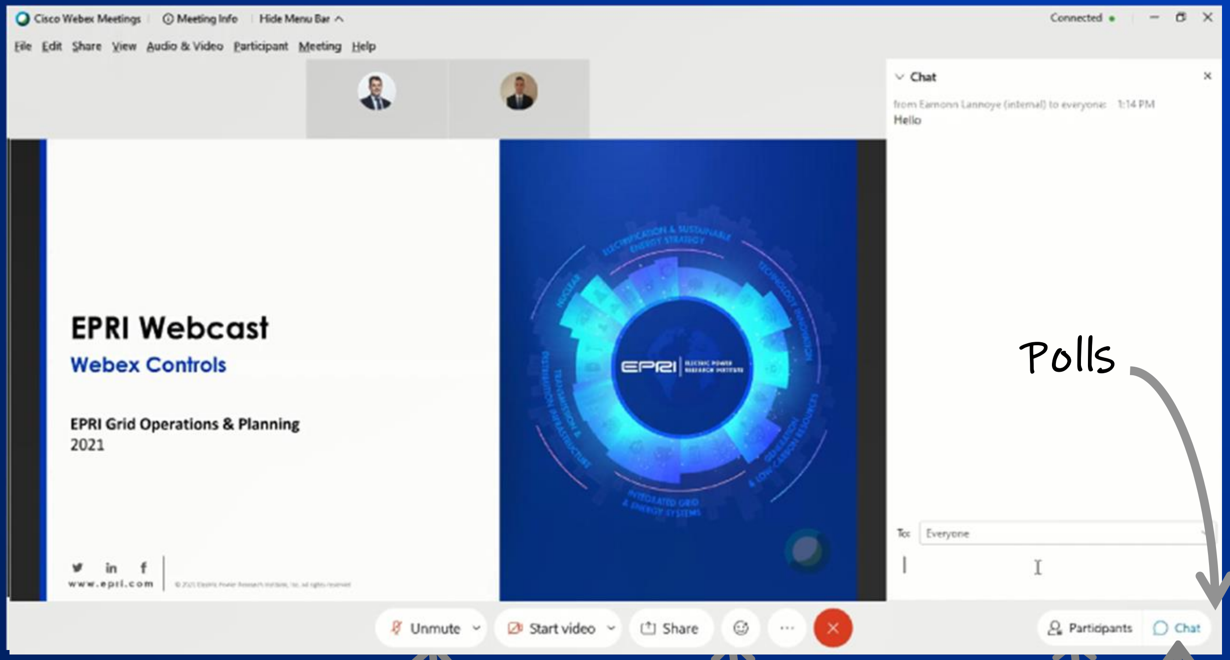
ELECTRIC POWER RESEARCH INSTITUTE

Welcome

Integration of Hybrids into Wholesale Power Markets

Advisory Call #3

April 13, 2023



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Recording paused in between Q&A

Integration of Hybrids into Wholesale Power Markets

Joint EPRI Market Operations and Design Task Force and Project Advisory Update Call

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Technical Advisory Update
April 13, 2023

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

Agenda

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1
- Project Overview & Hybrid Resource Participation Models

2
- Simulation Set-Up & Case Studies

3
- Study Results

4
- Recommendations for Next Steps

Project Overview and Hybrid Resource Participation Models

Exploring Hybrid Storage 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

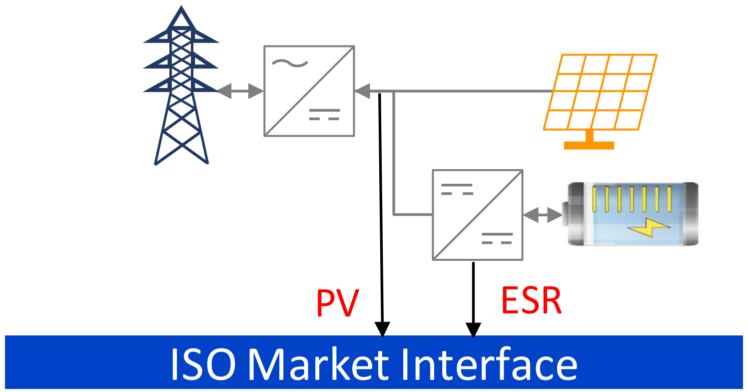
Option A: **2R ISO-Managed *Co-located* Model**

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

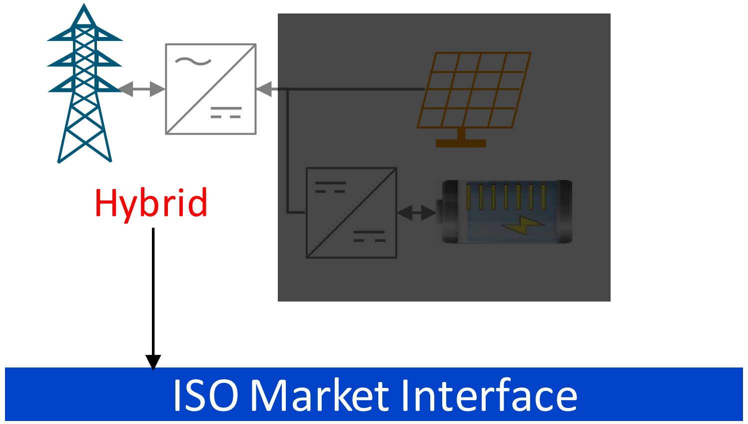
EPRI Proposed Market Modeling Options

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

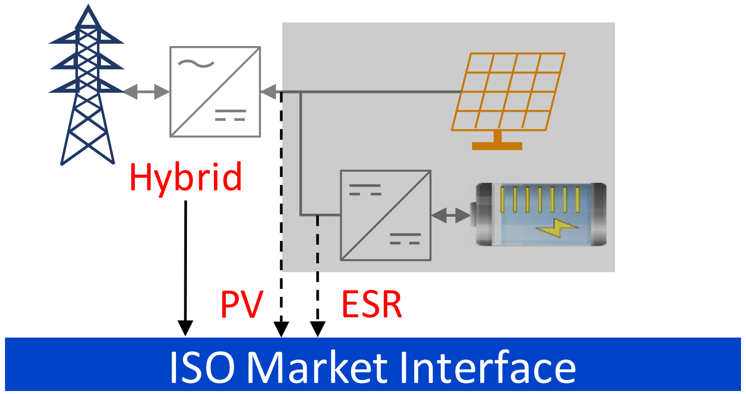
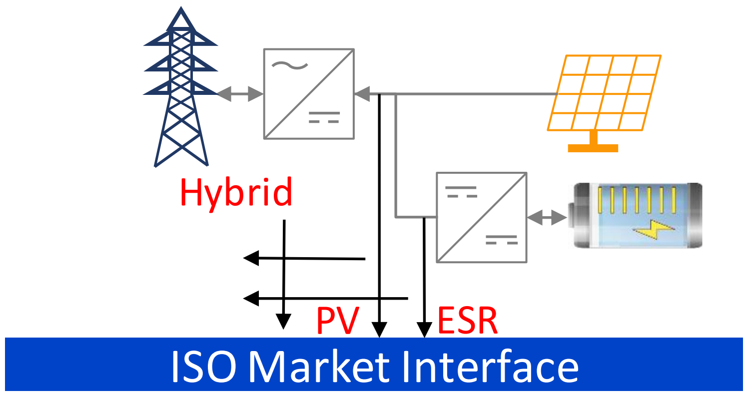


*figure illustrates dc-coupled strategy for demonstration purposes

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

Project Tasks

Scenario and Case Development

- Develop a test case power system to demonstrate case studies
- Determine realistic hybrid, renewable buildouts
- Conceptualize existing and future hybrid participation models

Enhance state-of-the-art software

- Implement advanced SOC management, RT/DA, and other features into SOA software
- Enable practical offer strategy module through advanced tools
- Mimic human behavior in SOA market software

Develop Offers for 1R Hybrids

- Create multi-day offers for all hybrid resources for all applicable case studies
- Develop offers for each band of initial SOC
- Objective: maximize profit, ensure feasibility; with realistic information available

Run Market Simulations

- Run multi-sequence simulations representing SOA market operation
- Compare and contrast all sensitivities for 1R and 2R participation models, system scenarios, and RT options
- Evaluate production costs, reliability, feasibility, computational efficiency, and short-run profit metrics

Key takeaways

Economic efficiency

- The 2R model generally provide greater cost savings
- Not found to be significant in these case studies

System Reliability

- No measurable impacts in any of these cases
- Sufficient quick-start capability to manage infeasible SoC or VER forecast error

Asset Incentives

- The 2R model provides greater short-run profits

Capability to follow directions

- Observed greater occurrences of inability to follow day-ahead schedule for 1R

Key takeaways

Load payments

- Dependent on cleared energy awards for the hybrid facilities that can differ considerably based on the submitted bid strategies or the explicit SoC consideration

Computational efficiency

- Using the 2R model with increasing numbers of hybrids add greater computational complexity and solve time

Modeling difficulties

- Difficult to represent the "human in the loop" and advanced strategies. Both models may show better performance with human trader

Simulation System Set Up and Case Studies

Case Studies: Simulation Tool

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

Reminder: 1R bid curves are designed to perform well across a set of generation and market price scenarios

Stochastic variable modeling

1. **Inputs**
- Historical data on renewable generation
- Day-ahead market prices from 2R simulations
- Desired number of scenarios for each uncertainty source

↓

2. **Build Time-series**

↓

3. **Scenario Generation**

→

Optimization problem

Maximize expected profit over 48-hr horizon

Subject to:

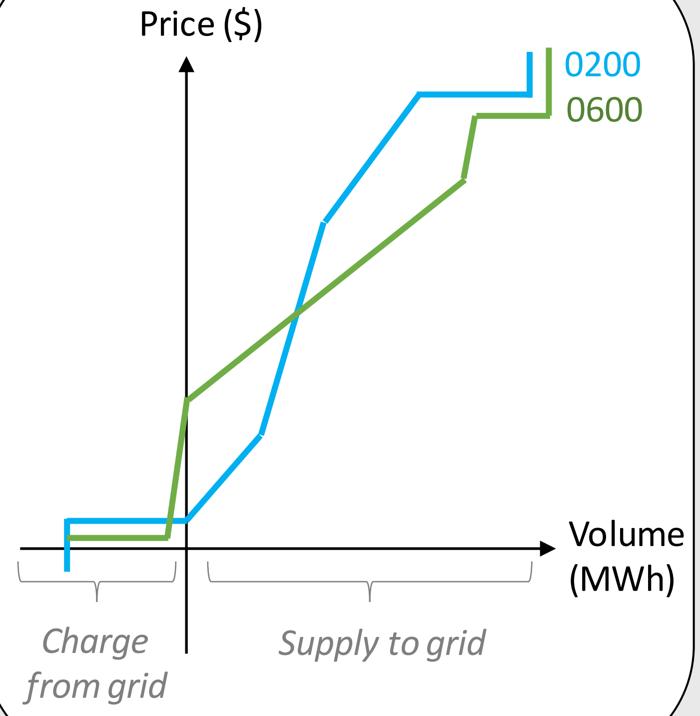
- Risk constraints
- Storage operational constraints
- Generation operational constraints
- Offer/bid curve constraints

Apply heuristics to account for unforeseen prices

↑ Resource parameters

→

Output



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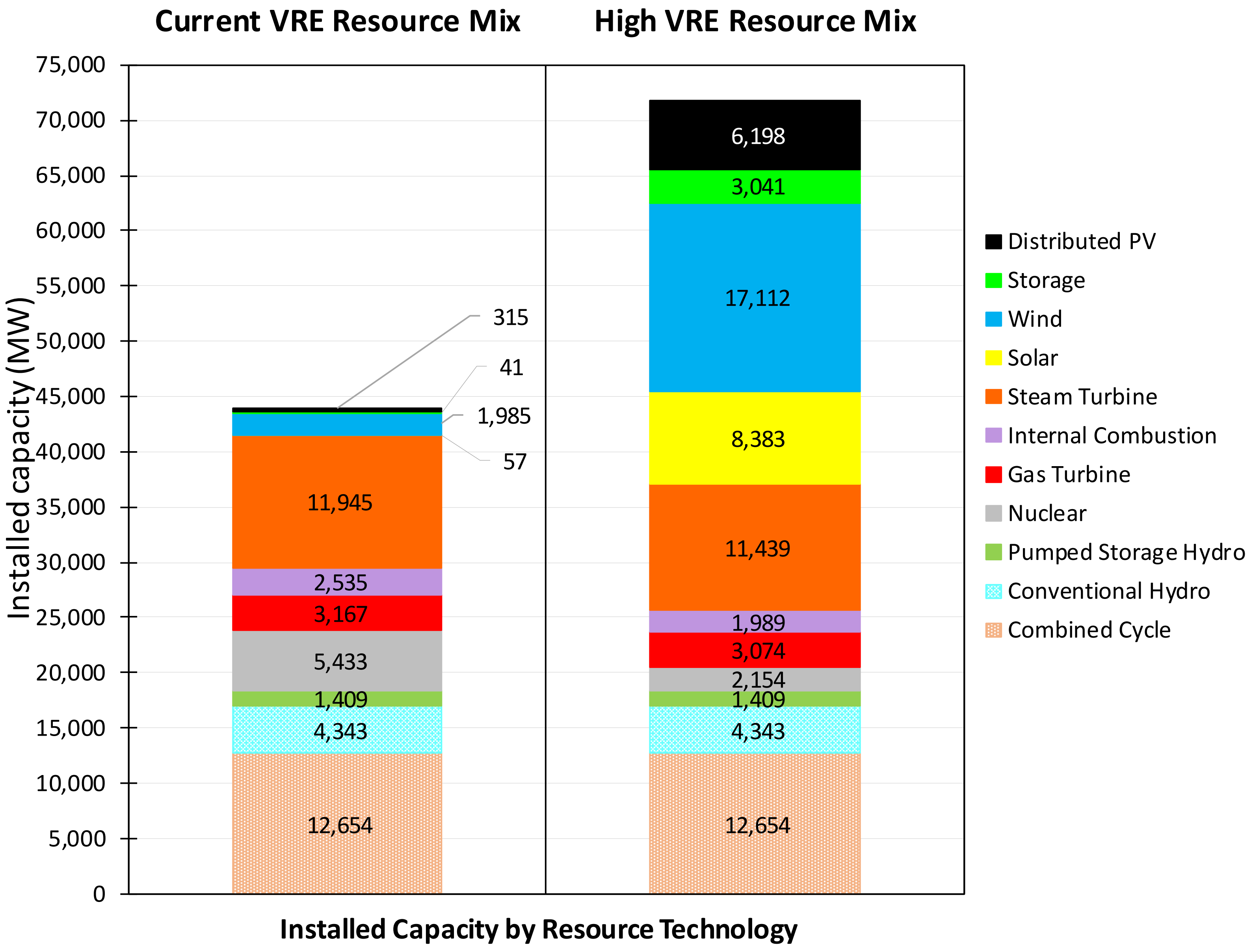
Real-time operation strategy

- In this study, real-time operation is represented by two different operation strategies of the hybrid resource's day-ahead schedule
  - In real-time, **VER forecast errors** and **SoC limits** can impact the operation of the hybrid from its 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 allows.
  - **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.
    - Updating bids in real-time, or utilizing real-time re-optimized state of charge management are out of scope for this study, with the current focus on day-ahead participation

New York Model Overview



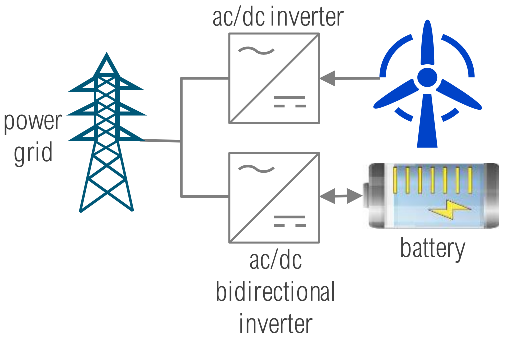
- This is **NOT** a New York study. The New York bulk power system is chosen based on availability of realistic dataset.
- Model Features:
  - Zonal model: includes key interfaces, and interchanges with neighboring regions
  - Generating unit operating characteristics, Fuel prices, Ancillary services
  - Load shapes, Wind generation profiles, Solar photovoltaic generation profiles
  - Instantaneous maximum load: April (18.44 GW) and July (30.96 GW) simulation periods

New York Model Overview

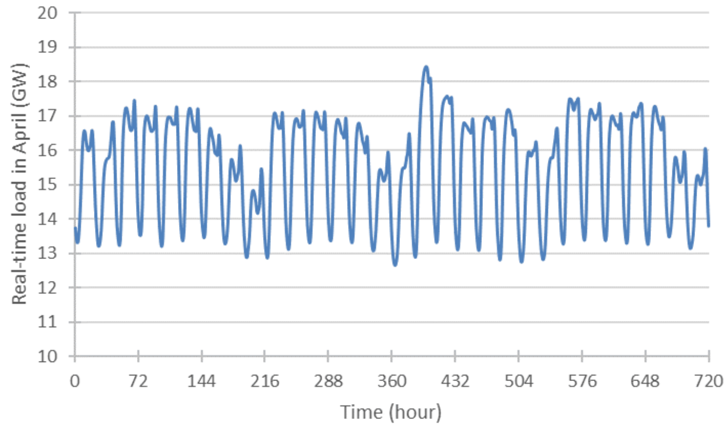
Installed Capacity (MW)	Low VRE, Low Hybrid	High VRE, High Hybrid
Standalone Storage	41	1,541
Standalone Wind	1,070	17,112
Standalone Solar	0	6,299
Hybridized Storage	473	1,500
Hybridized Wind	916	916
Hybridized Solar	57	2,084

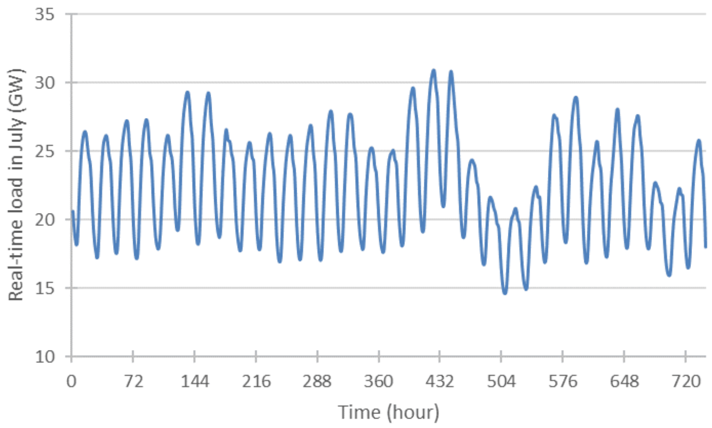
Installed Capacity (MW)	Low VRE, Low Hybrid	High VRE, High Hybrid
Hybridized Storage	473	1,500
Hybridized VRE	973	3,000

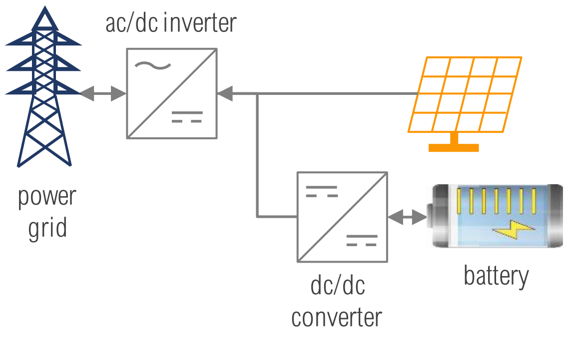
Point of Interconnection (POI) capacity is set to 100% of the variable renewable energy generator nameplate rating



ac coupled







dc coupled

Data Specs

Study Case Matrix for NY Region

Simulation Case/ Period	VRE Resource Penetration	Hybrid Resource Penetration	Participation Option	Grid Charging Option	RTM Operation Strategy
1: April, July	Low VRE	No Hybrid	N/A	N/A	N/A
2: April, July	Low VRE	Low Hybrid	2R ISO-Managed, Linked	No Grid Charging (NoGC)	Storage Follow
3: April, July	Low VRE	Low Hybrid	1R Self-Managed	No Grid Charging (NoGC)	Storage Follow
4: April, July	Low VRE	Low Hybrid	2R ISO-Managed	Unconstrained Grid Charging (UnGC)	Storage Follow
5: April, July	Low VRE	Low Hybrid	1R Self-Managed	Unconstrained Grid Charging (UnGC)	Storage Follow
6: April, July	Low VRE	Low Hybrid	2R ISO-Managed, Linked	No Grid Charging (NoGC)	Hybrid Balance
7: April, July	Low VRE	Low Hybrid	1R Self-Managed	No Grid Charging (NoGC)	Hybrid Balance
8: April, July	Low VRE	Low Hybrid	2R ISO-Managed	Unconstrained Grid Charging (UnGC)	Hybrid Balance
9: April, July	Low VRE	Low Hybrid	1R Self-Managed	Unconstrained Grid Charging (UnGC)	Hybrid Balance
11: April, July	High VRE	No Hybrid	N/A	N/A	N/A
12: April, July	High VRE	High Hybrid	2R ISO-Managed	Unconstrained Grid Charging (UnGC)	Storage Follow
13: April, July	High VRE	High Hybrid	1R Self-Managed	Unconstrained Grid Charging (UnGC)	Storage Follow
14: April, July	High VRE	High Hybrid	2R ISO-Managed	Unconstrained Grid Charging (UnGC)	Hybrid Balance
15: April, July	High VRE	High Hybrid	1R Self-Managed	Unconstrained Grid Charging (UnGC)	Hybrid Balance

Current and High VRE Mix: No new VRE are added to the hybrid cases. Existing VRE are hybridized with storage.

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)

VRE: Variable Renewable Energy

Study Results

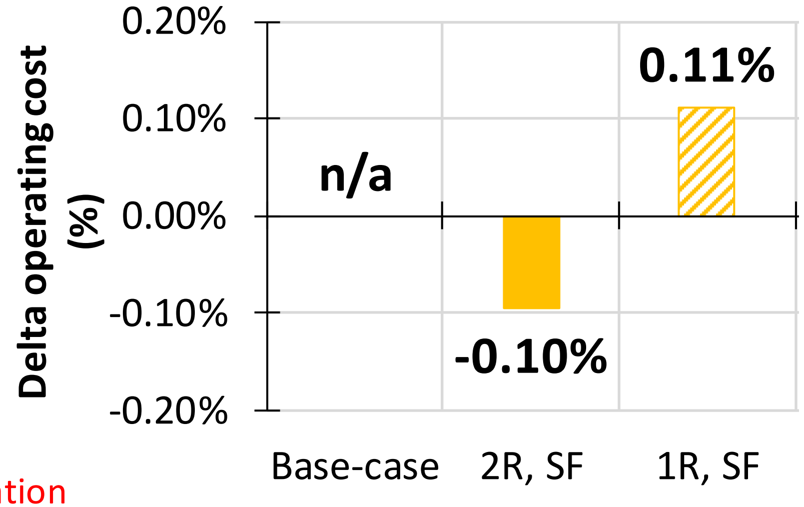
EPRI

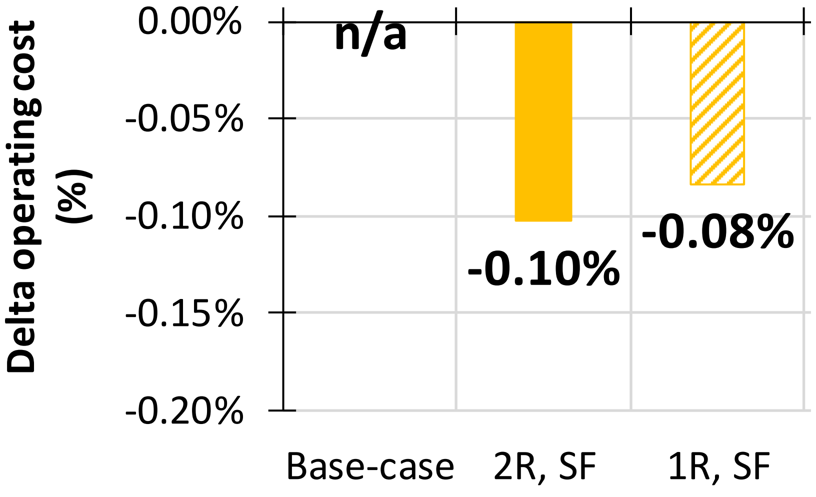
Economic efficiency implications

- 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 based on wholesale markets to buy and sell (degradation costs not considered)

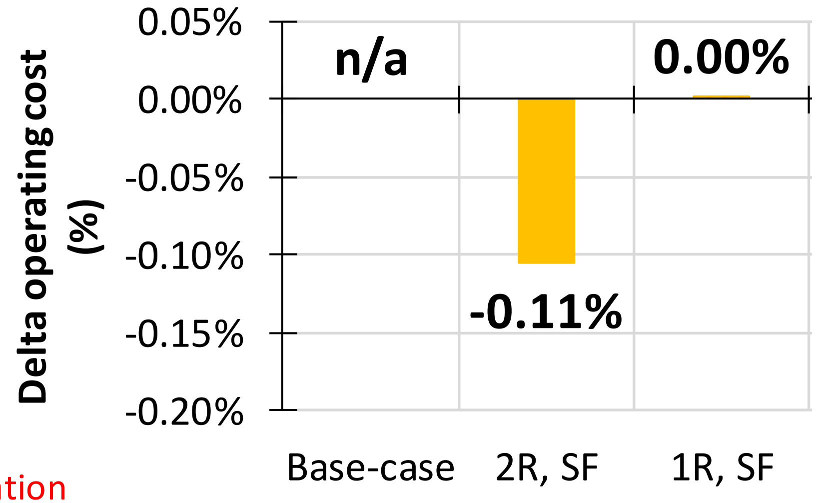
Production costs

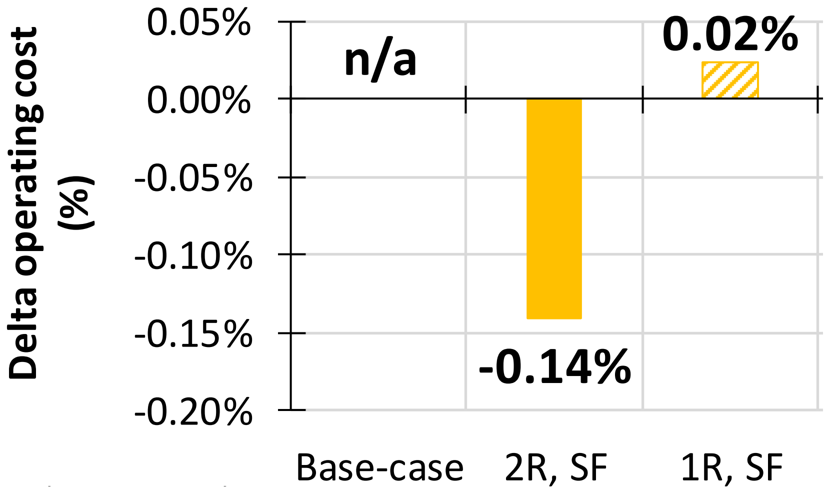
April simulation period





July simulation period





Low VRE, low hybrid penetration

High VRE, high hybrid penetration

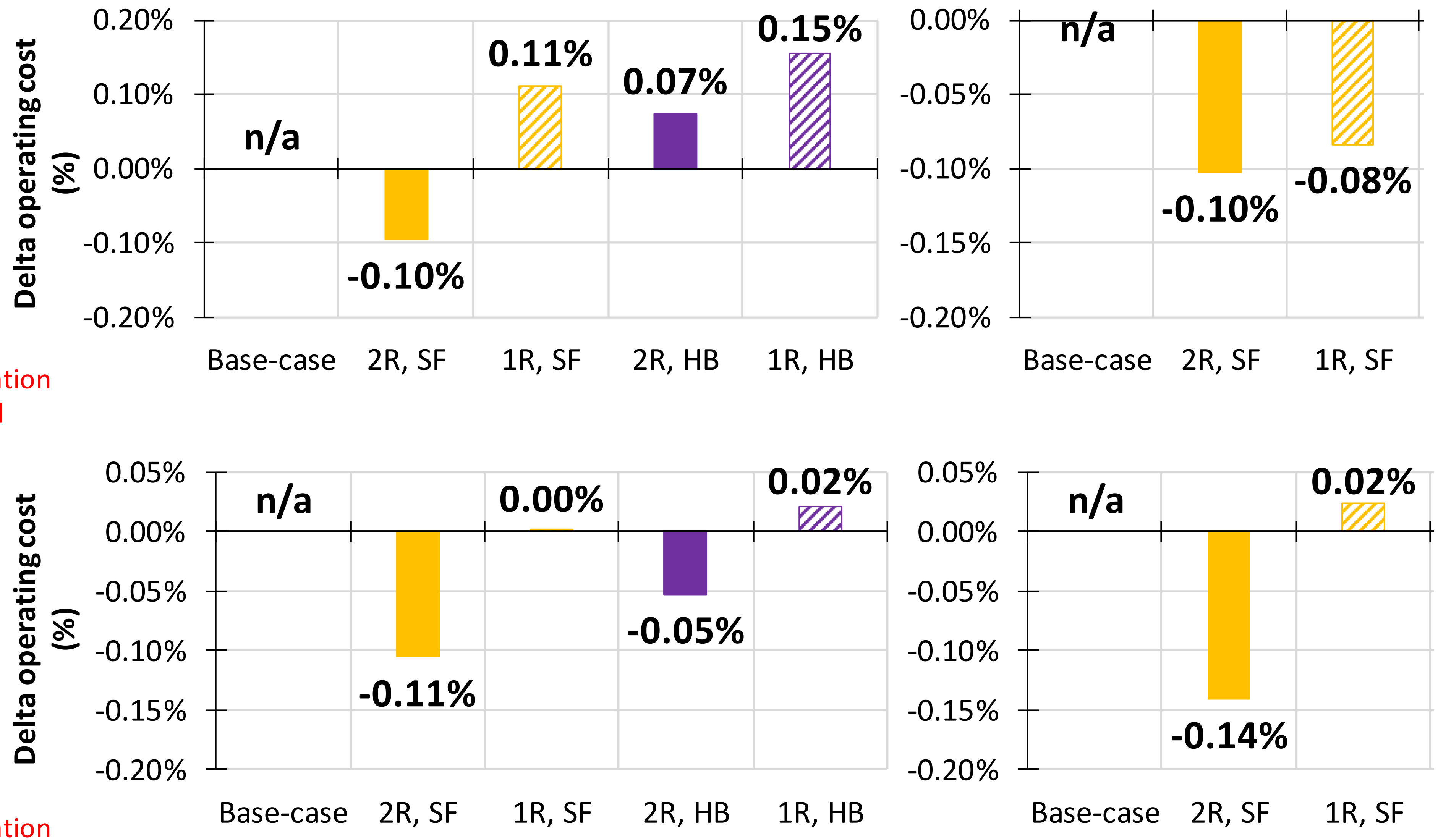
- Granular models such as the 2R option results in **savings** when compared to the base case without hybrids
- 2R option: **More efficient scheduling** of traditional resources and less reliance on expensive quick-start resources
- 1R option may even **increase** the operating costs when compared to the base case
- 1R option: Infeasible Day-ahead schedules in Real-time and **increased reliance** on more expensive quick-start resources

MIP Gap: 0.01%

Production costs

April simulation period

July simulation period



Low VRE, low hybrid penetration

High VRE, high hybrid penetration

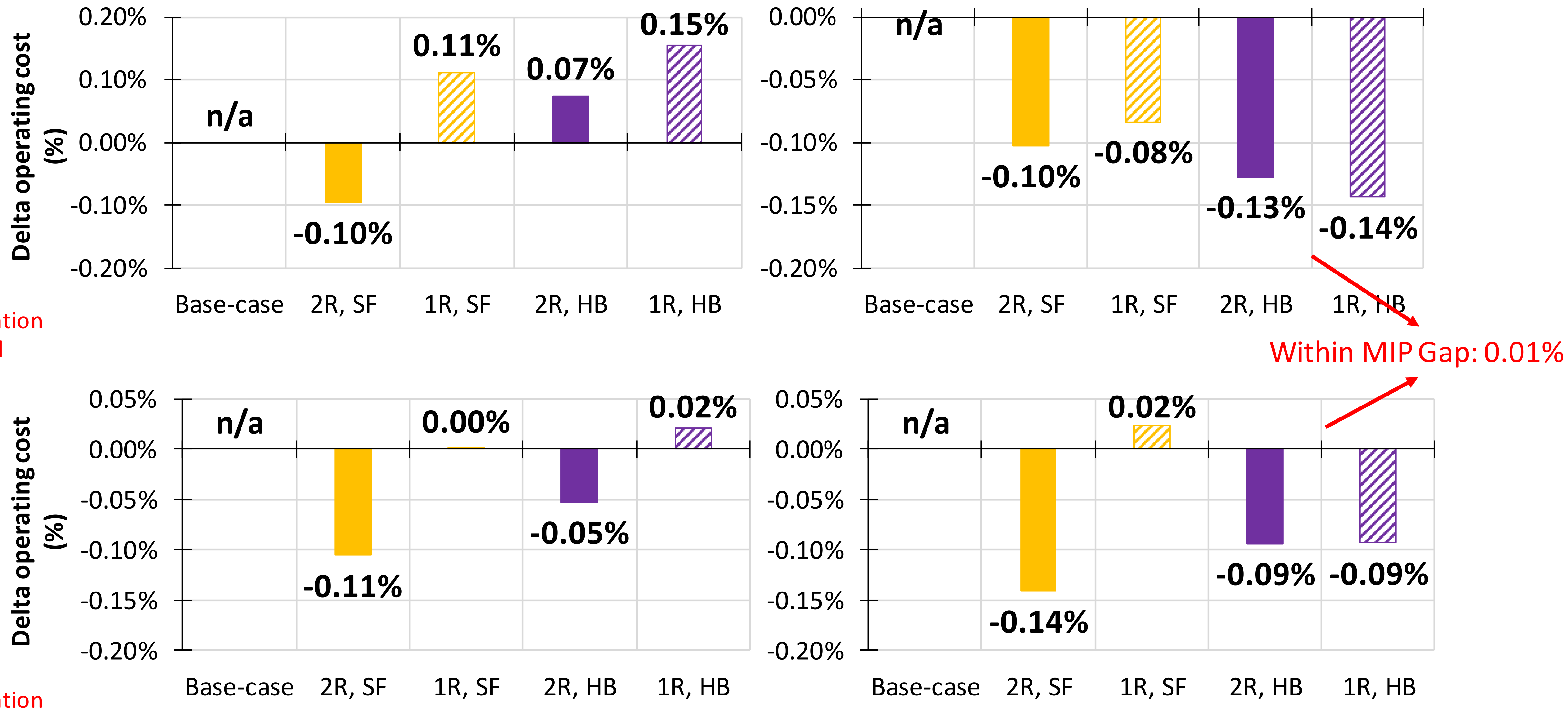
- HB real-time operation strategy exhibits a **similar trend** as SF with 2R option performing better than 1R
- Balancing hybrid schedule could **hinder** its ability to fulfill its day-ahead schedule later in the day, which could prove to be more advantageous for the system

MIP Gap: 0.01%

Production costs

April simulation period

July simulation period



Low VRE, low hybrid penetration

High VRE, high hybrid penetration

MIP Gap: 0.01%

Reliability implications

- For the test system and case scenarios analyzed in this study
  - No measurable instances of power imbalances (such as load-shedding or over-generation), or reserve shortages, or violations of the storage component's SoC constraints, or the hybrid facility's inverter constraints in the real-time market
- Sufficient quick start capability was able to cover any infeasible schedules.
- Lack of quick start resources, or insufficient reserve requirements in the future could potentially lead to reliability issues when offers lead to infeasible schedules.

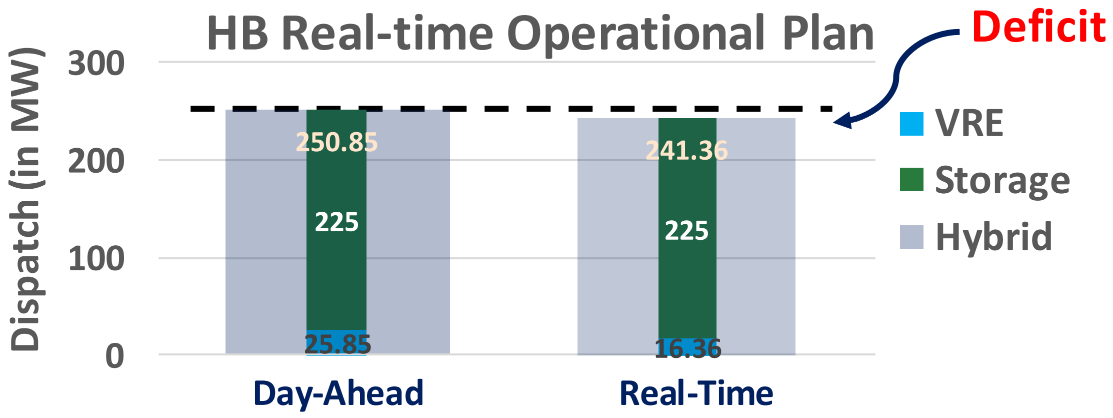
Hybrid resource capability to follow different real-time operation strategies

- Different real-time operation strategies are used to emulate possible behavior when forecasted conditions change from day-ahead.
  - **SF**: Have the storage component follow the day-ahead storage schedule, regardless of the renewable variation
  - **HB**: Follow day-ahead hybrid schedule, use storage to balance out renewable variation
- These plans are not always feasible to follow in real-time. Feasibility is observed through whether violation of the real-time operational plan occurs due to any of the following:
  - Storage has **insufficient discharge capacity** and cannot increase power output
  - Storage has **insufficient charge capacity** and cannot decrease power output
  - Storage has **insufficient SOC** and cannot increase power output
  - Storage has **maxed out SOC** capacity and cannot decrease power output
- These metrics can help anticipate how well a hybrid resource will be able to meet the needs of the system during real-time
- While violations of physical parameters of the storage component are not present, their enforcement may lead to a real-time strategy that does not follow the preferred plan.

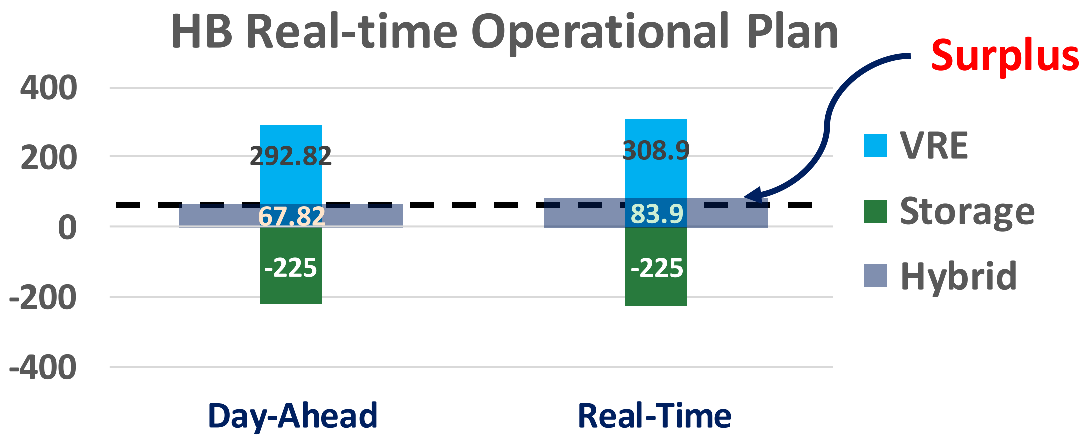
Ability to follow different real-time operation strategies

- Feasibility is observed through whether a violation of real-time operational plan occurs

- Insufficient discharge capacity



- Insufficient charge capacity

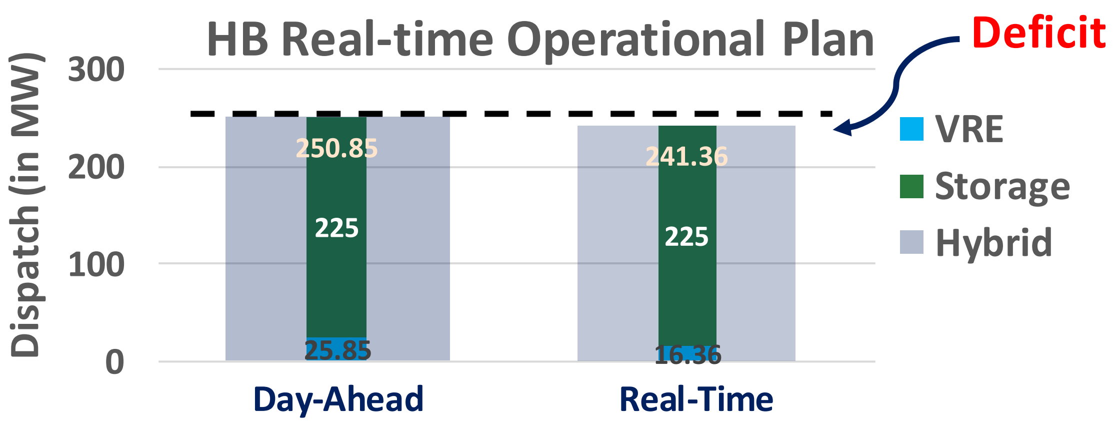


- Storage: Maximum discharge/charge capacity 225 MW, 4-hour duration

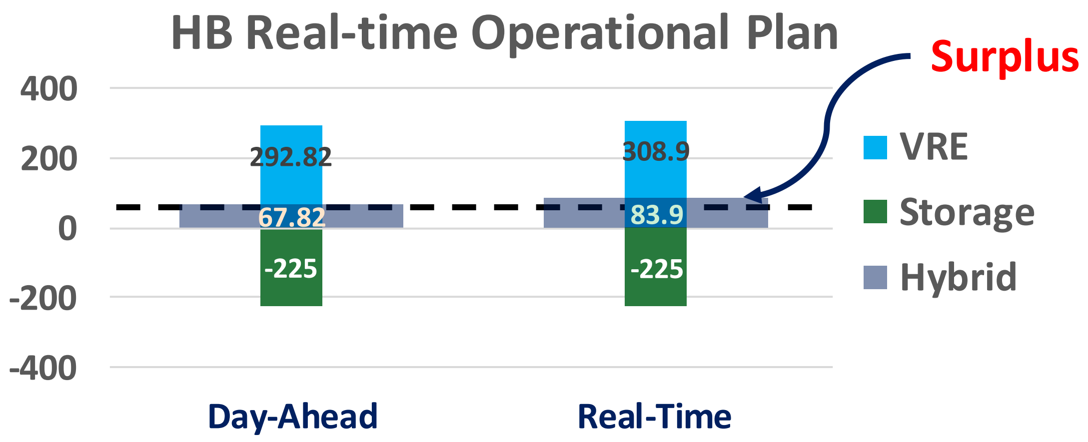
Ability to follow different real-time operation strategies

- Feasibility is observed through whether a violation of real-time operational plan occurs

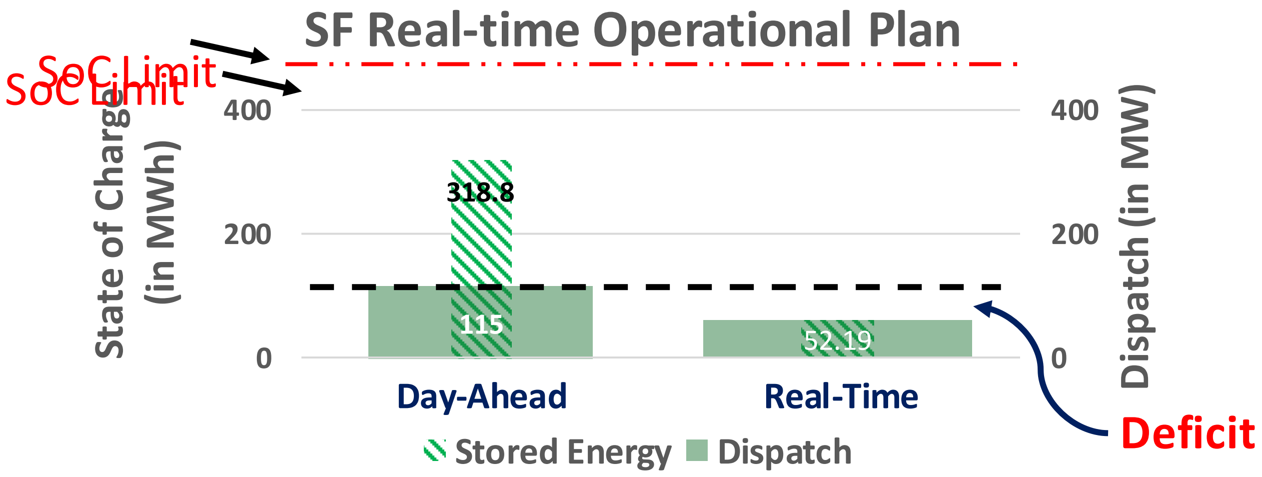
- Insufficient discharge capacity



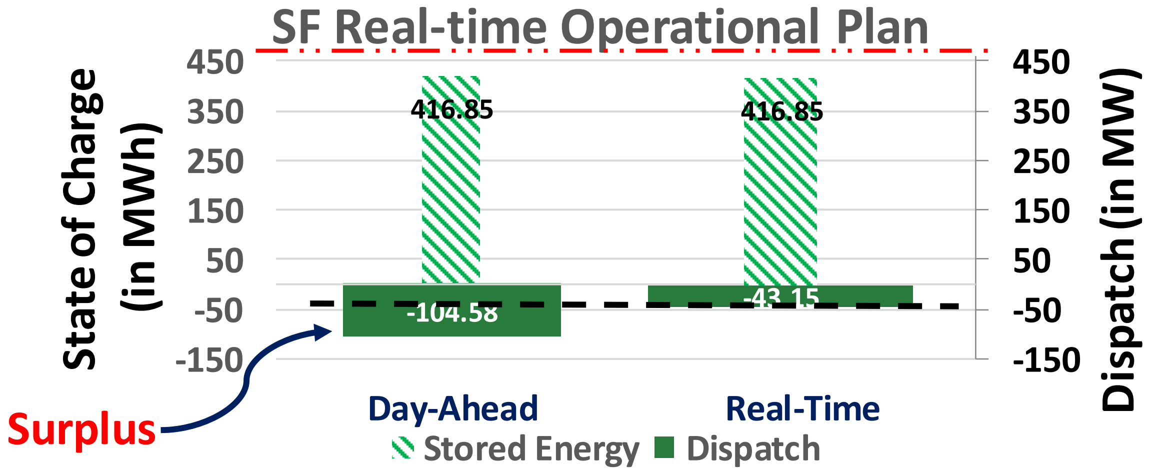
- Insufficient charge capacity



- Insufficient state of charge (SoC) or energy
- 4-Hr ESR component, Maximum capacity 900 MWh

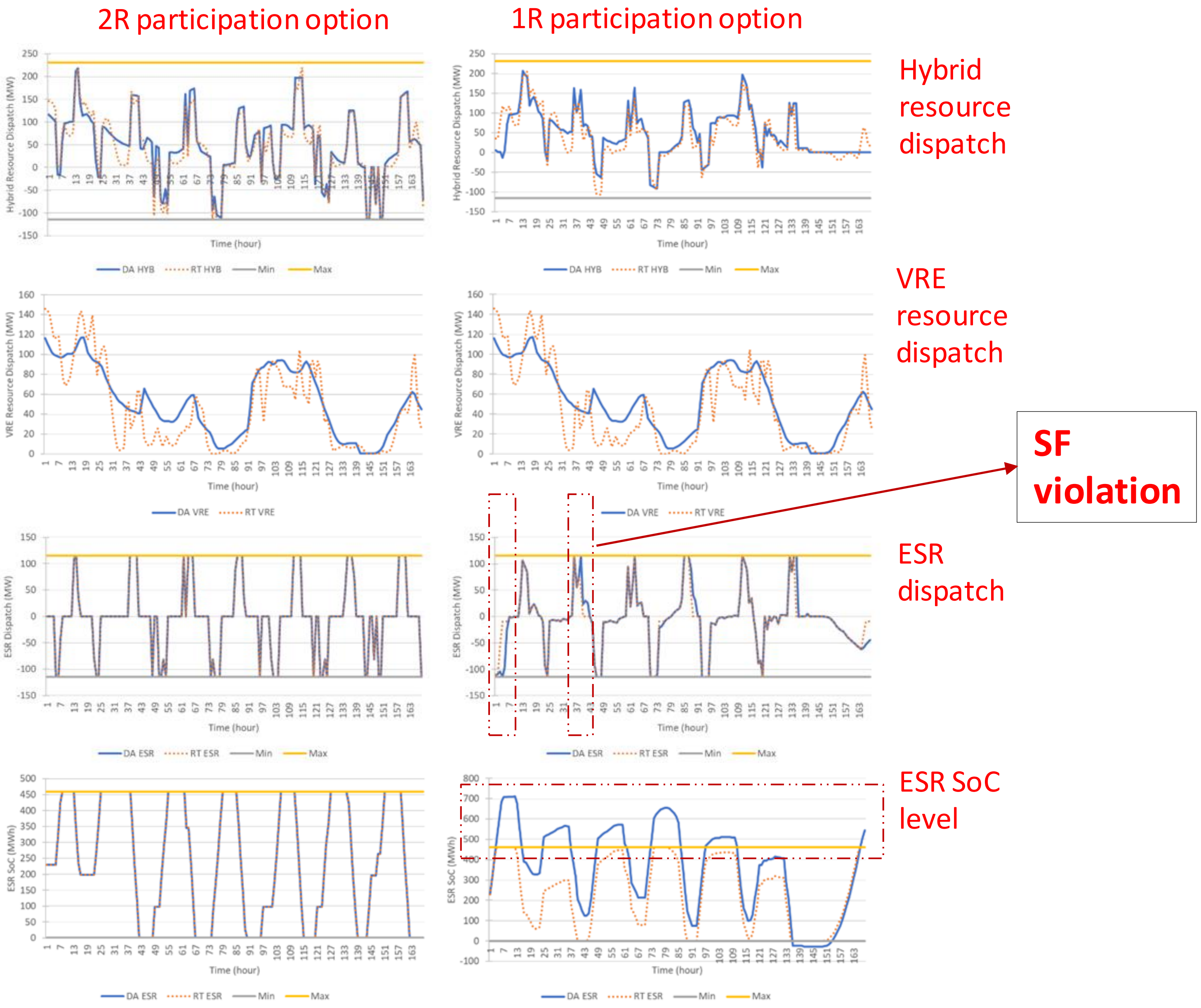


- Maximum state of charge (SoC) or energy



- Storage: Maximum discharge/charge capacity 115 MW, 4-hour duration

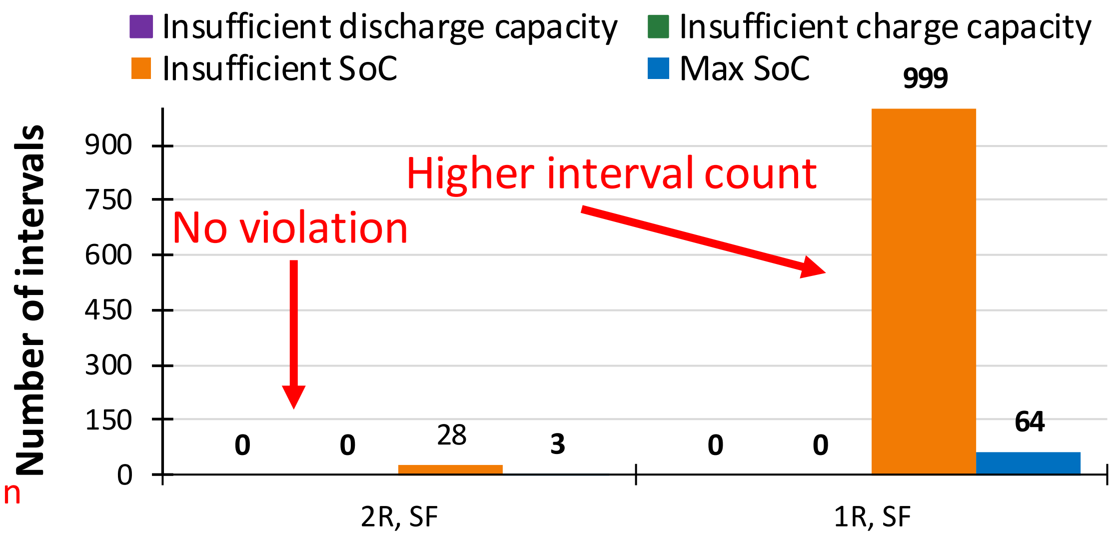
Ability to adhere to SF real-time operation strategy



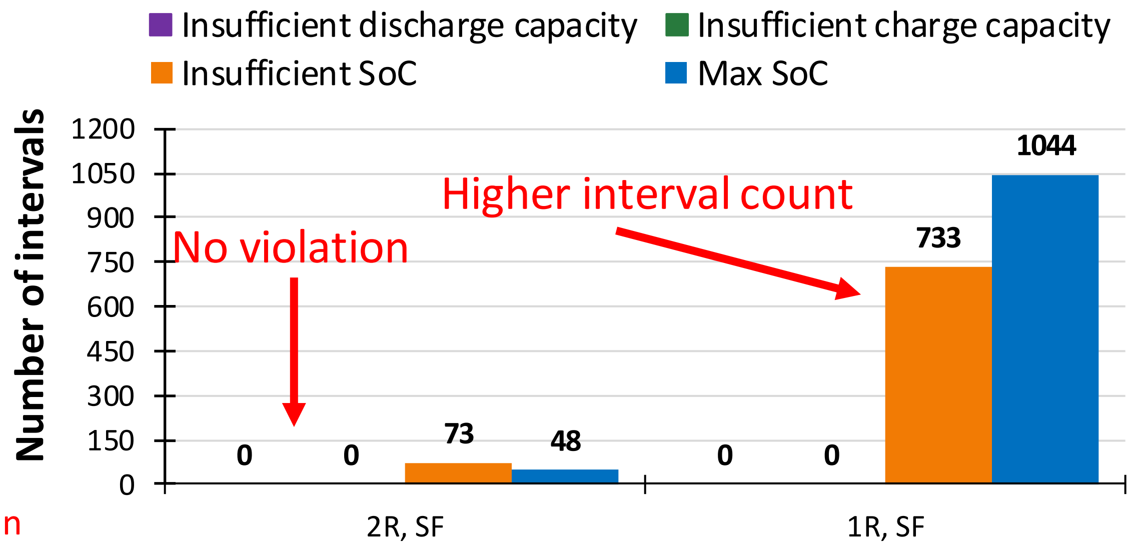
- Figure demonstrates the hybrid resource dispatch, VRE resource dispatch, ESR dispatch, and ESR SoC level for a wind hybrid facility in the low VRE, July simulation period (one sample week), for the unconstrained grid charging option under the SF real-time operation plan

Ability to follow different real-time operation strategies

April simulation period



July simulation period

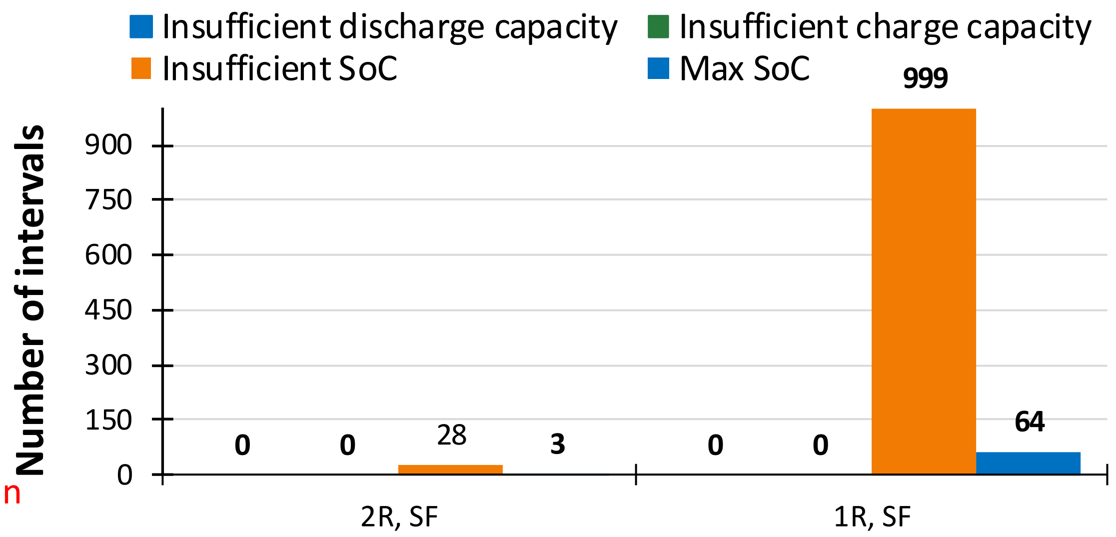


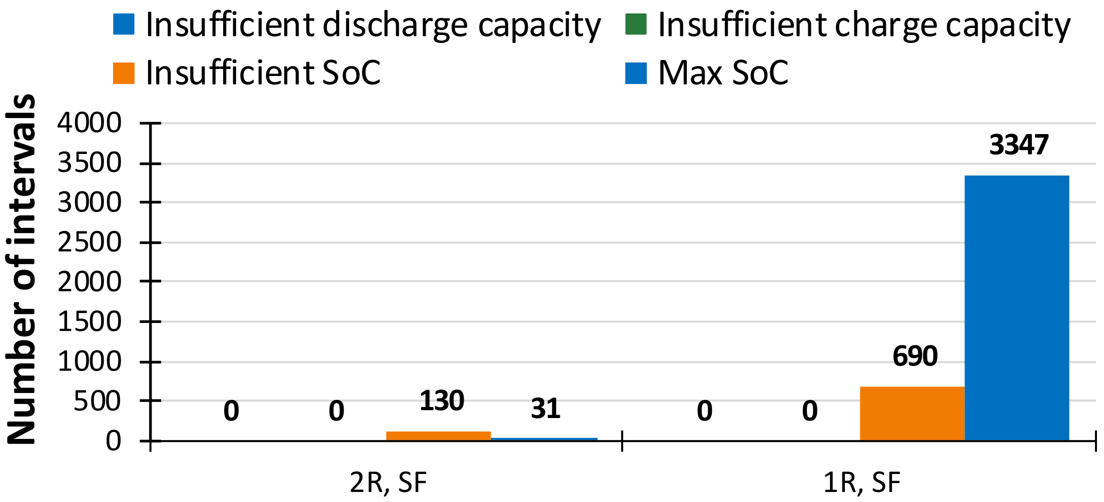
Low VRE, low hybrid penetration

- Zero insufficient discharge or charge capacity intervals for both 1R and 2R participation options
- Insufficient SoC or max SoC intervals may still exist
- 2R option better than 1R option due to the explicit consideration of SoC in the Day-Ahead stage
- Impacts from temporal coupling of the stored energy - Deviations in one real-time interval may impacts its ability to adhere to the SF real-time operational strategy in subsequent intervals

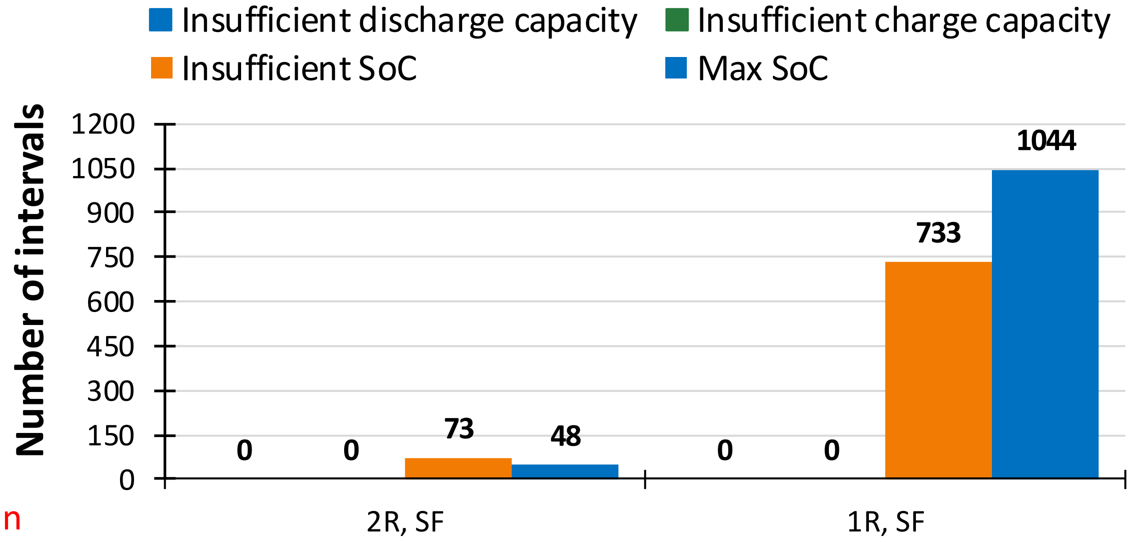
Ability to follow different real-time operation strategies

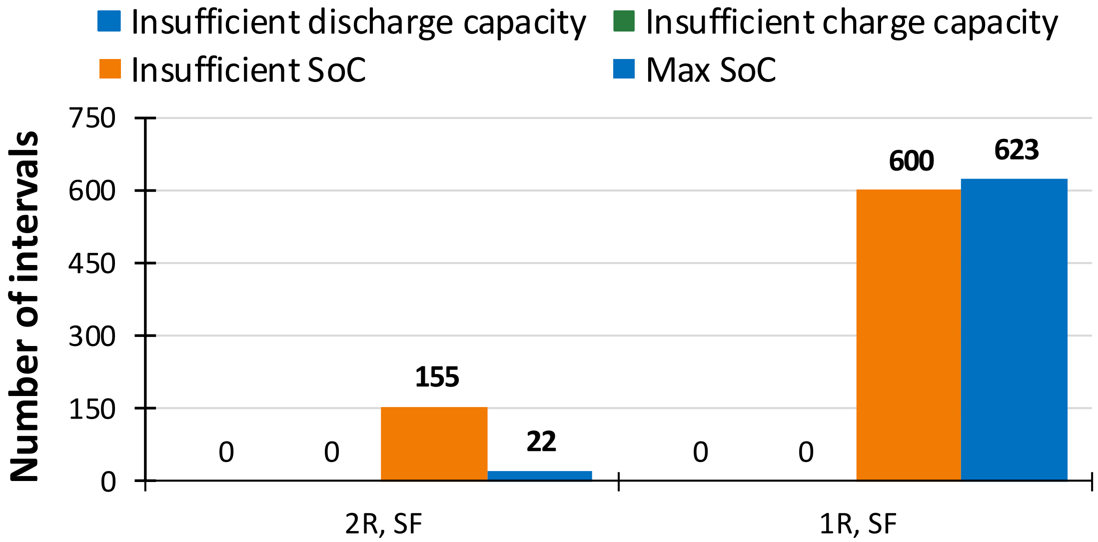
April simulation period





July simulation period





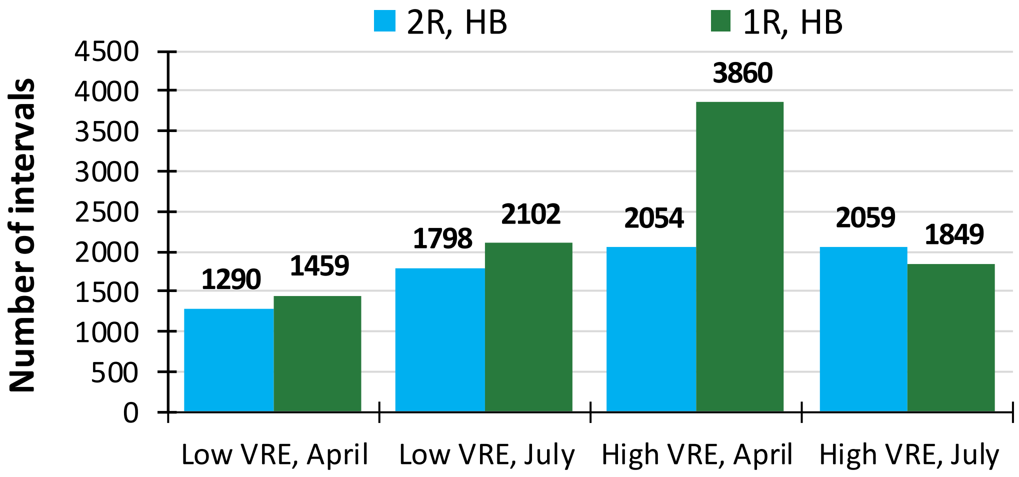
Low VRE, low hybrid penetration

High VRE, high hybrid penetration

Ability to follow different real-time operation strategies

- **For HB real-time operational plan** (adhere to hybrid facility day-ahead dispatch)
  - Insufficient Charge capacity and Max SoC intervals may **coincide**
  - Insufficient Discharge capacity and Insufficient SoC intervals may **coincide**
    - Deviation in storage component violates both physical constraint, e.g.,
      - Day-ahead dispatch: 250.85 MW (25.85 MW VRE + 225 MW ESR)
      - Real-time: 16.36 MW VRE meant 234.49 MW ESR (**limitation**: max limit 225 MW)
        < 225 MWh SoC meant insufficient energy level (**limitation**: min SoC level 0 MWh)

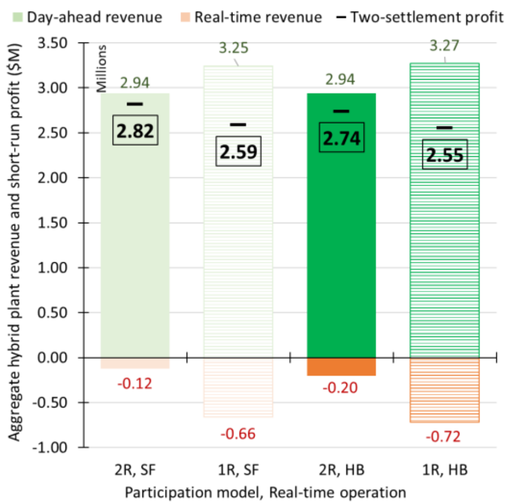
- Avoid such instances of double counting - Only included in the count of insufficient or max SoC intervals
- Analysis at an aggregate level instead of individual metrics
- 2R option results in fewer occurrences of instances limited by insufficient charge, discharge, or SoC capacity, or maximum SoC than the 1R option

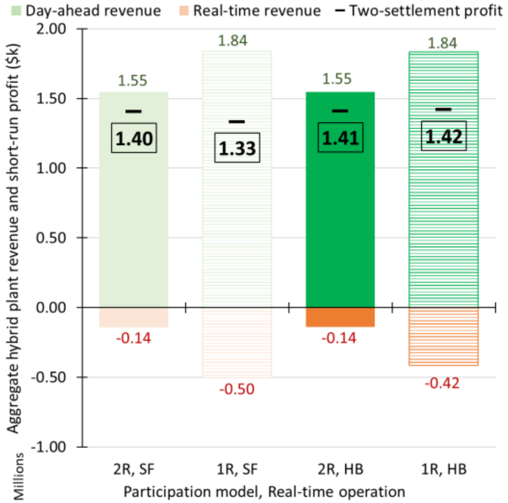


Profits and incentives

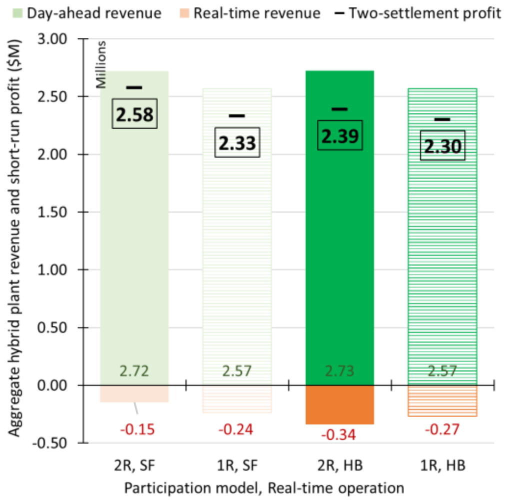
- Day-ahead revenue takes the sum of the product of the day-ahead schedules and the day-ahead LMPs for each hour of the simulation.
- Real-time revenue only takes the sum of the product of the deviation of real-time schedules from the day-ahead schedules and the real-time LMPs for each one-hour real-time period of the simulation. It essentially ignores the day-ahead schedules.
- Two-settlement profit day-ahead revenue and then adds (subtracts) the product of positive (negative) deviation from the day-ahead schedules based on real-time schedule and the real-time LMP.

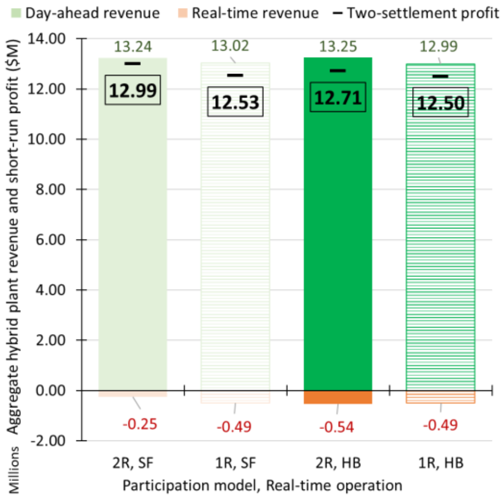
Aggregate hybrid resource revenue and short-run profit





April simulation period





July simulation period

Low VRE, low hybrid penetration

High VRE, high hybrid penetration

- 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.
- Granular models such as the 2R options provide greater short-run profits.
  - **Low-load April period**: Primarily due to less buy back purchases in the real-time market when compared to the 1R option (which has an increased likelihood for not being able to provide what was cleared in the day-ahead market in real-time due to the aggressive hybrid resource bidding strategies and the absence of explicit SoC consideration in the market clearing software when determining the cleared day-ahead hybrid resource schedules to begin with), or
  - **Peak-load July period**: This is due to greater revenues from the day-ahead market when compared to the 1R option due to the economics of the developed bidding strategies based on the simulation period under consideration.

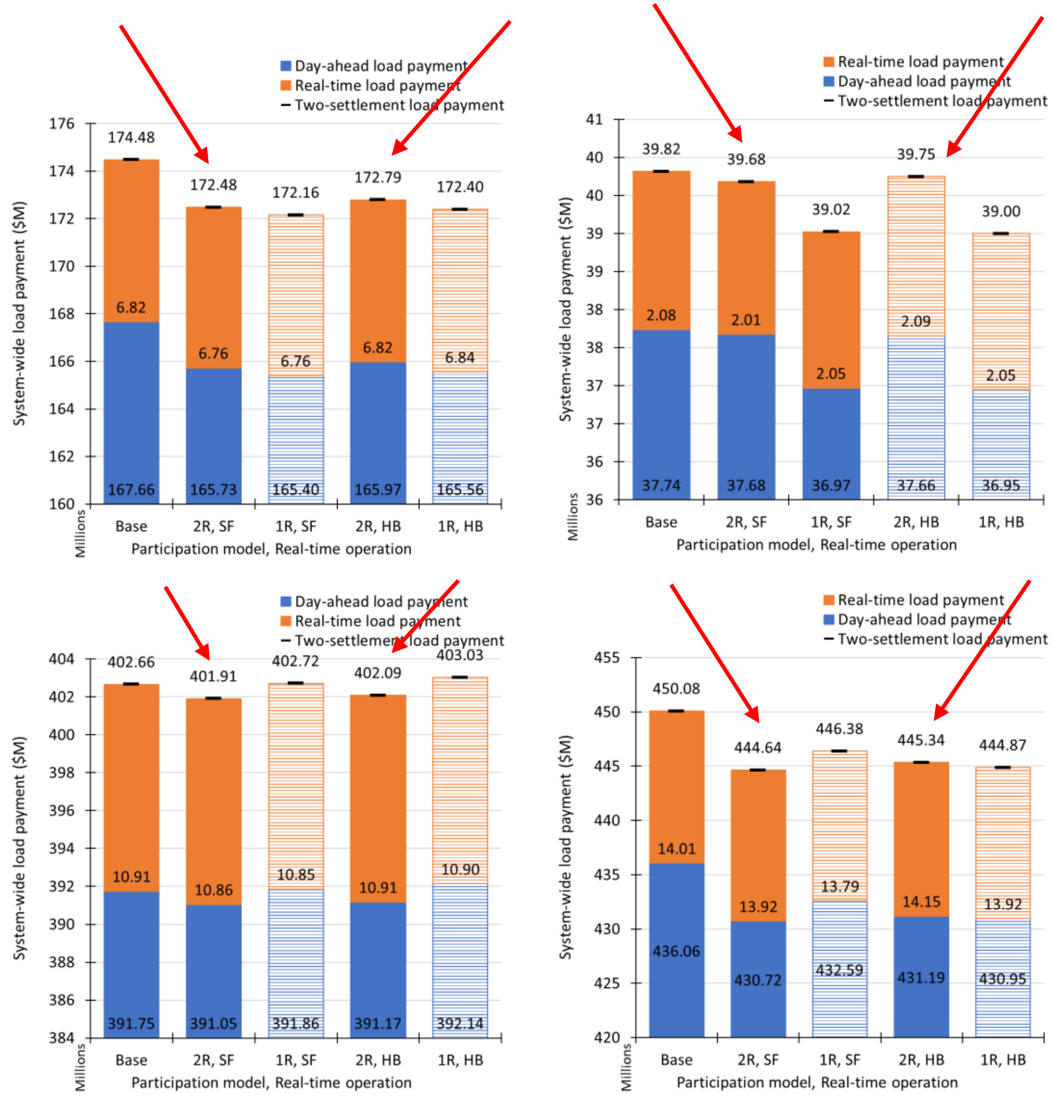
***Results do not reflect ITC benefits.

EPRI

Load payments

- Two-settlement load payment is calculated as the sum of the DA and RT load payments.
  - **DA load payment**: Calculated as the product of the DA load quantity (in MW) per hour and the DA LMP in its zone.
  - **RT load payment**: Calculated as the product of the RT load deviation from the DA load schedules (in MW) per hour and the RT LMP in its zone.
- In this study, DA load quantity per hour, and RT deviations from the DA load schedules per hour are each consistently the same across all the case scenarios.
  - The only difference among these cases is the DA and RT NYISO FP load price that is impacted by the choice of the participation option.

NYISO footprint load payments



April simulation period

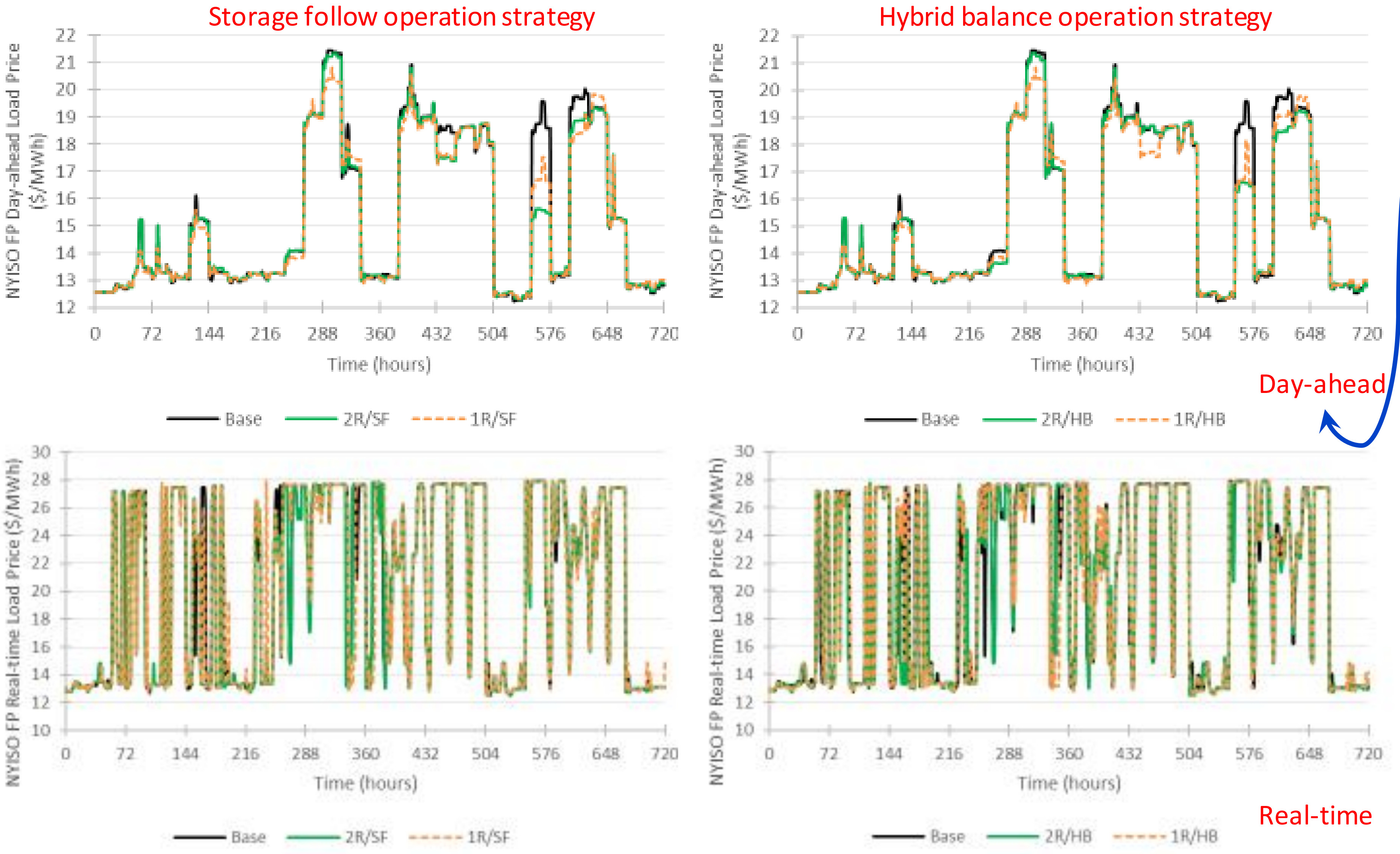
July simulation period

Low VRE, low hybrid penetration

High VRE, high hybrid penetration

- **DA load payment**: Significant impact on the two-settlement load payments (DA system load is much larger than RT deviations from DA load). Small differences in DA load prices between case scenarios can bring about large differences between the DA load payments.
- **Low-load April period**: Two-settlement load payment is consistently greater for the 2R option than the 1R option under both SF and HB RT operation strategies for both low and high VRE penetration levels.
  - Cleared DA hybrid schedules are generally higher for the 1R cases with the developed bidding strategies, which results in flatter DA load prices for the 1R cases due to the energy shifting nature of the ESR component. Thus, the DA load payments are consistently lower for the 1R cases, which reduces the two-settlement load payments significantly.
  - The opposite is true for the RT hybrid resource schedules and impact on load prices for the 1R cases since the hybrid facilities must buy back much of the energy that they cannot provide in RT due to SoC restrictions or otherwise.

NYISO footprint load prices

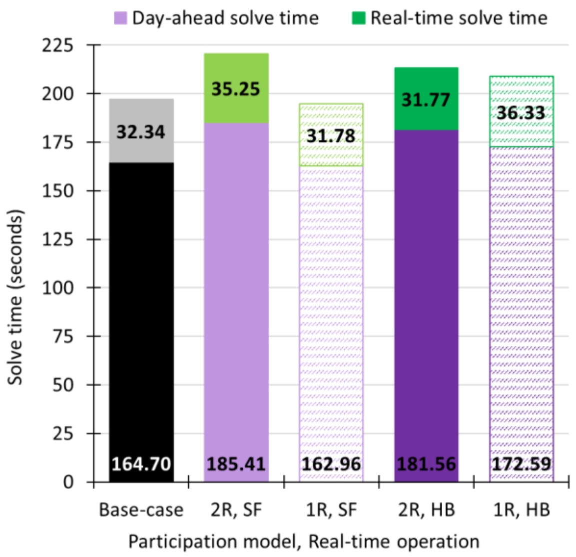


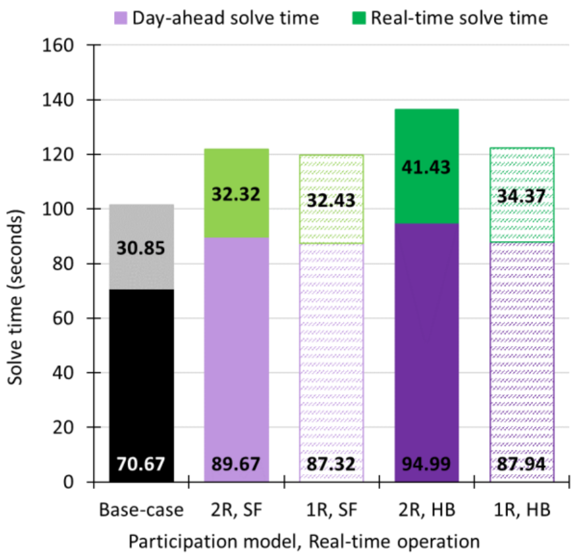
NYISO footprint load price ($/MWh) for the low VRE, April simulation period, for the unconstrained grid charging option, under SF (left) and HB real-time operation strategy (right), for day-ahead (top) and real-time (bottom).

Small differences in DA load prices between case scenarios can bring about large differences between the DA load payments, which then impacts the two-settlement load payments more significantly than real-time load payments.

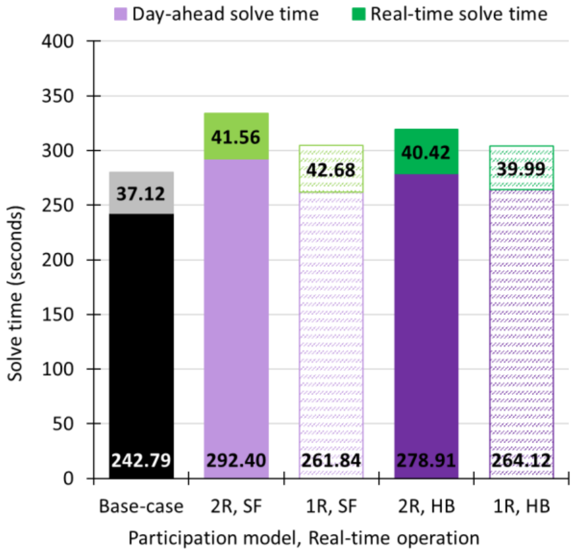
Implications on the load payments are decidedly dependent on the cleared energy awards for the hybrid facilities that can differ based on the submitted bidding strategies or the explicit SoC consideration under the alternate participation options, since the cleared awards then impact the LMPs and the calculated load payments.

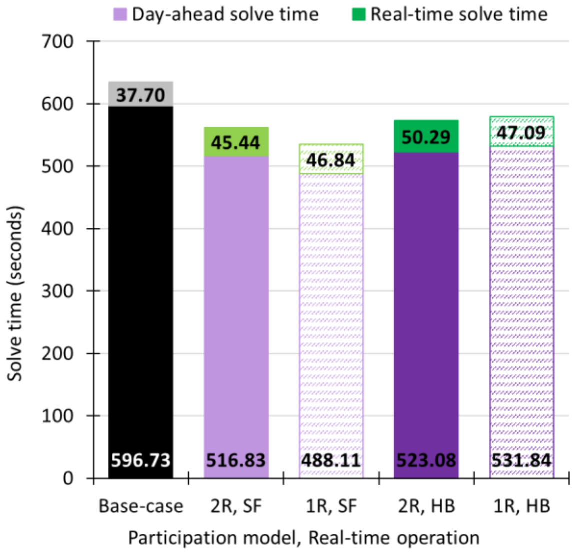
Computational efficiency





April simulation period





July simulation period

Low VRE, low hybrid penetration

High VRE, high hybrid penetration

- Granular models such as the 2R option tend to provide theoretical efficiency gains, but they also add computational complexity to the market clearing software, observed through greater DA solve times compared to the 1R model.
  - Explicit modeling of the hour-to-hour chronology for the storage component of the hybrid facility
  - *Exception*: Stressed system conditions, e.g., peak load conditions observed [illegible]

interaction with other constraints such as unit commitment and inter-temporal ramp-rate constraints can potentially impact the feasibility space and consecutively the solve times unpredictably (see counterintuitive base case solve time)
- DA solve times for cases where no grid charging was allowed are mostly greater than cases where grid charging was allowed for both 2R and 1R options.
- Since the RTM is structured in the same manner across the different participation options to conduct a fair comparison, the total solve times for the RT stage are comparable as presumed.
- Although the 2R model may be potentially advantageous for both the asset owner and the ISO/RTO, they may be too computationally intensive to enable, especially when larger amounts of these emerging resources integrate into the grid without improvements to the software or hardware to support.

Modeling difficulties

- These models are difficult to represent due to the “human in the loop” that changes offer behavior and advanced offering strategies that were not explored.
  - While the offer strategies were generally considered state-of-the-art, they cannot match a set of educated staff changing behavior or altering strategies computed by software.
  - In this case, some of the 1R cases may be considered somewhat conservative and can perform better in practice.
  - Some empirical evidence with greater participation of both options in practice can help substantiate these results as these resources begin to play a larger role in markets.

Key takeaways

Economic efficiency

- The 2R model generally provide greater cost savings
- Not found to be significant in these case studies

System Reliability

- No measurable impacts in any of these cases
- Sufficient quick-start capability to manage infeasible SoC or VER forecast error

Asset Incentives

- The 2R model provides greater short-run profits

Capability to follow directions

- Observed greater occurrences of inability to follow day-ahead schedule for 1R

Key takeaways

Load payments

- Dependent on cleared energy awards for the hybrid facilities that can differ considerably based on the submitted bid strategies or the explicit SoC consideration

Computational efficiency

- Using the 2R model with increasing numbers of hybrids add greater computational complexity and solve time

Modeling difficulties

- Difficult to represent the "human in the loop" and advanced strategies. Both models may show better performance with human trader

Recommendations for next steps

Evaluating additional scenarios

Participation in real-time markets

Enhanced participation models (including degradation)

Hybrid participation in ancillary services

Capacity contribution of different participation models

Advanced computational techniques

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