QUICK GUIDE: AT-SCALE ISO STATE-OF-CHARGE MANAGEMENT OF STORAGE RESOURCES USING SIMPLIFYING WRAPPER ENERGY CONSTRAINTS

Unlocking massive storage integration by exploring alternative modeling solutions for ISO state-of-charge management without adverse economic efficiency, reliability, and computational impacts.

RESEARCH QUESTIONS

Can wrapper energy constraints be used to implicitly model the state-of-charge (SoC) of electric storage resources (ESRs)? What are the implications of replacing the explicit modeling of hour-to-hour chronology of SoC with the implicit modeling of chronology through fewer wrapper constraints for storage? How broadly can this implicit modeling approach be applied?

KEY POINTS

- Complete decarbonization of the electric sector necessitates a swift adoption of diverse emerging technologies, including new forms of renewable resources, dispatchable emissions-free resources, demand response, and energy storage, among others.
- FERC Order No. 841 required each ISO/RTO to provide ESRs with the option to self-manage their SoC (Self-SOCM) instead of mandating ISO SoC management (ISO-SOCM).
- Prior research has shown that ISO-SOCM offers several benefits over Self-SOCM in terms of economic efficiency, reliability, SoC feasibility guarantees, and profits. However, at higher levels of ESR market participation, the computational complexity of ISO-SOCM may become unmanageable due to the time-coupled and hard SoC constraints in the market optimization problem.
- Wrapper energy constraints that implicitly model the amount of energy exchanged by an ESR over a time window, akin to energy constraints that are contemporarily used to model fuel limitations for conventional generating resources, provide an alternate modeling solution for ISO-SOCM instead of the explicit hour-to-hour SoC constraints.
- The Wrapper Energy Constraint Formulation is straightforward and adaptable, allowing it to effectively tackle the computational tractability challenges while maintaining the numerous advantages of ISO-SOCM. Notably, it can prove to be considerably valuable for both operational and long-term planning problems.

ELECTRIC STORAGE RESOURCE PARTICIPATION IN WHOLESALE ELECTRICITY MARKETS AND EVALUATION OF STATE OF CHARGE MANAGEMENT OPTIONS

Energy storage is an emerging technology that is used for a range of electricity market, grid operator and customer-focused applications, e.g., provision of bulk power system services such as ancillary services, capacity and energy, asset investment deferral, and supply backup. It has witnessed substantial growth over the past few years due to a significant decrease in its cost, and since it is a key enabler for renewable energy technologies such as wind and solar photovoltaic, acting as a buffer against the variable and intermittent characteristics of these technologies. Particularly, its increasingly vital role in the United States electricity grid has been underlined through various regulatory rulings, policy drivers, economic incentives (e.g., rebates or subsidies such as the storage investment tax credits), and state procurement targets for energy storage deployment. This includes the Federal Energy Regulatory Commission (FERC) Order No. 841 that enabled ESR participation in Regional Transmission Organization (RTO) and Independent System Operator (ISO) markets. The installed ESR capacity in the United States grid is expected to increase drastically to about 30 GW by 2025[1], which will invariably lead to greater ESR penetration in the wholesale electricity markets.

As ESR market participation increases, it is imperative that their SoC be managed adequately to avoid potential economic and reliability consequences. SOCM is important from the perspective of both the ESR owner and the system operator. For ESR, it enables them to closely follow their dispatch schedules and avoid non-performance penalties. Furthermore, it helps them satisfy different operational constraints that they may be subject to, particularly when they are multi-use resources. For the system operator, appropriate SOCM leads to increased certainty in scheduling operations and potentially better resource utilization, which in turn lowers the system operating costs and enhances the system reliability.

The guidelines for SOCM of ESR were provided in FERC Order No. 841. Based on these guidelines, the SOCM options can be broadly categorized as either *Self* or *ISO* managed. Under the Self-SOCM option, an ESR is treated as any other traditional generating resource and needs to provide an offer curve to get cleared in the market. Importantly, any constraints corresponding to the resource's SOCM need to be determined and incorporated implicitly into the offer by the ESR itself. Consequently, the ESR owner is responsible to ensure feasibility and optimality of SoC, and the ISO schedules the ESR without SoC consideration. On the other hand, the ISO-SOCM option requires information about the resource's physical and operating constraints and the target SoC that the ESR desires to reach by the end of the horizon. The ISO incorporates these constraints into its market optimization problem to ensure SoC feasibility and optimizes the ESR schedules across time to minimize cost. An ESR may or may not provide an offer curve under the ISO-SOCM option.

Prior research has evaluated the implications of the Self- and ISO-SOCM options and found the ISO-SOCM to have several system and resource-level benefits with regards to economic efficiency, reliability, SoC feasibility guarantees, and resource profits and incentives[2]. An additional benefit is that ISO-SOCM allows participants to bid the physical capabilities of ESR with limited need for bid costs (other than to reflect degradation costs from cycling). This allows the resource owner and balancing authorities to better utilize the capabilities of storage and can also eliminate market-power concerns associated with the Self-SOCM option. However, the ISO-SOCM option may become computationally intractable at higher penetration levels of ESR market participation, primarily due to a greater number of inherently complex *time-coupled* and *hard* SOC constraints in the market optimization problem. The primary goal of this work is to introduce and investigate an alternate (wrapper energy constraint) approach to modeling the ISO-SOCM option in the

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[1] U.S. Energy Information Administration, U.S. battery storage capacity will increase significantly by 2025, December 2022. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=54939.

[2] *Integrating Electric Storage Resources into Electricity Market Operations: Evaluation of State of Charge Management Options.* EPRI, Palo Alto, CA: 2019. 3002013868.

Evaluating Challenges of Stand-alone Electric Storage Resources and Integration into Electricity Market Clearing: Implications of Software Design on SOC Management. EPRI, Palo Alto, CA: 2020. 3002018649.

day-ahead market that may potentially alleviate the computational tractability issues while still maintaining the SoC feasibility guarantee, and economic efficiency and reliability benefits.

Results here are based on a NYISO test system, with ESR providing energy arbitrage in the day-ahead market and with the underlying assumption that ESR do not provide offer curves that are otherwise needed by the traditional and suggested alternate ISO-SOCM options. This evaluation is focused on the impacts to the day-ahead markets and does not include the less computationally difficult challenge of SOC management in real-time markets. Also, procurement of reserves from storage is not addressed but can be included in all suggested SOC approaches.

MATHEMATICAL DEPICTION OF THE ISO-SOCM OPTION: UNVEILING THE EXPLICIT SOC CONSTRAINT- AND IMPLICIT WRAPPER ENERGY CONSTRAINT-BASED OPTIMIZATION FORMULATIONS

The traditional approach for modeling the ISO-SOCM option is to incorporate an explicit representation of the SoC constraints to monitor the hour-to-hour energy changes that occur due to ESR dispatch. SoC at the end of a given hour is the sum of SoC at the end of the preceding hour and the amount of energy that is charged or discharged over the given hour, taking into account losses due to roundtrip efficiency. Furthermore, SoC feasibility is ensured by explicitly including constraints that bound the SoC level of an ESR to be above its minimum SoC limit and below its maximum SoC limit.

Applying these constraints allows ISO-SOCM to optimize the amount of energy to charge or discharge over each hour of the day. Moreover, at the end of each day-ahead horizon (i.e., hour ending 24 in this case), a target SoC is enforced to ensure that a specified amount of energy capacity is retained by the ESR for the next optimization horizon to prevent myopic ESR behavior that may unduly prioritize current decisions over future impacts. Absent this feature, the myopic decisions will empty out the ESR without leaving stored energy for future days.

Figure 1 visually depicts the traditional SoC constraints, referred to here as the 'SoC Constraint Formulation'. This explicit chronology approach leads to numerous *time-coupled* and *hard* SoC constraints. In some circumstances, market optimization problems that include these constraints may not be computationally tractable, especially if the market has a high penetration of ESRs.

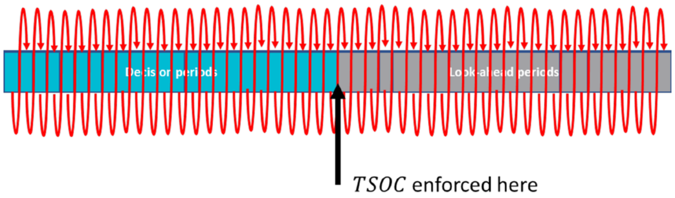


Figure 1: *SoC Constraint Formulation links the ESR SoC from one hour to another and enforces a Target SoC (TSOC) at the end of the decision period [Source: Polaris Systems Optimization].*

An alternative approach is to use "wrapper" constraints that apply to energy exchanged over time windows (e.g., over 12 hours or 24 hours). The key idea is that if the amount of energy exchanged and duration of time window are determined "intelligently," then the SoC of an ESR can remain within limits. Importantly, this approach allows the direct linking (or "*wrapping*") of hourly energy charging and discharging decisions through constraints (Figure 2). Thus, each dispatch decision and the impact of target SoC are directly linked through a small number of constraints (instead of hour-by-hour across). SoC feasibility is ensured (as well as storage efficiency and endurance) by constraints that specify the total energy charged and discharged over each time window. Figure 2 visually depicts the alternative approach, referred to here as the 'Wrapper Energy Constraint Formulation'.

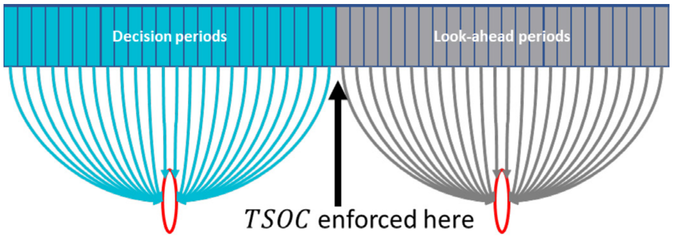


Figure 2: *Wrapper Energy Constraint Formulation couples the charging and discharging decisions into a single constraint which also enforces the TSOC [Source: Polaris Systems Optimization].*

The optimization formulations for the two ISO-SOCM approaches described above are presented in Table 1. For this study, it is assumed that ESRs do not provide bids/offers under the ISO-SOCM option. Models are solved for 2-day horizons with the second day used for efficient commitment of thermal resources. Decisions identify binding results in the first day and look-ahead (advisory) results in the second day. For brevity, constraints are presented for the first day.

Discharging and Charging Limit Constraints. Constraints (1), (2), and (3) identify ESR dispatch limits.

SoC Constraints. These constraints track SoC in each hour and are present only in the SoC Constraint Formulation. More specifically, (4a) calculates the SoC at the end of hour 1 by considering the SoC at the start of the day, (4b) relates the SoC from one hour to the next through the discharge and charge decision variables adjusted for efficiency losses, and (4c) specifies the target SoC at the end of the day. The maximum and minimum SoC limits are enforced through (4d) and (4e).

Storage Efficiency Constraint. Constraint (5) in the Wrapper Energy Constraint Formulation includes the impact of efficiency on discharge and charge decisions to identify total energy exchanged over the time window. This enforces energy conservation by constraining decisions by the change in SoC over the time window. Note that for a 24-hour time window, the target SoC is the desired SoC at the end of the day. For smaller time windows (e.g., 12-hour), energy exchanged over *each* window must be chosen so as to reach the desired target SoC by the end of the day.

Storage Duration Constraints. Constraints (6a) and (6b) in the Wrapper Energy Constraint Formulation ensure that the maximum energy discharged and charged over the time window are within an ESR's capability. Thus, these constraints implicitly guarantee that SoC is feasible over the time window.

Both formulations assume that there is no need for integer variables to avoid simultaneous charging and discharging. This is reasonable so long as locational marginal prices (LMPs) have positive values. Charging or discharging occur only when there is sufficient price separation to overcome losses from less than perfect storage efficiency. With zero or negative LMPs, although simultaneous charging and discharging may occur to create artificial losses, additional modeling tricks are needed (such as adding a small cost to either the charge or discharge decisions).

Note that the storage efficiency constraint (5) is functionally similar to the SoC constraints (4a)–(4c), as they both relate the dispatch variables, define a target SoC and help track the SoC. However, (5) just uses a single constraint per time window whereas (4a)–(4c) need multiple constraints over the day. Similarly, storage duration constraints (6a) and (6b) implicitly ensure SoC feasibility using two constraints per time window, whereas (4d) and (4e) do the same explicitly but at the cost of using more constraints per day. The SoC Constraint Formulation may face potential computational issues, which arise not only due to the large number of constraints but also the time-coupled nature of these constraints. The decisions regarding charge or discharge at the beginning of the horizon can impact decisions at the end of the horizon, affecting all the intermediary constraints and possibly introducing numerical issues in the optimization problem. This may have further adverse implications if the optimal solution is degenerate, e.g., at high electric storage penetration levels where the marginal energy prices are comparable across all hours, the ESR is indifferent to the specific hour of charging or discharging. On the other hand, the Wrapper Energy Constraint Formulation links all the decisions directly using a single constraint, making it relatively straightforward from a numerical optimization perspective. Although the Wrapper Energy Constraint Formulation is computationally more tractable, it can be conservative in terms of ESR utilization, depending on the risk tolerance of the storage owner. In this work, storage is assumed to start at 50% SoC and returns to 50% at the end of the day. Constraints (6a) and (6b) ensure SoC feasibility under all circumstances, but the value of storage is less than what can be achieved with better understanding of market conditions, forecasts, and risk tolerance.

For example, consider a 100 MWh ESR with a maximum charging/discharging limit of 25 MW. With a 24-hour time window and an initial SoC of 50 MWh, the maximum energy discharge and charge over the time window will be restricted to 50 MWh each—see (6a) and (6b)—which is only half an ESR cycle. Although ESR utilization over a time window is limited, the total utilization over a day can be increased by modifying the duration of the time window. For instance, a 12-hour time window can allow one (instead of half) cycle over a day as shown in Figure 3. Another way of achieving better ESR utilization with wrapper energy constraints is to use dynamic schedules, i.e., specify different energy exchange values over the time windows by modifying the right-hand side of (5), (6a), and (6b). The general idea is to use system load or pricing forecasts (or system's prior knowledge) to drive ESR dispatch behavior which can benefit both the resource and the system operator.

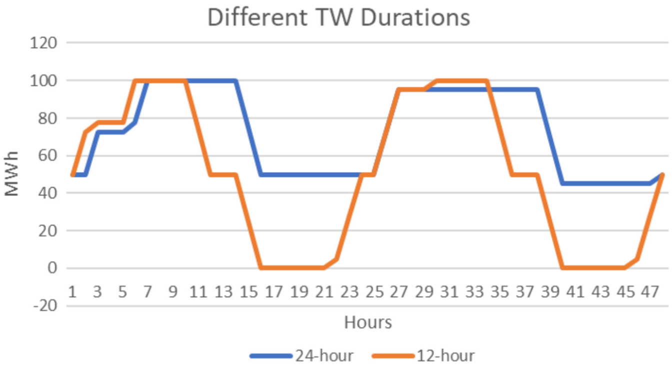


Figure 3: *Impact of duration of Time Window (TW) on ESR dispatch and utilization.*

Table 1: *SoC Constraint- and Wrapper Energy Constraint-based Optimization Formulations for modeling the ISO-SOCM option.*

<table>
<tr><th>SOC CONSTRAINT FORMULATION</th><th>WRAPPER ENERGY CONSTRAINT FORMULATION</th></tr>
<tr><td colspan="2">DISCHARGING AND CHARGING LIMIT CONSTRAINTS</td></tr>
<tr><td colspan="2">$G_{k,t} - L_{k,t} \leq MaxD_{k,t} \quad \forall t,k \quad (1)$
$L_{k,t} - G_{k,t} \leq MaxC_{k,t} \quad \forall t,k \quad (2)$
$G_{k,t} \geq 0, \quad L_{k,t} \geq 0 \quad \forall t,k \quad (3)$</td></tr>
<tr><td>SOC CONSTRAINTS</td><td>STORAGE EFFICIENCY CONSTRAINT</td></tr>
<tr><td rowspan="3">$SOC_{k,1} = SSOC_k - \frac{1}{\eta_k^G} G_{k,1} + \eta_k^L L_{k,1} \quad \forall k \quad (4a)$
$SOC_{k,t} = SOC_{k,t-1} - \frac{1}{\eta_k^G} G_{k,t} + \eta_k^L L_{k,t} \quad \forall t,k \quad (4b)$
$SOC_{k,24} = TSOC_k \quad \forall k \quad (4c)$
$SOC_{k,t} \leq SOC_k^{max} \quad \forall t,k \quad (4d)$
$SOC_{k,t} \geq SOC_k^{min} \quad \forall t,k \quad (4e)$</td><td>$\sum_{t \in TW} \left(\frac{G_{k,t}}{\eta_k^G} - \eta_k^L L_{k,t} \right) = E_{k,TW}^{init,MWh} - TSOC_{k,TW} \quad \forall TW, \forall k \ (5)$</td></tr>
<tr><td>STORAGE DURATION CONSTRAINTS</td></tr>
<tr><td>$\sum_{t \in TW} \left(\frac{G_{k,t}}{\eta_k^G} \right) \leq E_{k,TW}^{init,MWh} - SOC_k^{min} \quad \forall TW, \forall k \quad (6a)$
$\sum_{t \in TW} \left(\eta_k^L L_{k,t} \right) \leq SOC_k^{max} - E_{k,TW}^{init,MWh} \quad \forall TW, \forall k \quad (6b)$</td></tr>
</table>

Nomenclature

Sets and Indices

k: storage resource index

t: hour index

TW: time window

Variables

G: scheduled discharge (MW)

L: scheduled charge (MW)

SOC: state-of-charge level (MWh)

Parameters

$MaxD$: maximum discharge limit (MW)

$MaxC$: maximum charge limit (MW)

$SSOC$: start state-of-charge at the beginning of the optimization horizon (MWh)

$TSOC$: target state-of-charge at the end of the optimization horizon (MWh)

η^G, η^L: discharging efficiency, charging efficiency

$E^{init,MWh}$: initial SoC level at the start of the time window (MWh)

SOC^{min}: minimum SoC limit (MWh)

SOC^{max}: maximum SoC limit (MWh

NUMERICAL RESULTS

The two ISO-SOCM formulations are simulated and compared across various evaluation metrics, including problem size, economic efficiency, computational efficiency, ESR revenue, and other variables of interest such as LMPs and SoC trajectory.

Simulation Setup. The test system used for the simulations is New York ISO's Fundamentals Model developed by Newton Energy Group (NEG). This is not a NY specific study, but rather the test system is chosen based on availability of realistic dataset. The system comprises of 11 different areas and 568 generating resources, totaling up to about 46 GW capacity, and includes key inter-zonal network constraints. To simulate the scale of energy storage in a future resource mix scenario, 1000 ESRs were added to the test case across six different areas (i.e., A, C, D, E, I, K) where the ESRs added to a specific area were fairly homogeneous in terms of their characteristics. The added ESR had MW capacity between 3 MW–40 MW, whereas their MWh capacity ranged between 18–200 MWh. The storage duration varied from 1.5–10 hours. The total ESR MW capacity that was effectively added to the system was around 8 GW, which is a little higher than NYISO's anticipated goal of 6 GW by 2030. The production cost model was simulated in the Power System Optimizer (PSO) software tool with the wrapper energy constraint time window set to 12 hours. The initial and target SoC for both formulations were set to 50%. Notably, these SoC values were enforced over each 12-hour time window for the wrapper energy constraints, which meant that they were enforced over every 24-hours as well.

Problem Size. The problem sizes for the two formulations, as shown in Table 2, are expectedly different. The SoC Constraint Formulation has both a larger number of constraints and variables, which can be explained by the additional hour-to-hour chronology equations (and variables) that are required to track the SoC evolution in the traditional formulation. However, since both the formulations do not include any integer variables from ESRs, the number of integer variables are the same.

Table 2: *Problem size comparison between the two ISO-SOCM formulations.*

PROBLEM CHARACTERISTIC	SOC CONSTRAINT	WRAPPER ENERGY CONSTRAINT
Avg. num. of constraints	255k	206k
Avg. num. of variables	362k	312k
Avg. num. of integer variables	2.6k	2.6k

Objective Function. The objective function values are used to compare the economic efficiency impacts of the two formulations. As can be seen in Figure 4, the values are fairly close together across all day-ahead horizons over the course of a year. In fact, the average objective values in SoC and Wrapper Energy Constraint Formulations are $15.33 million and $15.39 million respectively, which represent a difference of only 0.43%. For reference, the default MIP Gap is set to 0.01%. Importantly, the Wrapper Energy Constraint Formulation can be improved further in terms of economic efficiency by leveraging factors such as time window duration and dynamic energy schedules.

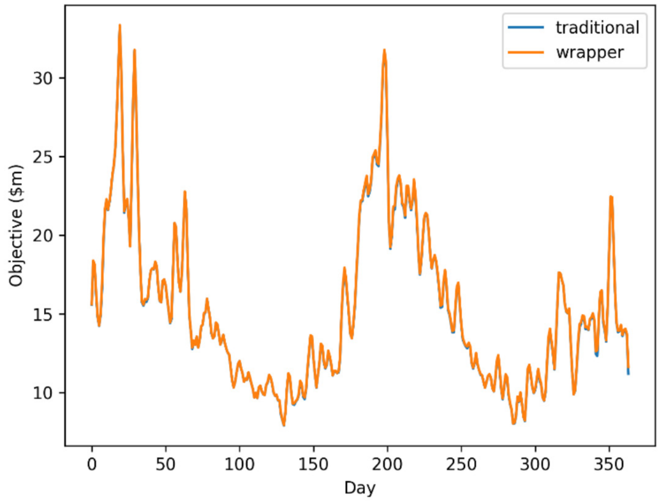
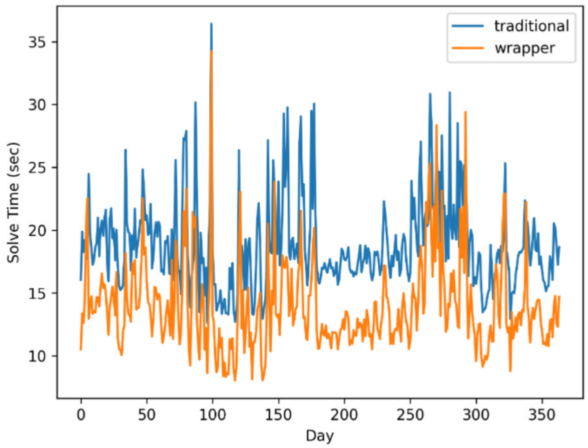
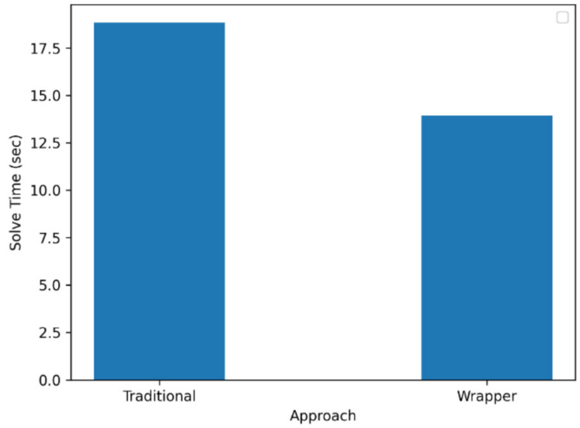


Figure 4: *Objective function value (in $ millions) for the two ISO-SOCM formulations.*

Computational Time. The computational time required to solve each formulation on a day-ahead basis is presented in Figure 5(a). It can be seen that the Wrapper Energy Constraint Formulation is generally faster to solve, which follows from its smaller problem size and relatively simple constraints that capture the interactions of decision variables all at once. Figure 5(b) compares the average time per horizon for the two approaches, i.e., 18.84 seconds with SoC constraints versus 13.90 seconds with wrapper energy constraints. Note that the computational time for the simulated system is not too large to begin with but the Wrapper Energy Constraint Formulation is still able to achieve ~26% performance improvement. For computationally stressed systems, the improvement can be expected to be even larger.



(a) Time for each horizon.



(b) Average time per horizon.

Figure 5: *Computational time (in seconds) for the two ISO-SOCM formulations.*

SoC Trajectory and LMP. The SoC trajectory and LMPs are observed for an ESR over an entire year to better understand the differences between the two approaches from the perspective of an ESR owner. The considered ESR had energy and power capacity of 50 MWh and 12.5 MW, respectively, with charging and discharging efficiencies both equaling 0.85. In Figure 6, the ESR can be seen to have lesser utilization based on the SoC trajectory from the Wrapper Energy Constraint Formulation but the LMPs are not too different between the two approaches.

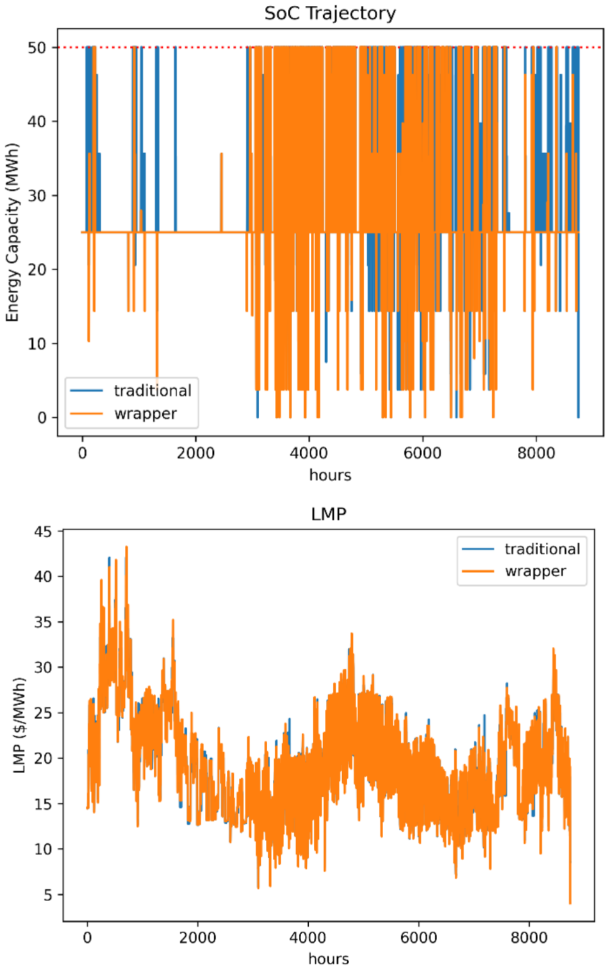


Figure 6: *SoC and LMP profile comparison over the year for the two ISO-SOCM formulations.*

Upon closer inspection of the daily profiles for a week in Figure 7, it can indeed be verified that the utilization of the ESR is lesser with wrapper energy constraints. This is due to the 12-hour time window, which forces the ESR to return to 50% SoC (25 MWh) mid-day each day even when the resource may benefit from delaying its discharge to later hours (as is the case with traditional SoC Constraint Formulation). Notably, the lower ESR utilization translates to slightly higher LMPs for the Wrapper Energy Constraint Formulation, which can also be seen in the figure.

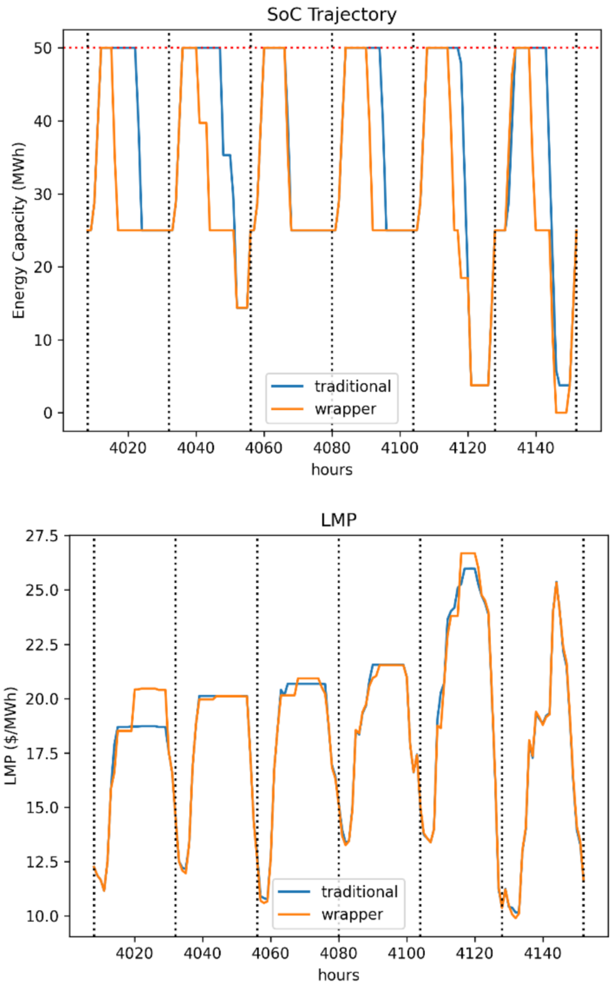


Figure 7: *SoC and LMP profile comparison for a period of 6-days for the two ISO-SOCM formulations.*

Resource Revenue. The annual revenue earned by the different ESRs under the two formulations is compared in Figure 8. Unsurprisingly, the greater ESR utilization with SoC constraints (and almost similar LMPs as wrapper constraints) leads to a larger annual revenue in the traditional SoC Constraint Formulation. This can be seen for storage resources in areas K and I. However, observe that area A and E resources earn almost zero annual revenue in both formulations, primarily because of their low round-trip efficiencies and inadequate energy arbitrage opportunities in these areas. The purpose of including these low efficiency ESRs in the simulation is to replicate the stressed cases that have been reported by the industry as having computational tractability issues. Interestingly, area D resources also earn almost zero annual revenue in the Wrapper Energy Constraint Formulation. However, this happens for reasons that are different from efficiency since these ESRs have much larger revenues with the traditional SoC Constraint Formulation. In fact, the issue is to do with the duration of the time window (i.e., 12 hours), which adds additional operational constraints and prevents the ESRs from benefitting from the LMP profile in the area.

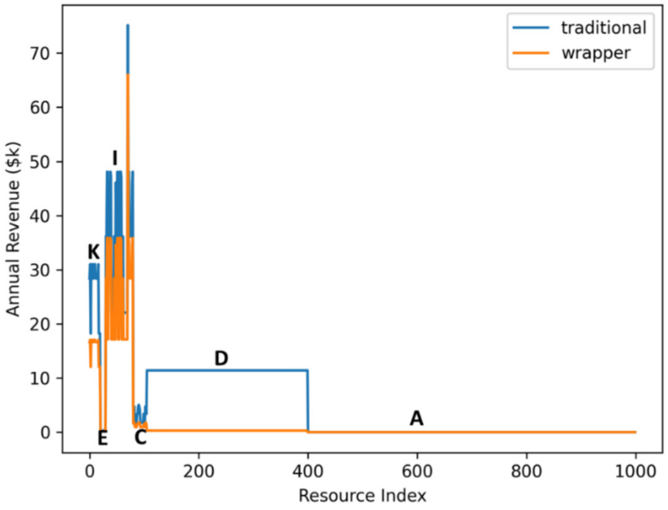


Figure 8: *Annual ESR revenue (in $ thousands) for the two ISO-SOCM formulations.*

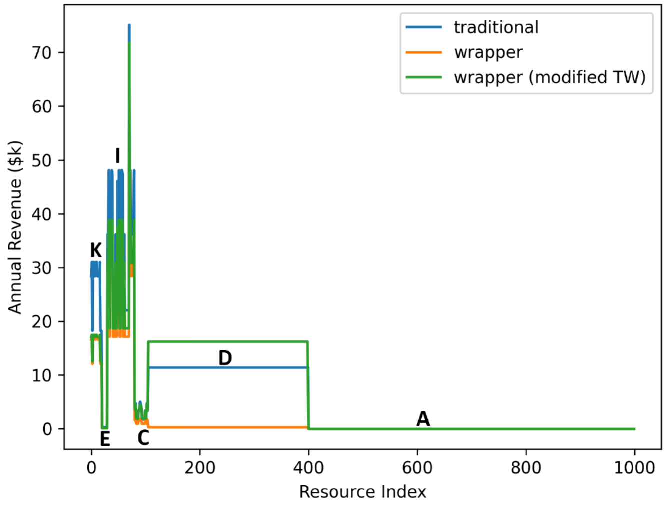


Figure 9: *Annual resource revenue (in $ thousands) when area D resources have 24-hour (green) time window instead of 12-hour (orange) time window. Other areas have ESR with 12-hour time window in both wrapper cases.*

Upon further investigation, it is observed that some of the revenue related shortcomings of the Wrapper Energy Constraint Formulation can be overcome by modifying the time window for area D resources. For example, in Figure 9, the time window for area D resources was changed from 12 hours to 24 hours and as a result, the ESR revenue increased significantly. In fact, it improved beyond the SoC Constraint Formulation's revenue for area D resources, while also increasing the revenue for some other areas (e.g., area I). Additionally, this change had a positive impact on the objective function value and the computational time of the formulation as shown in Table 3. Note that, in this specific case, the increase in the time window duration was beneficial since the 12-hour time window was the bottleneck in better resource utilization (as seen in the SoC trajectory subsection). In other cases, the opposite may be true. Overall, this phenomenon indicates that improvements in different metrics can be attained with the Wrapper Energy Constraint Formulation, i.e., if the formulation's parameters are appropriately modified based on prior system knowledge or forecasts.

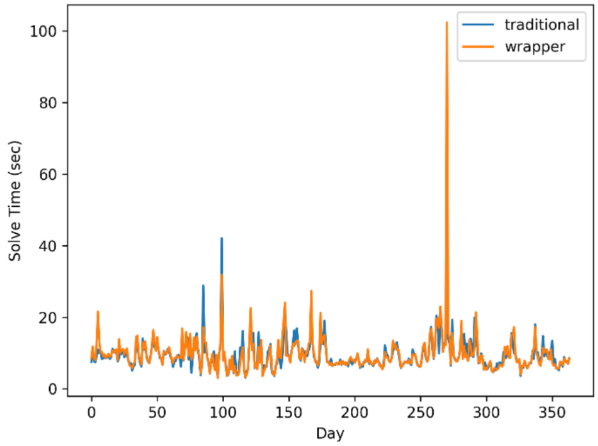
Table 3: *Impact of area D resources' time window duration on economic and computational efficiency.*

METRIC (AVG)	SOC	WRAPPER	WRAPPER MODIFIED TW
Objective ($m)	15.33	15.39	15.36
Comp. Time (sec)	18.84	13.90	13.61

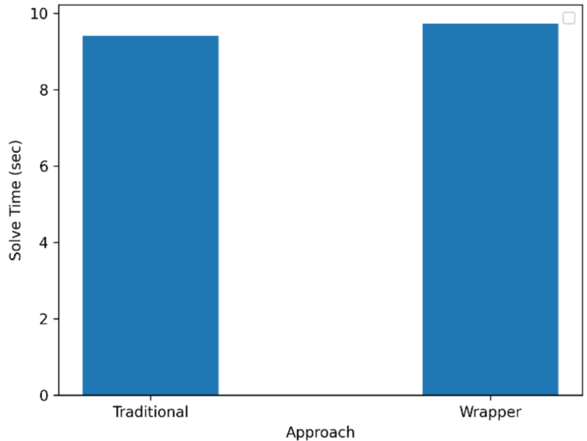
Comparison at Low ESR Penetration Levels. The ESR penetration level is adjusted to assess the performance of the two formulations. Higher ESR levels may show different impacts as there is potential for greater computational burden when more ESRs are modeled using the traditional SoC Constraint Formulation. Therefore, a low ESR penetration level was simulated to show closer conditions to what may be expected on the existing NY system. This scenario includes about 50 storage resources, totaling around 720 MW of installed ESR capacity, with characteristics matching those in the simulation setup described earlier.

When comparing the two formulations at low ESR penetration, computational advantages of the Wrapper Energy Constraint Formulation are not clearly evident. Figure 10 shows that solve times for both formulations are very similar in this scenario. However, differences in other metrics are smaller compared to high ESR penetration. For instance, the objective functions differ by merely 0.04%, i.e., $15.44 million in the traditional SoC Constraint Formulation versus $15.45 million in the Wrapper Energy Constraint Formulation.

Although differences between the two formulations might not stand out at low ESR penetration levels, it would be imprudent to rule out the usefulness of the Wrapper Energy Constraint Formulation altogether. The benefits of the Wrapper Energy Constraint Formulation become more apparent for the projected high ESR penetration levels across different regions globally, as was observed for the high ESR penetration level presented in this study. This becomes especially relevant for current or future resource mixes, particularly if the underlying systems are larger in scale, have higher modeling fidelity, and/or experience computationally demanding system conditions. In contrast, the test system used in this study is relatively manageable.



(a) Time for each horizon.



(b) Average time per horizon.

Figure 10: *Computational time (in seconds) for the two ISO-SOCM formulations at the current storage resource mix.*

SUMMARY

SoC management is integral to effective ESR participation in wholesale electricity markets. There are several system and resource level benefits in having the ISO perform SoC management (i.e., ISO-SOCM). However, ISO-SOCM may become computationally intractable at high ESR penetration levels. This is due to its traditional approach of modeling the explicit hour-to-hour SoC chronology for each ESR, which requires a large number of time-coupled and hard constraints, and thus significantly increases the size and complexity of ISO's market optimization problem. There is a need to balance abstract ideals with practicality since computational performance is crucial to market clearing software augmentations. An alternative modeling approach is to instead consider the energy exchanged by each ESR over a time window and thus implicitly track the SoC. This approach couples the different ESR dispatch decision variables over the time window using a single simplified constraint, which significantly reduces the total number of constraints and variables in the formulation. Such an approach can prove to be more efficient but requires heuristics. Preliminary simulation results have shown the wrapper energy constraint approach to be promising in terms of reducing the computational times while keeping intact most of the other benefits of ISO-SOCM such as economic efficiency, reliability, and incentive compatibility.

FUTURE RESEARCH DIRECTIONS

There are multiple research directions that can be further explored with regards to the Wrapper Energy Constraint Formulation as listed below with a brief description.

- Identify stressed day-ahead cases based on actual ISO/RTO experience with slow SOC Constraint Formulation performance to see if wrapper energy constraints help the case. In addition, evaluate if performance issues are due to other causes (e.g., model degeneracy).
- Conduct a more exhaustive quantification of the impacts of time window duration and dynamic schedules on different evaluation metrics, especially in the context of different resource mixes (e.g., solar versus wind dominated systems) and system loading/pricing patterns.
- Obtain a more wholistic understanding of the relationship between ESR revenue and specific parameters of the Wrapper Energy Constraint Formulation to better optimize the asset revenue for each ESR in the system.
- Propose improvements that further streamline and automate the ad hoc and intuition-driven selection of Wrapper Energy Constraint Formulation's parameters while still preserving its numerous benefits.
- Extend the wrapper energy constraints to also consider the provision of ancillary services and analyze the differences when compared to the energy only case seen here.
- Analyze the impact of using the Wrapper Energy Constraint Formulation in the context of planning problems (such as capacity expansion) that may run multi-year models with hourly granularity, since such problems can greatly benefit from the faster computation times and modest economic efficiency implications.
- Apply the Wrapper Energy Constraint Formulation to the real-time dispatch problem and identify any requirements that may be unique to their use for problems with shorter optimization horizons.
- Apply the wrapper energy constraints to hybrid storage resources without needing to explicitly represent the SoC of the storage component.

CONTACT INFORMATION

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POLARIS SYSTEMS OPTIMIZATION RESOURCES

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