment, **DA SCED**: Day-ahead Security Constrained Economic Dispatch, **RT SCUC**: Real-time Security Constrained Unit Commitment, **RT SCED**: Real-time Security Constrained Economic Dispatch

Real-time market structure

- Market Simulations reflect state-of-the-art market operations in RTO/ISO regions: day-ahead commitment followed by real-time operation and dispatch, with forecast errors occurring between
- Real-time scheduling cycle structured to demonstrate the effectiveness of the participation models based on **physical capabilities and limitations,** such as
  - Variable renewable energy (VRE) forecast errors
  - Electric storage resource (ESR) minimum state-of-charge (SOC) and maximum SOC limitations
  - Hybrid resource interconnection limitations, e.g., restricted grid charging and point of interconnection (POI) capacity constraints
- Real-time is represented as real-time operation (i.e., not a separate real-time market with updated bids), allowing for understanding of the isolated impacts from participation in DAM
  - This assists in separating out the impacts from real-time re-optimization that may be evaluated in a future phase of the study, as well as potentially separating out the challenges associated with ancillary services impacts on participation models.

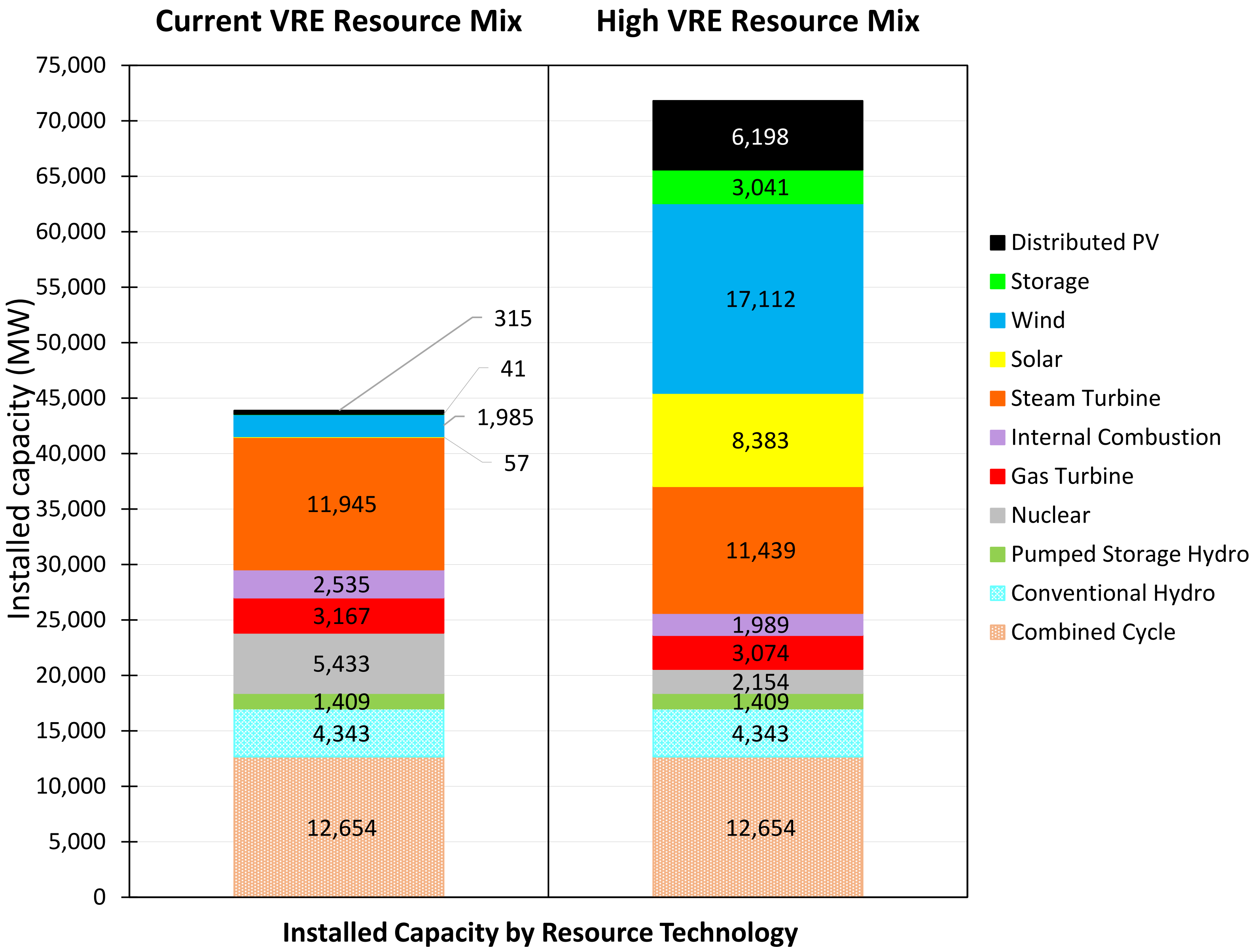
Real-time market structure

- Real-time operation is represented by two different operational plans of the hybrid resource's day-ahead schedule
  - Storage Follow (SF): Schedules for the storage component of the hybrid resource will be interpolated from its day-ahead market schedules as long as SOC is at a level that it can do so.
  - Hybrid Balance (HB): Allow for the storage component to do whatever it needs to do to meet the DA hybrid schedule when there are VER forecast errors.
  - There will be load and VER forecast error (including VER from the hybrid facility) occurring between the day-ahead and real-time scheduling in both real-time operational plans.
  - Each option is an approximated real-time market strategy and allows for the study team to have more confidence in the study on day-ahead participation
  - Updating bids in real-time, or utilizing real-time re-optimized state of charge management are both complex and out of scope for this study, with the focus on day-ahead participation

Case Studies: Preliminary Proposed Metrics

- Economic
  - Economic options from a societal benefit perspective: What leads to least production costs? Why?
  - Which option may be most advantageous for the hybrid asset owner assuming truthful cost-based offer strategies? Why?
- Reliability
  - Is it possible for scenarios (particularly with high levels of hybrid resource penetrations) – to lead to infeasible schedules awarded that can have reliability implications?
  - How often may this happen and what is the reasoning for its occurrence? Is there immediate enhancements to prevent it from happening?
  - Unserved energy, reserve shortages, risk
- Computational efficiency
  - What computational issues may be present in each option?
- *How do these metrics differ based on participation model (1R, 2R), real-time participation, at different hybrid penetration levels, different VER penetration levels, hybrid resource sizing, different resource mixes, different ITC charging strategies, etc.?*

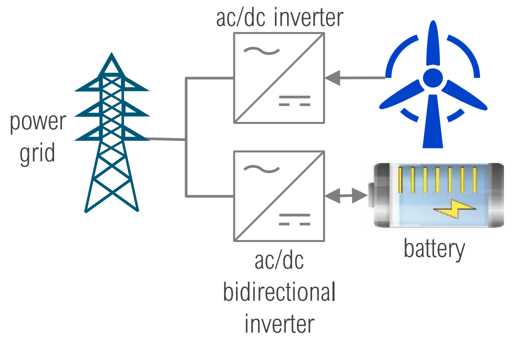
New York Model Overview



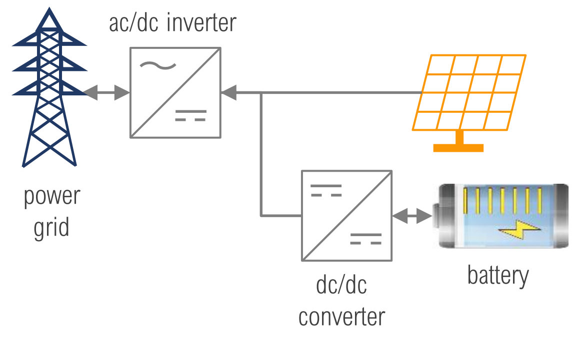
- This is **NOT** a New York study. The New York bulk power system is chosen based on availability of realistic dataset.
- Model Features:
  - Zonal model: includes key interfaces, and interchanges with neighboring regions
  - Generating unit operating characteristics, Fuel prices, Ancillary services
  - Load shapes, Wind generation profiles, Solar photovoltaic generation profiles
  - Instantaneous maximum load of the simulation period: 18.32 GW (April 2019)

NYISO: Hybrid configurations in the low hybrid penetration scenario

Hybrid Technology	Battery Storage Capacity, Energy, Roundtrip Efficiency	Variable Energy Resource Capacity
1. Battery+Wind in NY Area A	50 MW, 200 MWh, 85%	100.5 MW
2. Battery+Wind in NY Area C	60 MW, 240 MWh, 85%	125 MW
3. Battery+Wind in NY Area C	60 MW, 240 MWh, 85%	118.1 MW
4. Battery+Wind in NY Area E	115 MW, 460 MWh, 85%	231 MW
5. Battery+Wind in NY Area D	100 MW, 400 MWh, 85%	215.2 MW
6. Battery+Wind in NY Area C	60 MW, 240 MWh, 85%	126 MW
7. Battery+Solar in NY Area K	15 MW, 60 MWh, 85%	31.5 MW
8. Battery+Solar in NY Area K	12.5 MW, 50 MWh, 85%	25 MW



ac coupled



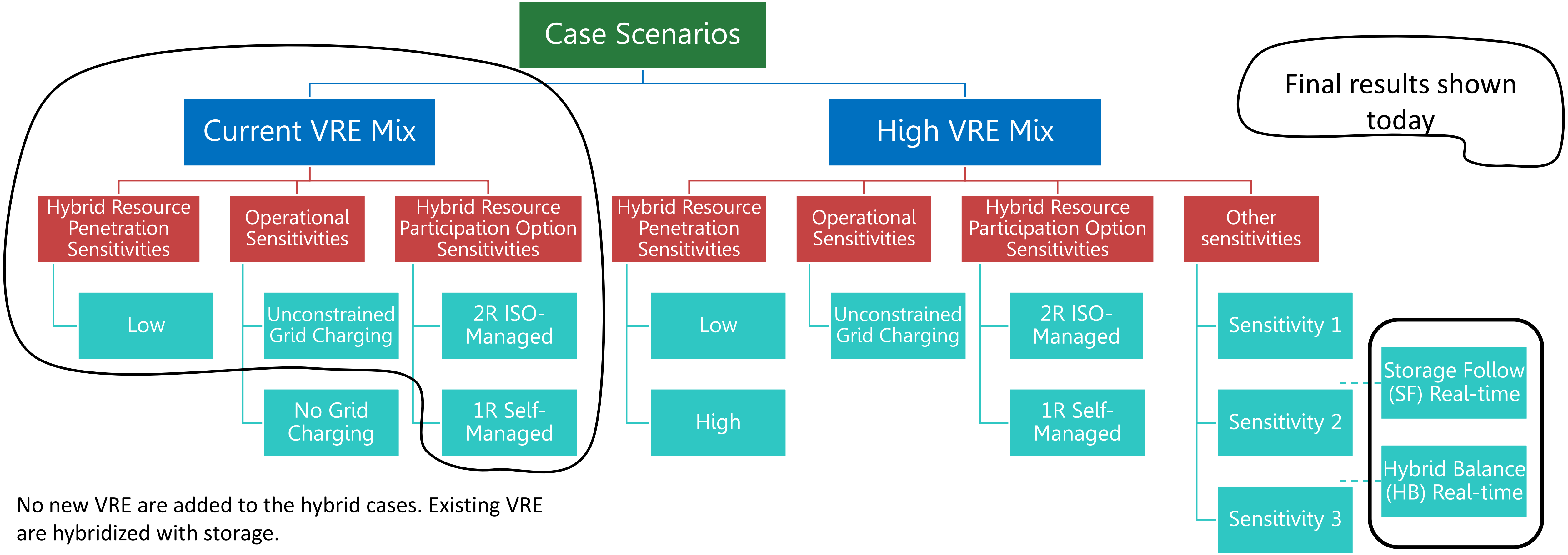
dc coupled

Point of Interconnection (POI) capacity is set to 100% of the variable renewable energy generator nameplate rating

Data Specs

EPRI

Tentative Study Case Matrix for NY Region



No new VRE are added to the hybrid cases. Existing VRE are hybridized with storage.

Priority of key cases based on input from advisors

VRE: Variable Renewable Energy

SF: Storage Follow (storage follows its interpolated day-ahead schedule in real-time if SOC is at a level that it can do so)

HB: Hybrid Balance (storage does whatever it needs to do in real-time to balance the day-ahead hybrid schedule when there are VER forecast errors)

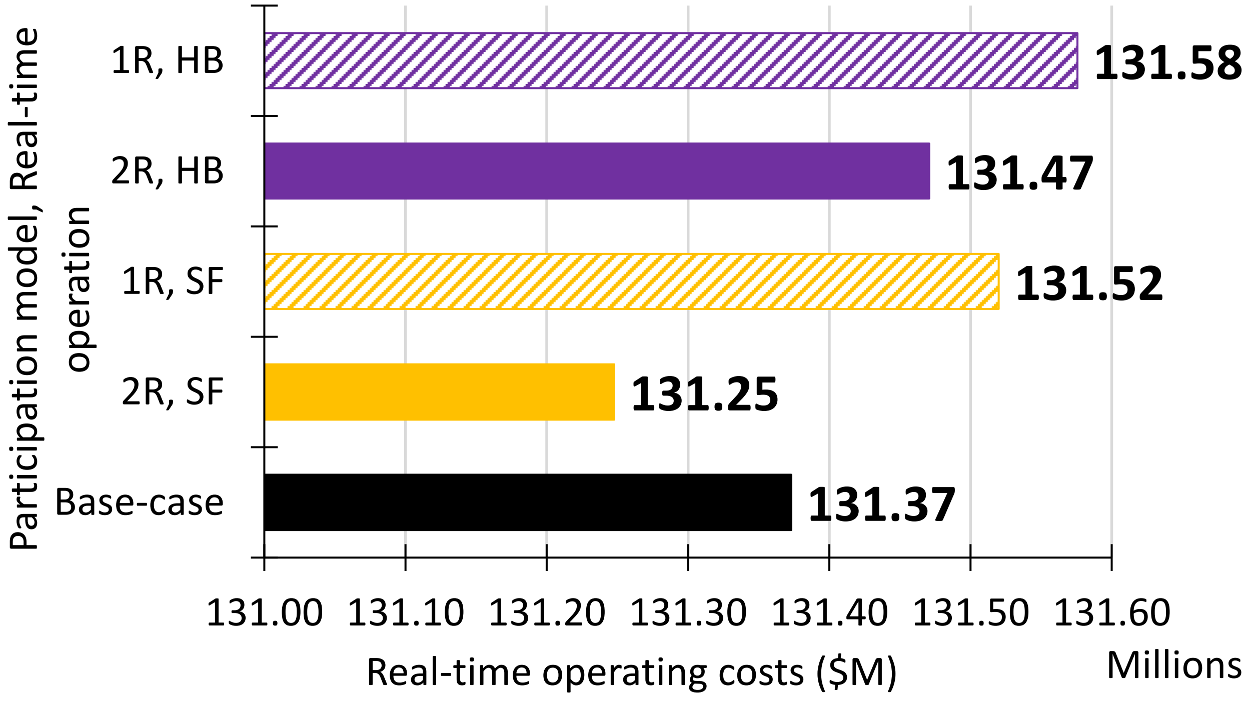
Numerical Results and Analysis

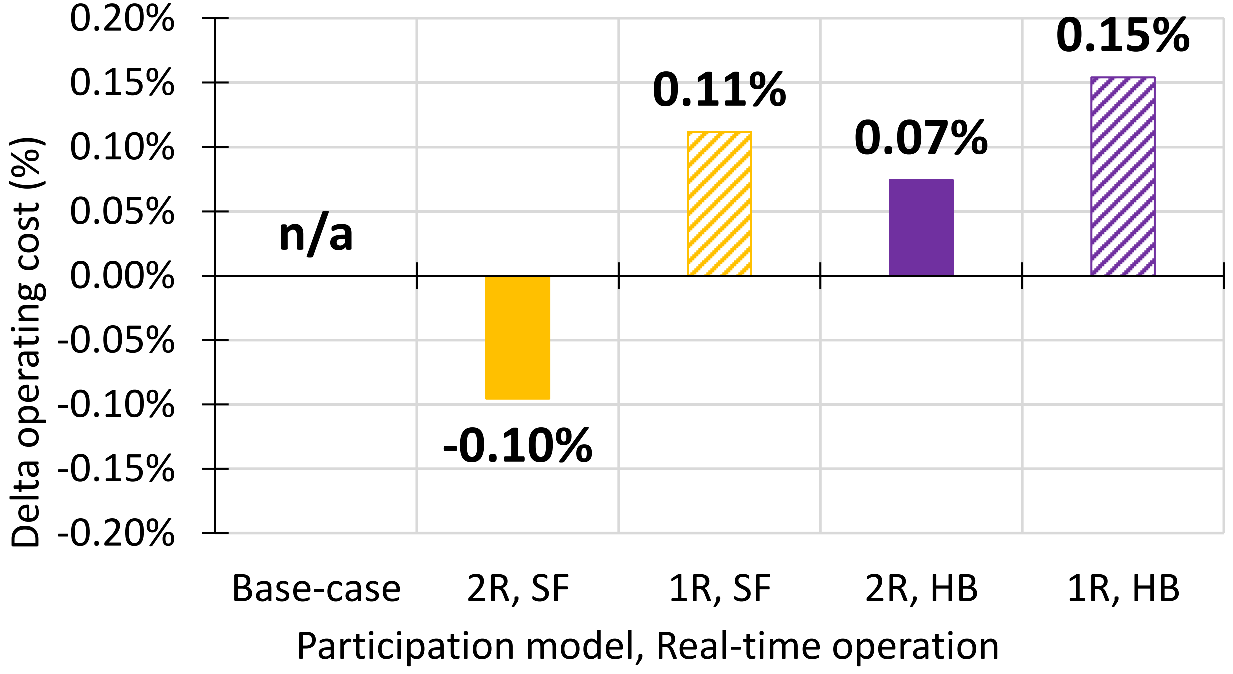
Examining two separate months (April and July)

Economic efficiency implications

- Analysis: What participation options leads to maximum societal benefit? Which option may be most advantageous for the hybrid asset owner assuming truthful cost-based offer strategies?
  - Operating (or production) costs: Real-time
  - Profits: Aggregate and individual hybrid resource profits
    - Day-ahead revenue, real-time revenue, two-settlement (day-ahead plus real-time) revenue
    - Revenue = short-run profit (only costs considered are those payments incurred while charging; degradation costs are not considered)

Economic efficiency implications: Production costs





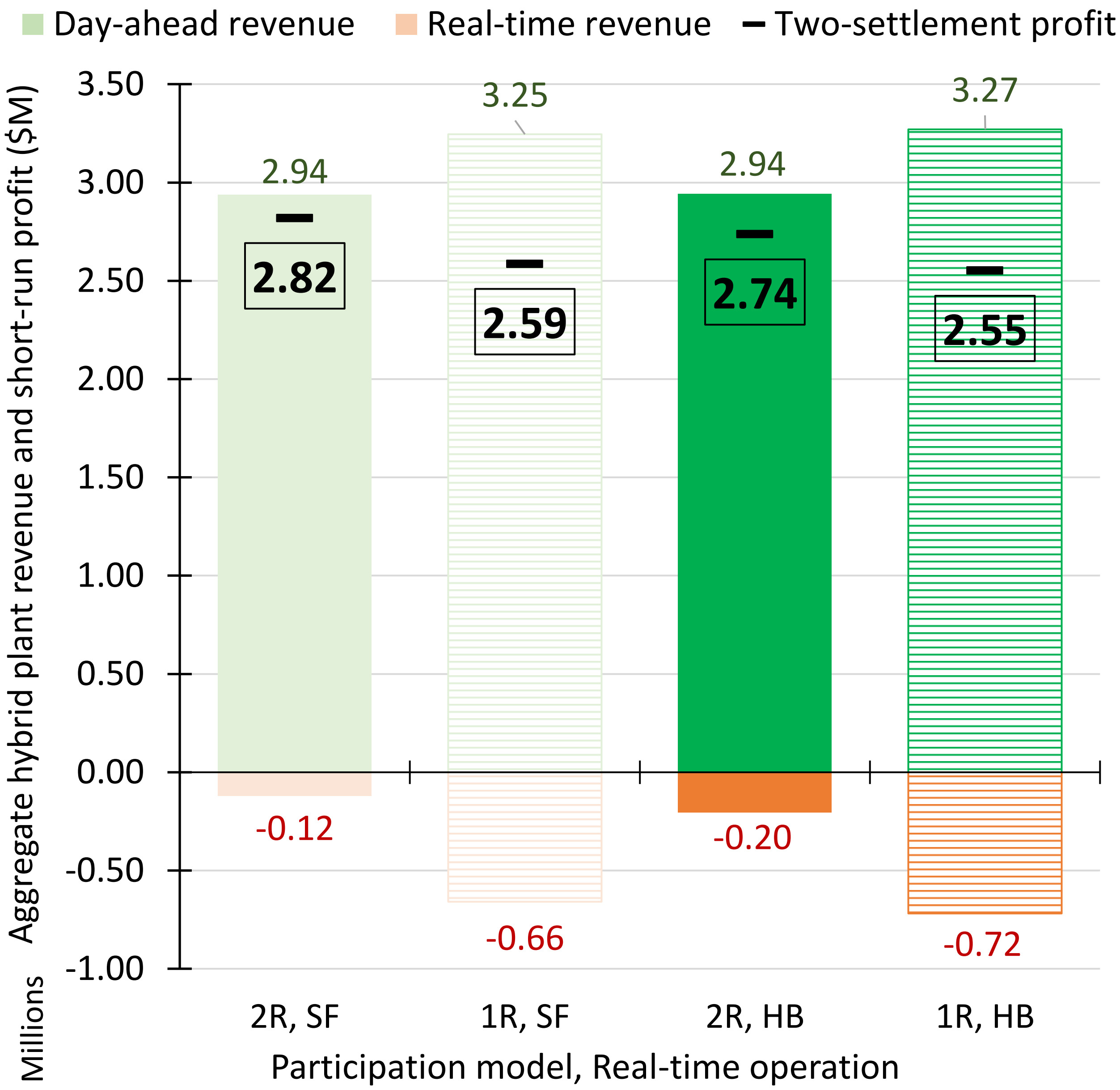
*** MIP Gap: 0.01%.

2R ISO-Managed Co-located Participation Model presents greater production cost savings

SF: **S**torage **F**ollow (storage follows its interpolated day-ahead schedule in real-time if SOC is at a level that it can do so)
HB: **H**ybrid **B**alance (storage does whatever it needs to do in real-time to balance the day-ahead hybrid schedule when there are VER forecast errors)

Aggregate hybrid revenue and short-run profit results

***Results do not reflect ITC benefits.



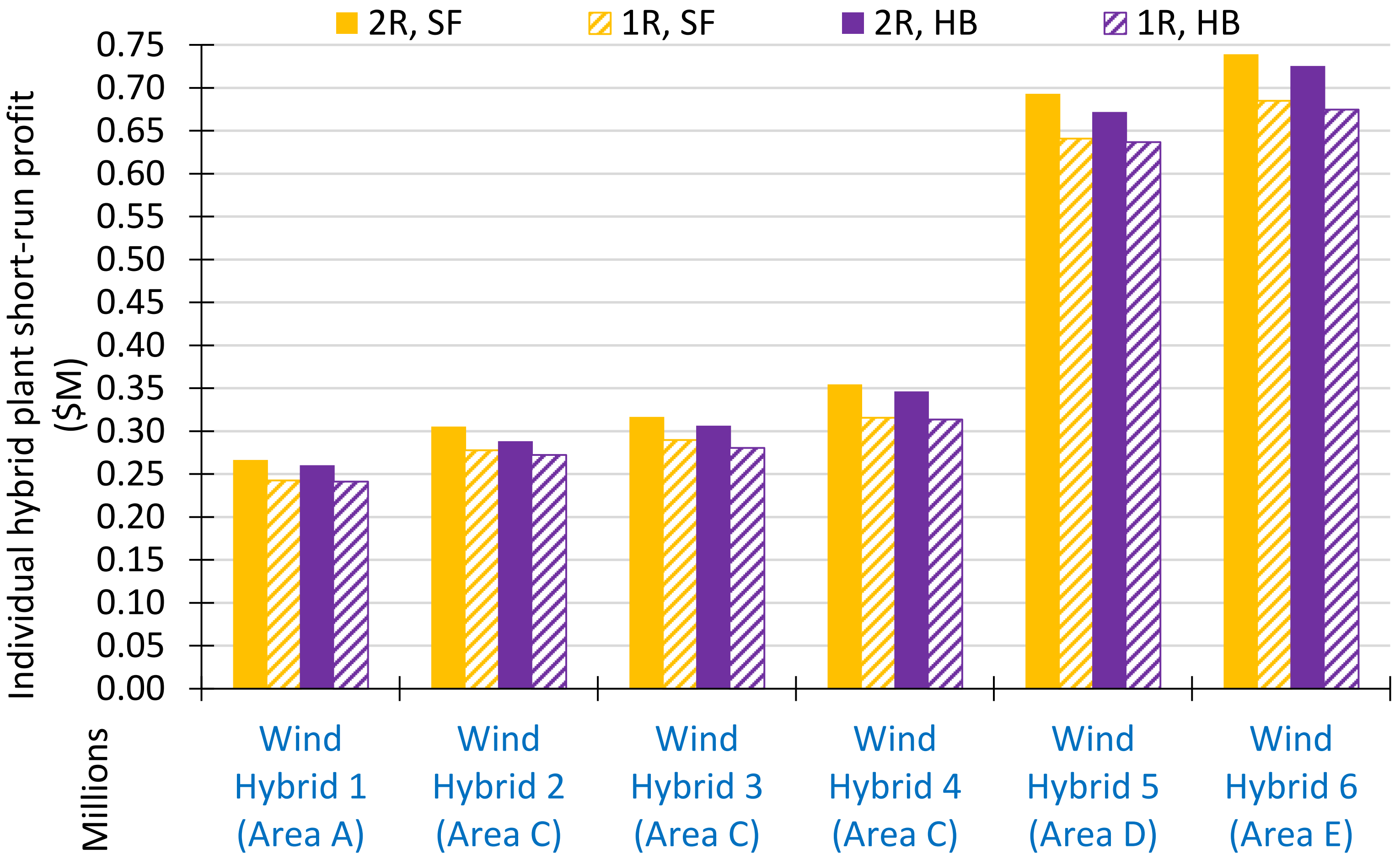
How do negative payments occur in real-time?

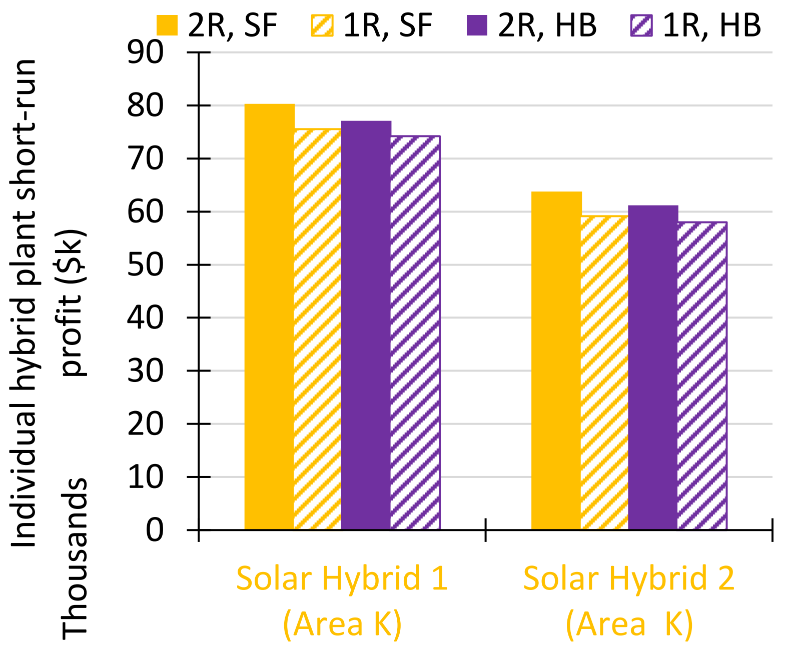
- SF will have an imbalance payment in any period that has forecast error.
- HB will have an imbalance payment when the SOC unexpectedly runs low or high from trying to balance out forecast errors in earlier instances.
- Both SF and HB schemes for 1R will have imbalance payments from any infeasible day-ahead schedules.

2R ISO-Managed Co-located Participation Model presents greater short-run profits

SF: **S**torage **F**ollow (storage follows its interpolated day-ahead schedule in real-time if SOC is at a level that it can do so)
HB: **H**ybrid **B**alance (storage does whatever it needs to do in real-time to balance the day-ahead hybrid schedule when there are VER forecast errors)

Individual hybrid plant short-run profit results





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Reliability and Schedule Feasibility implications

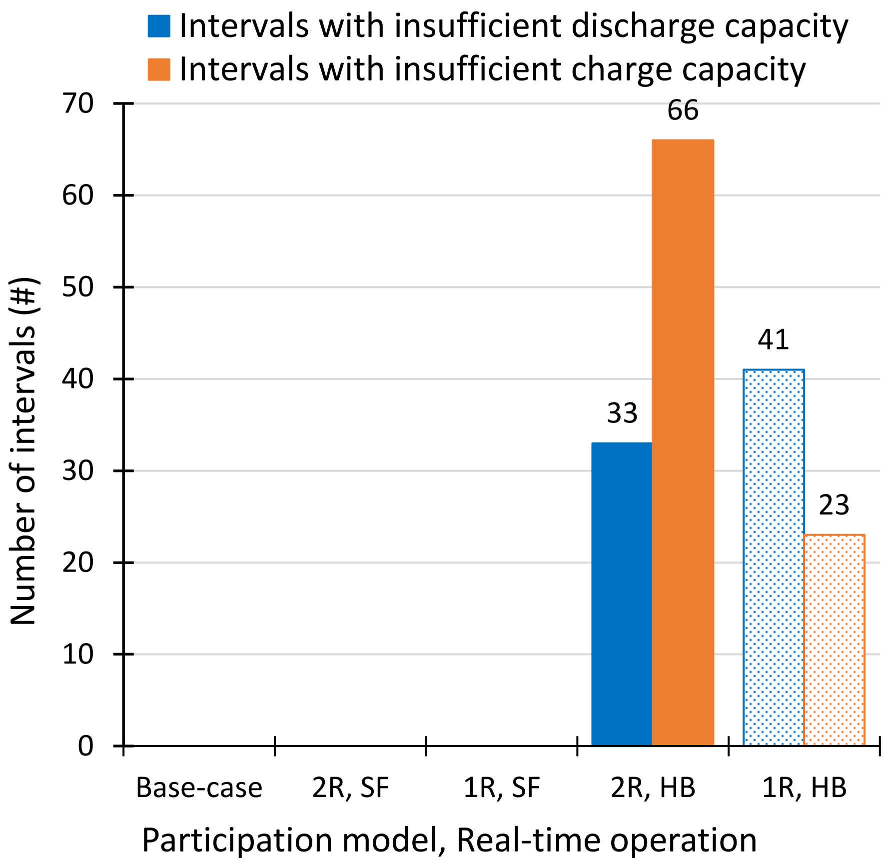
- No instances of violation of the storage constraints in the real-time market
- No instances of violation of the inverter or interconnection constraints in the real-time market
- No instances of power imbalances, such as load-shedding or over-generation, or reserve shortages in the real-time market
- No instances of renewable curtailments

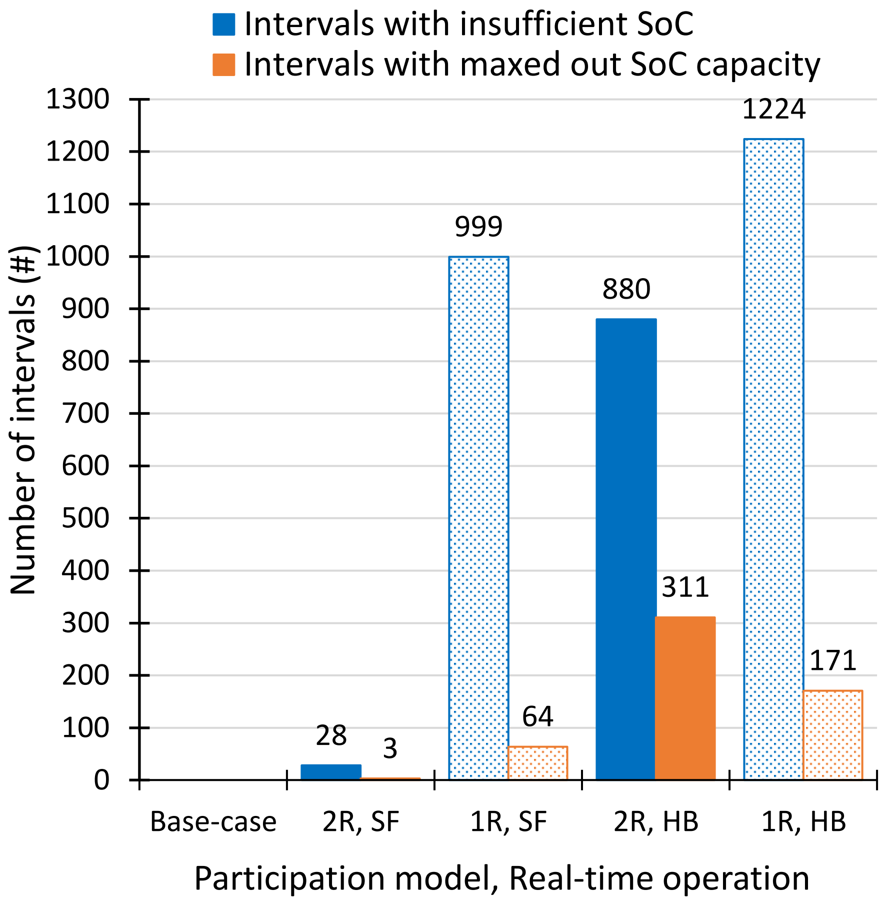
Feasibility of dispatch schedules in real-time

- Feasibility is observed through violation of the constraint that describes the operation of storage component in the real-time market
  - Intervals with insufficient discharge capacity
  - Intervals with insufficient charge capacity
  - Intervals with insufficient SOC
  - Intervals with maxed out SOC capacity
  - Impact of day-ahead to real-time VRE forecast errors in combination with inverter/ interconnection restrictions
- The 1R participation model results in a greater number of intervals with such violations in contrast to the 2R participation model

1R Self-Managed Participation Option results in greater occurrences of feasible dispatch violations

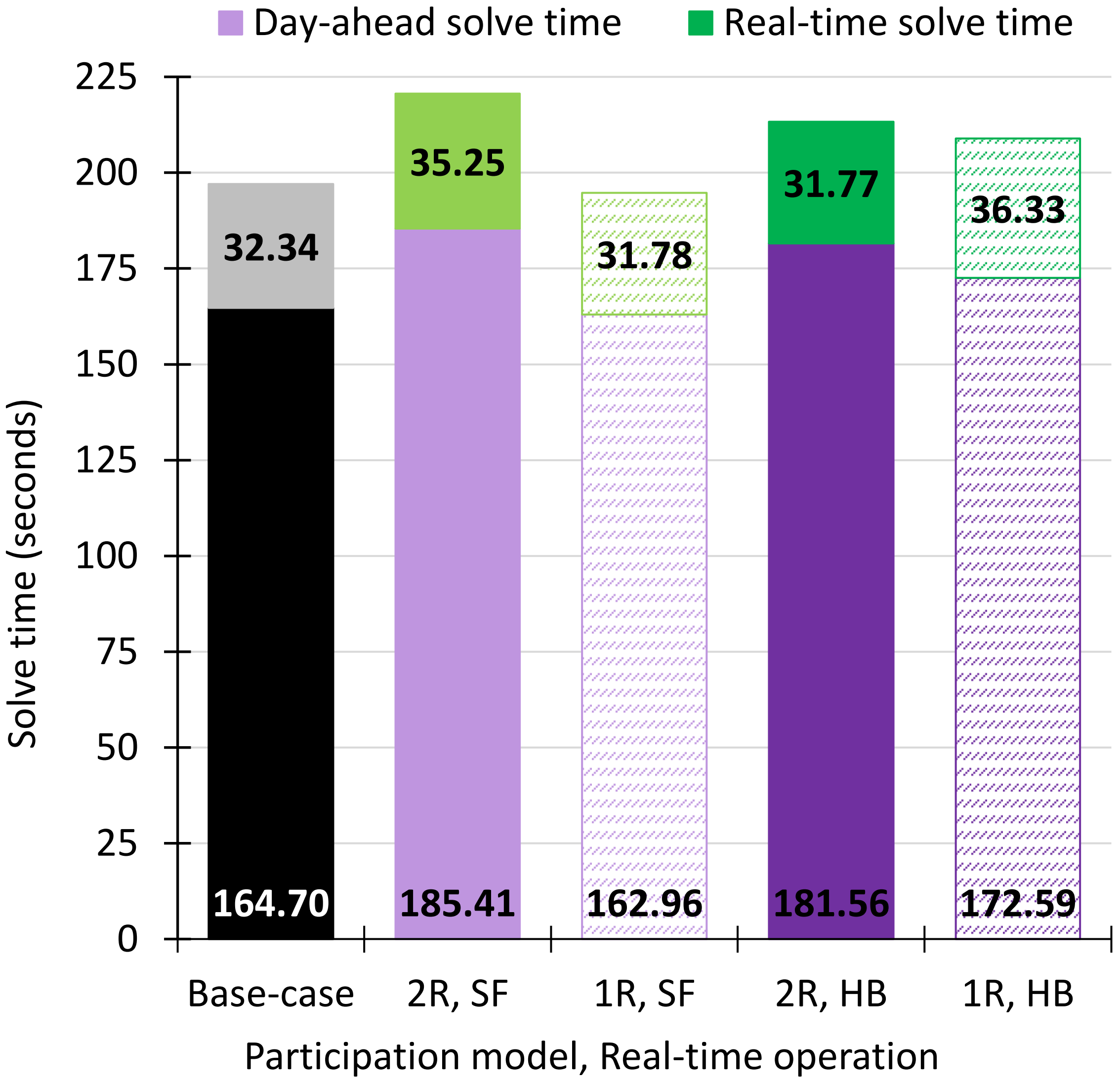
Feasibility of dispatch schedules in real-time





SF: Storage Follow (storage follows its interpolated day-ahead schedule in real-time if SOC is at a level that it can do so)
HB: Hybrid Balance (storage does whatever it needs to do in real-time to balance the day-ahead hybrid schedule when there are VER forecast errors)

Computational efficiency implications



- What computational issues may be present in each participation option?

SF: **S**torage **F**ollow (storage follows its interpolated day-ahead schedule in real-time if SOC is at a level that it can do so)

HB: **H**ybrid **B**alance (storage does whatever it needs to do in real-time to balance the day-ahead hybrid schedule when there are VER forecast errors)

State-of-charge management adds complexity to the market clearing software

Key Takeaways for the Current VRE Mix, Low Hybrid Penetration Sensitivity

- ***Economic efficiency***
  - Granular models such as the 2R ISO-Managed Co-located Participation Option provide greater savings in system operating costs, but this is contingent upon the location of the hybrids and the system operating conditions under consideration. For the case scenarios studied so far, the operating costs implications aren't significant, but this may change for cases with higher penetration of hybrids.
- ***Profits and incentives***
  - Granular models such as the 2R ISO-Managed Co-located Participation Option provide greater short-run profits. This is primarily due to less buy back purchases in the real-time market.
- ***Reliability***
  - No instances of power imbalances, reserve shortages, renewable curtailments, or violations of the storage and interconnection constraints observed under either of the participation options at these levels
- ***Feasibility of dispatch schedules***
  - Occurrences of feasible dispatch violations are greater under the 1R Self-Managed Participation Option
- ***Computational efficiency***
  - Granular models such as the 2R ISO-Managed Co-located Participation Option add computational complexity to the market clearing software compared to 1R models, primarily due to the SOC time-coupling constraint

Next steps...

- Analysis of the implications of the 2R-Linked and Self-Scheduled participation options, including the impact of no grid charging policies
- Detailed sensitivity analysis for the different cases in the case matrix under different system operating conditions
- Future work:
  - Hybrid storage real-time energy market and ancillary services market participation
  - Evaluation of unique hybrid storage configurations: storage duration, storage to generator capacity ratio, point of interconnection capacity, limited grid charging, etc.

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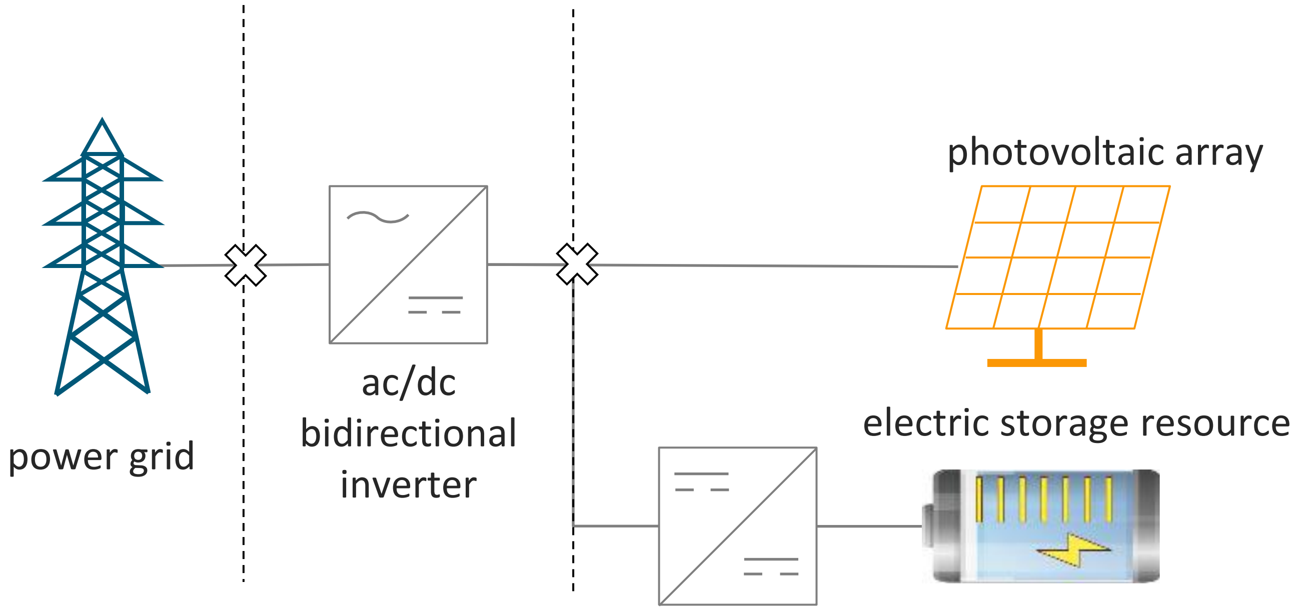
Appendix

Preferred Violation Sequence

Preferred Violation Sequence in the Market Clearing Software

1. First to violate storage real-time operational plan, i.e., SF & HB, constraints
2. Second to curtail VRE in real-time
3. Third to violate power balance constraints
4. Fourth to violate hybrid interconnection (or inverter) constraints
5. Last to violate SoC feasibility restrictions

Penalty prices are set to guide the optimization model to follow this sequence (not factored into pricing/costs)



ISO Market Interface

SF: Storage Follow (storage follows its interpolated day-ahead schedule in real-time if SOC is at a level that it can do so)
HB: Hybrid Balance (storage does whatever it needs to do in real-time to balance the day-ahead hybrid schedule when there are VER forecast errors)