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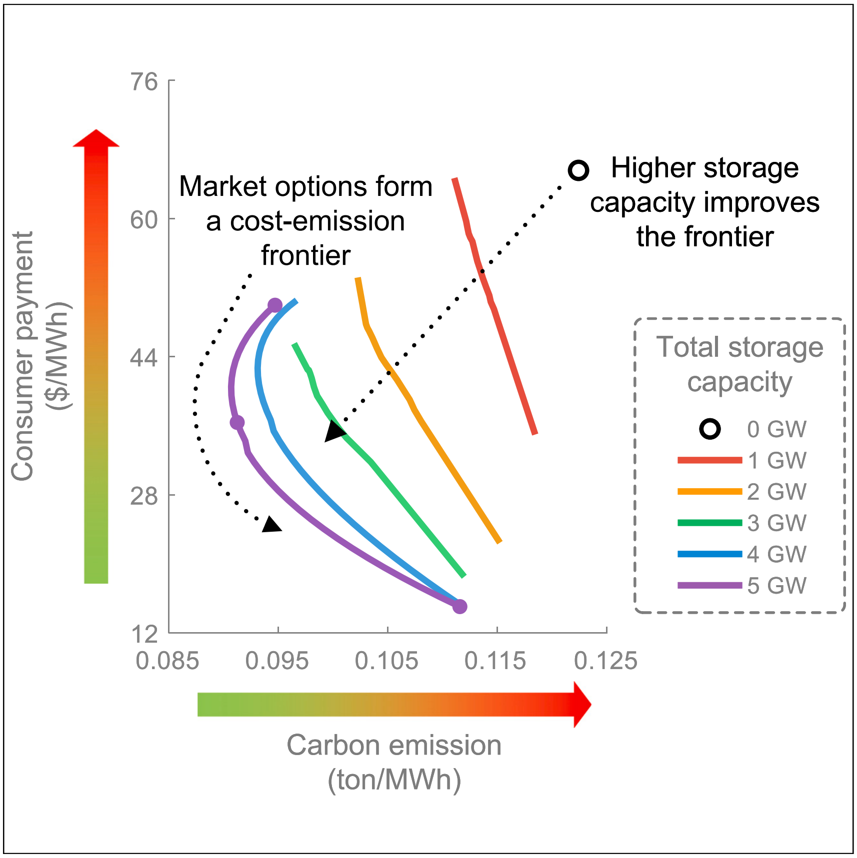

This study analyzes why electricity market design is a significant factor to affect energy storage's contribution to the cost-efficient decarbonization in power systems. We show that the existing electricity pool market design facilitates early-stage storage adoptions but may encounter challenges to balancing economics and emissions as storage capacity increases. We also demonstrate that policy incentives are critical to properly distribute storage in different markets for maximizing social welfare.

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Highlights

Storage operations play an increasingly important role as power systems decarbonize

Market participation choices of storage have asymmetrical effects on cost and emission

Market design for storage affects up to 53% of consumer cost and 16% of emission reduction

Future market designs must balance storage's economic and emission impacts

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The role of electricity market design for energy storage in cost-efficient decarbonization

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SUMMARY

Energy storage is widely recognized by power system utilities and regulators as a crucial resource for achieving energy decarbonization. However, in deregulated power systems, investor-owned storage participates in electricity markets with a profit-driven motive. The alignment of such profit-driven operations with social welfare critically depends on market design and storage's participation choices. This study employs an agent-based approach and investigates the impact of different market participation options on storage's contribution to reducing electricity costs and carbon emissions. Our findings suggest that the existing electricity pool market design in North America may encourage early-stage storage adoptions but hinder progress toward deep decarbonization. We found that day-ahead markets are more effective in utilizing storage to reduce carbon emissions, while real-time markets are more effective in reducing costs. We compare different combinations of storage market participation choices and conclude trade-offs between consumer energy affordability and carbon emissions.

INTRODUCTION

Grid-scale battery energy storage ("storage") contributes to a cost-efficient decarbonization process provided that it charges from carbon-free and low-cost renewable sources, such as wind or solar, and discharges to displace dirty and expensive fossil-fuel generation to meet electricity demand.[1] However, this ideal assumption is not always feasible in practice, particularly in deregulated power systems. Energy storage participates in electricity markets by submitting economic bids to earn revenue.[2] Whether a storage unit charges or discharges at a specific time is not directly based on the system cost or carbon emissions but instead depends on market clearing, which is influenced by the storage's bid prices, bids submitted by other participants, and the system's demand and renewable share. Therefore, the storage's market participation options and the market design play critical roles in determining whether storage can facilitate cost-effective decarbonization in future power systems.

Previous studies examining storage integration in power systems have largely neglected the market participation aspect, assuming vertically integrated systems where system operators have direct control over storage. These studies have concluded that storage investments reduce the cost of electricity,[3–9] while the impact on carbon emissions is mixed and largely depends on the system resource mix.[10–17] However, these results may be too optimistic as they overlook the complexity introduced by market participation. Another group of studies has focused on storage's participation in electricity markets, proposing various methods to control storage and design bids to optimally maximize market revenue.[18–24]

CONTEXT & SCALE

Energy storage is key to decarbonize power systems by allowing excess renewable energy to be stored and released back to the grid as needed. Ideally, storage should be charged from carbon-free and low-cost renewables and discharged to replace dirty and expensive fossil-fuel generation. However, in reality, energy storage participates in electricity markets with a profit-driven motive, its impact on reducing system costs or emissions is dependent on market design and storage's participation choices. In some cases, storage may increase system costs or emissions if the market design or incentives are not aligned with renewable and storage capacity present in the system.

This study aims to evaluate how market designs can affect the contribution of energy storage to electricity economics and decarbonization, from early to deep decarbonization stages. The proposed open-source framework can be used by researchers and policymakers to assess emerging technologies and policy incentives.

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However, most of these studies have not considered how storage alters system operation, as they assume that storage is an emerging participant and will not impact market clearing prices, i.e., price takers. A few studies have attempted to analyze the impact of storage participation on market clearing results but have only focused on equilibrium analysis with small storage installations.[25–30] A recent study has investigated the market participation of virtual power plants using a multi-scale model.[31] The results highlight the importance of modeling bidding processes, which provides different results than price taker or vertically integrated studies.

Understanding the impact of increasing storage participants in electricity markets on system cost and emissions is critical for guiding future market designs and regulatory incentives, especially given the rapid deployment of energy storage worldwide, which is driven by policy incentives and decreasing investment costs. Organized electricity markets in North America and Europe have allowed storage to participate and submit charge and discharge bids.[32,33] California is a leader in storage deployments, with total storage capacity participating in electricity markets surging from around 200 MW in 2020 to over 4,000 MW in 2022, accounting for 10% of California's total electricity demand.[34] As storage capacity increases, arbitrage in wholesale markets has replaced frequency regulation as the main market service for storage in California.[35] Similar trends in storage deployments and market choices are observed in other nations and regions, including Texas, Australia, and Germany.[36]

This study aims to bridge the gap between storage participation bidding models and system-level cost and emission analysis. We propose an agent-based two-stage market model that employs innovative algorithmic designs to provide a more realistic and comprehensive analysis of storage's impact on system cost and carbon emissions. The model includes accurate technical market-clearing and storage operation models, which yield more precise results. Our study investigates storage market participation perspectives that have been often overlooked by previous storage integration studies, such as bidding strategies and the choice of day-ahead or real-time markets. We perform a comprehensive analysis to understand how private incentives align with social welfare, including system cost and carbon emissions. This innovative setting enables us to uncover critical insights into the challenges and opportunities associated with storage market participation in cost-efficient decarbonization.

RESULTS

Methodology and data

Two-stage electricity market model

We consider a typical two-stage electricity pool market clearing model, also called centralized market clearing, consisting of day-ahead and real-time markets, which is commonly used in North America[37] as shown in Figure 1. This wholesale electricity market model aims to match supply with demand economically while also fulfilling operating reserve provision requirements. One day before the operating day, the system operator collects predicted demand and wind generation data from participants[38] and then clears the day-ahead market by solving a unit-commitment problem to clear the market and to determine the start-up and shut-down schedule of thermal generators. The unit-commitment problem is expressed as follows:

$$\min \sum_{t=1}^{T} C^m(g_t) + C^n(u_t) + C^s(y_t) + C^e\left(p_t^d\right) \quad \text{(Equation 1)}$$

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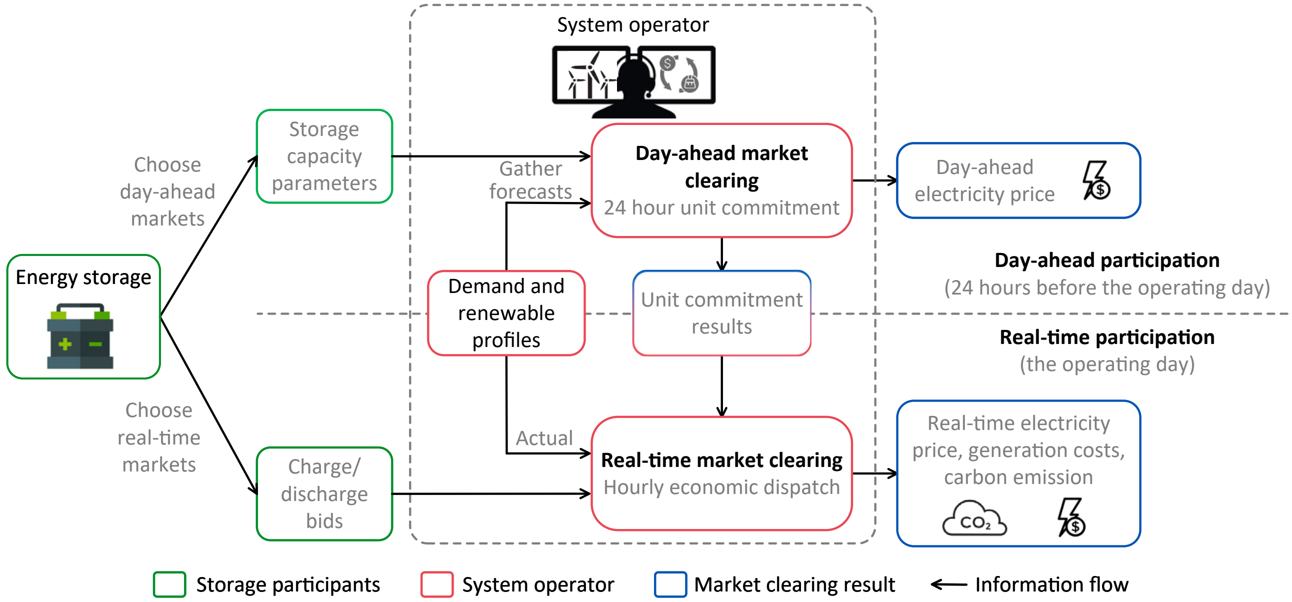

Figure 1. Overview of the proposed agent-based storage market participation model

The electricity market model in this paper is a typical wholesale electricity model that includes two stages: the day-ahead market and the real-time market. The day-ahead market schedules resources 24 h before the operating day, while the real-time market tackles renewable and demand fluctuation and maintains real-time generation-demand balance. The optimization models of the two stages are introduced in Methodology and data above. An energy-storage participant can choose to participate in day-ahead markets, real-time markets, or both, depending on its preferred market participation option. To participate in the day-ahead market, storage participants submit their operational parameters. To participate in the real-time market, storage must design charging/discharging bids separately for each real-time market period.

subject to unit commitment constraints, reserve requirements, generator operational constraints, and storage operational constraints, where $C^m(g_t)$, $C^n(u_t)$, $C^m(y_t)$ are generator operational cost, no-load cost, and start-up cost, respectively. $C^e(p_t^d)$ is the marginal physical cost for discharge, considering degradation. T indicates the total time periods in a day.

During the operating day, the system operator solves an economic dispatch problem (Equation 2) shortly before each time period (t) by utilizing the most recent system information and then updates the dispatch of generators accordingly:

$$\min C^m(g_t) + B_t^d \cdot p_t^d - B_t^c \cdot p_t^c \qquad \text{(Equation 2)}$$

subject to generator operational constraints and storage operational constraints, where B_t^d and B_t^c indicate storage discharging and charging bids, respectively; and p_t^d and p_t^c are storage discharging energy and charging energy. To access detailed mathematical models of the day-ahead and real-time markets, please refer to supplemental information.

Storage participation settings

We consider three participation options for storage over the proposed two-stage market-clearing model.

1 Day-ahead (DA) participation: storage participates in day-ahead markets by bidding its physical parameters. The system operator schedules storage in the day-ahead unit commitment with other generators over a 24-h horizon. Storage does not participate in real-time markets and does not respond to

real-time price signals. Storage revenue in day-ahead markets is cleared using day-ahead prices.

2 Real-time (RT) participation: storage submits separate charge and discharge bids for each market period to participate in real-time markets. These bids are designed by solving a profit-maximization problem, as outlined in supplemental information. For each time period, the storage submits a charging bid, indicating the price below which it is willing to charge, and a discharging bid, indicating the price above which it is willing to discharge. We assume that the storage uses day-ahead price forecasts to design bids for the real-time markets. The system operator clears the storage bids, along with those of other generators, in real-time markets. The storage's revenue in the real-time markets is cleared using real-time prices.
3 Day-ahead and real-time (DA + RT) participation: storage participates in both day-ahead and real-time markets. One day prior to the operating day, the storage participates in day-ahead markets following the rules of DA participation. During the operating day, the storage uses the published day-ahead price signal to design bids to update their buy (charge) and sell (discharge) positions in real-time markets (please note that DA + RT participation is not a bidding strategy based on stochastic programming. While participating in the DA, storage does not withhold charging/discharging capacity through bidding, which means they can buy back or sells more in real-time markets).

Test system and data

The simulations are conducted using the independent system operator (ISO) New England test system.[39] The system demand varies from 9 to 17 GW, with an average of 13 GW. The system has 76 generators with a total capacity of 23.1 GW. The generation mix (without renewables) includes: natural gas, 10.63 GW (46% of the total, cost range, \$22.2–\$400/MWh); nuclear, 4.66 GW (20.2%, cost range \$5–\$11/MWh); coal, 2.40 GW (10.4%, cost range \$18.1–\$20/MWh); and oil 5.4 GW (23.4%, cost range \$54–\$350/MWh).

We select five representative demand and wind profiles for our study using a K-means approach, as explained in supplemental information, with the average wind capacity factor of 0.4. To model the impact of storage with growing renewable capacity, we scale the wind-generation capacity into three cases according to its maximum power capacity: low, medium, and high, representing 50% (6.5 GW), 100% (13 GW), and 200% (26 GW) average system demand, respectively. For each demand and wind scenario, we employ a Monte Carlo method to generate five real-time scenarios to consider real-time wind fluctuations, in which the average mean absolute error (MAE) of wind fluctuations is 11.53%. Thus, each demand-wind scenario corresponds to five real-time realizations, providing a total number of 25 scenarios for each wind-capacity case. We analyze the impact of integrating energy storage ranging from 1 MW to 5,000 MW into energy systems. All storage units considered in our analysis are 4-h batteries with a one-way charging/discharging efficiency of 90%, which is consistent with typical power systems' resource-adequacy requirements.[40]

Comparison of electricity cost and carbon emission per storage market participation model

We begin by examining the impact of storage on the suppliers' cost of electricity generation and carbon emissions from a social welfare perspective of the power system operator. We simulate various storage participation options and compare the results as storage capacity increases. Figures 2A–2C display the average fuel costs

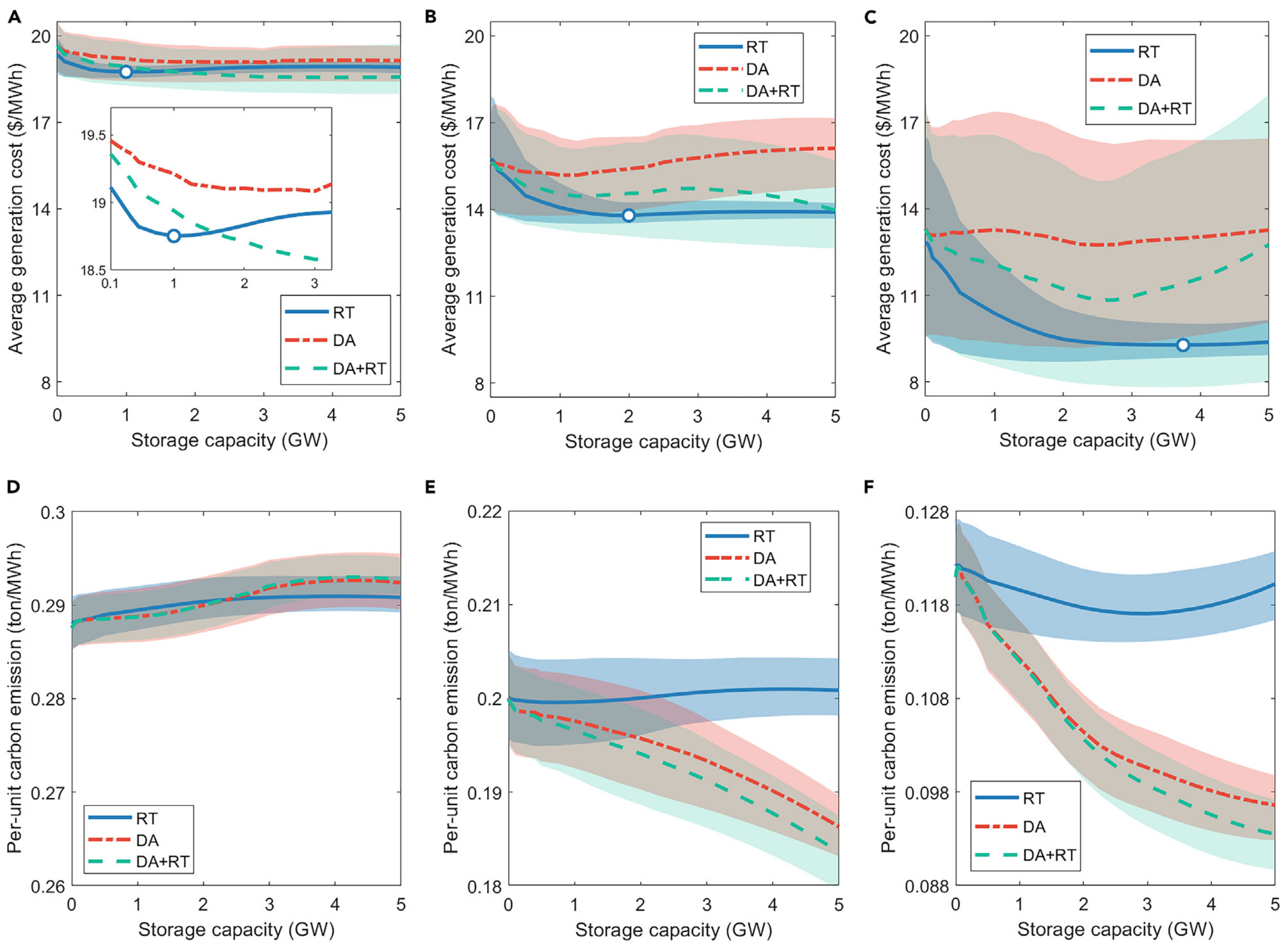

Figure 2. Average system generation cost and carbon emission

(A–C) Generation costs under (A) low, (B) medium, and (C) high wind penetrations.

(D–F) Carbon emissions under (D) low, (E) medium, and (F) high wind penetrations. The presented curves are the weighted average results of 5 different day-ahead demand and wind scenarios, with the corresponding shaded areas indicating the variance across the 25 considered scenarios. Legends: RT, DA, and DA + RT, indicate RT participation, DA participation, and DA + RT participation, respectively. Curves are smoothed by Savitzky-Golay filter to remove fluctuations introduced by start-up and shut-down decisions from day-ahead unit commitments, as detailed in supplemental information. Note that plots (D)–(F) have the same y axis spacing, but the ranges differ.

of electricity generation, and Figures 2D–2F display the average carbon emissions across the three wind-penetration levels considered.

Results show that storage participating in real-time markets can more effectively reduce system operating costs than in day-ahead markets. However, we also found that in the medium-wind case, increasing storage capacity can result in higher system costs in day-ahead markets. This is because storage displaces committed generators in the day-ahead market, leading to more frequent dispatch of expensive peaker generators in real-time to ensure generation/demand balance, which in turn causes price spikes and generation cost increments. Despite this, storage participation in day-ahead unit commitment can still lead to lower carbon emissions by displacing more thermal generators.

Real-time markets provide the opposite effect of day-ahead markets over storage participation: Real-time markets are more effective in reducing generation costs while not significantly reducing carbon emissions. Storage shows a clear saturation effect in cost reduction, in which more storage capacity beyond a certain level—depending on the wind penetration—no longer reduces the system cost. In the low-wind scenario, only 1 GW of storage capacity is needed to achieve the lowest generation cost; in the medium- and high-wind scenarios, the lowest-cost storage capacity increases to 2 and 3.75 GW, respectively. Similar to the day-ahead case, we find that costs increase with high storage capacity, but the driving cause is different. The primary reason is that the cycle efficiency loss of storage increases the overall energy demand and outweighs the savings from energy shifting as storage capacity increases. Another cause is that storage bids may mismatch with demand peaks and valleys because the real-time prices become more deviated than day-ahead predictions. The market-clearing results may lead storage to charge during high demand and discharge during low demand, which drives up the cost of electricity.

As storage capacity increases, participating in both day-ahead and real-time markets outperforms participating in day-ahead markets only regarding generation cost and carbon emission. The DA + RT cases fall between DA and RT in cost reduction but outperform DA and RT in carbon-emission reduction. In DA + RT participation, fewer thermal generators are committed in day-ahead unit commitment, while the storage still has the flexibility to buy back its day-ahead position in real-time and reduce the generation from peaker units compared with DA cases, leading to the overall lowest carbon emission.

We also notice that storage participants always produce higher carbon emissions under the low-wind scenario than those having no storage in all participation options. This indicates that storage is more often charged from fossil-fuel generators than wind generation since renewable accommodation is very close to 100%. Hence the higher the storage capacity, the higher the emission due to storage's charging/discharging efficiency loss.

Storage arbitrage profits

This section takes the perspective of storage participants to investigate the arbitrage profits under different market participation options. Figure 3 shows that storage profitability diminishes quickly as storage capacity increases. The per-unit storage profit in DA decreases at a steadier rate, which dropped to below $15 MWh per day at similar storage capacities in all three wind penetrations, while the storage profit in RT and DA + RT starts higher but reduces more quickly and even drops to negative.

The results show that DA participation offers lower profits at low storage capacity, but that profits become more stable as storage capacity increases. In contrast, RT and DA + RT options provide high profits at low storage capacity, but the profit potential quickly diminishes as storage capacity increases, particularly in the low-wind case. The profitability of storage is closely correlated with price variability. In day-ahead markets, the combined effect of wind plus storage causes fewer baseload generators to be committed in unit commitments, while more expensive but also more flexible generators are kept to mitigate system variability. This helps to maintain price volatility, resulting in stable profitability. Figure 3 shows that, regardless of wind capacity, storage profits are always greater than zero and higher than the profits of RT or DA + RT models under large storage capacities. Conversely, for small storage capacity, the profits of DA participation are only half of those of RT participation because of its inability to capture large price volatility in real-time markets.

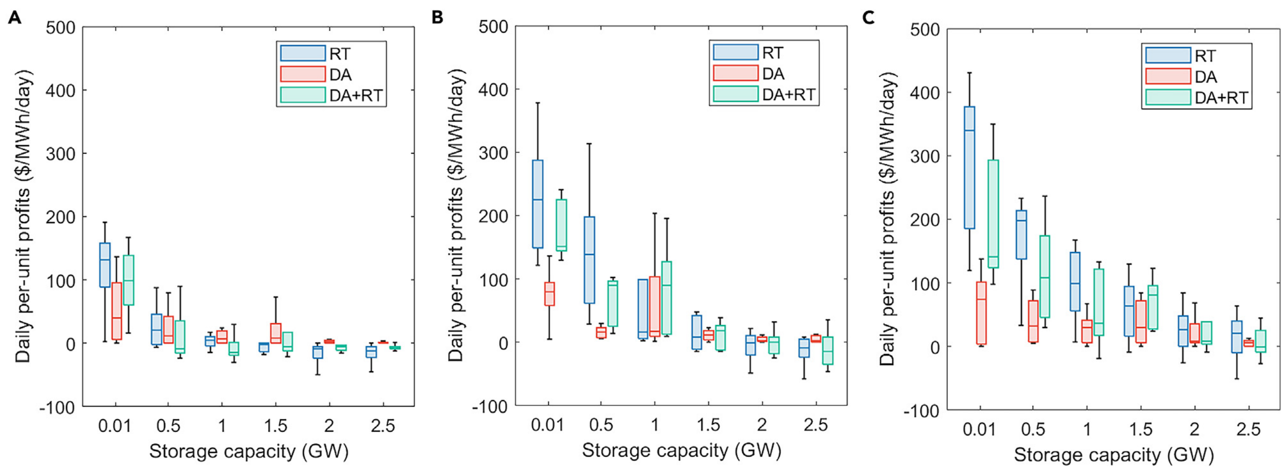

Figure 3. Box chart of per-unit storage arbitrage profits with DA, RT, and DA + RT market participation options
(A–C) (A) Low wind penetration; (B) medium wind penetration; (C) high wind penetration. The per-unit profits indicate storage arbitrage profits per MWh of capacity per day considering the storage marginal costs for discharge. The average profits curves under all storage capacities are provided in supplemental information.

The profits of RT participation under small storage capacity are much higher than those of DA participation due to higher price volatility, especially in the medium- and high-wind scenarios. However, the profits quickly diminish and may become negative as the storage capacity increases. This is because the price predictions used to generate bids become more deviated from the actual market prices due to storage's participation. By comparing Figures 3 and 2, we notice that there are close saturation points in storage profits and generation costs in real-time markets: 1 GW storage for low wind, 2 GW storage for medium wind, and 3.5 GW storage for high wind, respectively. This shows that, despite errors in bid designs, storage's profit objective aligns with social welfare in reducing generation costs.

DA + RT participation is less profitable than RT participation under all wind-penetration scenarios. Our study assumes storage to be truthful bidders in day-ahead markets by submitting only physical costs and parameters. As a result, storage often clears a portion of its capacity in day-ahead markets and must buy those capacities back in real-time markets to arbitrage more volatile real-time prices. This approach lowers the storage profit as storage did not design DA bids strategically by considering real-time arbitrage opportunities. Therefore, our study suggests that storage participants may prefer to participate in real-time markets only to earn maximal profits and tend to avoid being scheduled in day-ahead markets. This conclusion aligns with observations from the recent California market, where storage participants bid unreasonably high prices in day-ahead markets with the purpose of not being cleared.[41]

Pareto frontier analysis trading-off consumer affordability and environmental sustainability

We now examine the impact of energy storage on the cost of electricity and carbon emissions from the perspective of consumers. Based on our previous findings on the disparate effects of day-ahead and real-time market participation options for energy storage, we use Pareto frontiers to analyze how different participation options of energy storage affect energy affordability, measured as average consumer payment (A brief introduction of electricity market pricing principle is provided in supplemental information) calculated as the demand-weighted average of market clearing prices, and sustainability, measured as average carbon emissions. Note that consumer

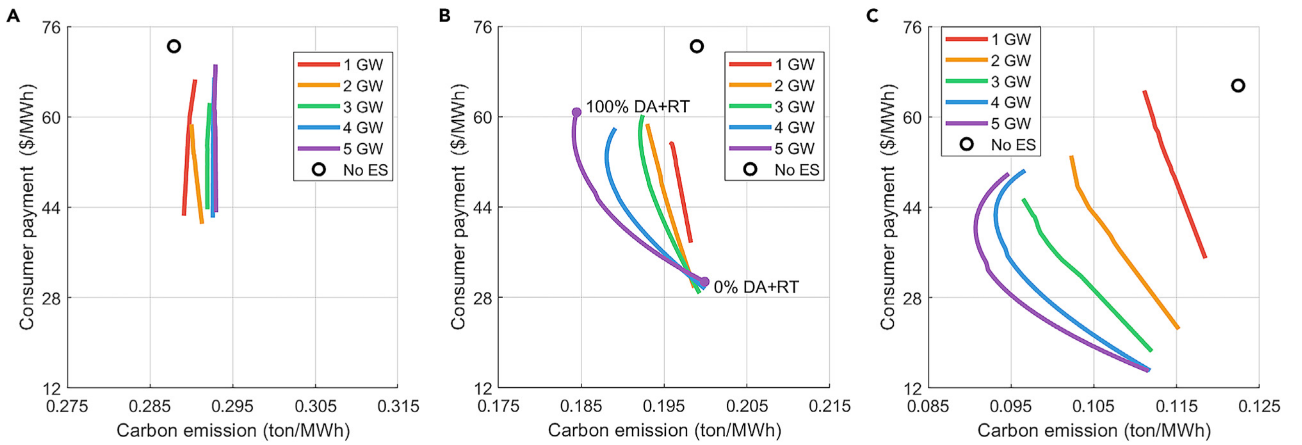

Figure 4. Pareto frontier of average consumer payments and carbon emissions

(A–C) (A) Low wind penetration; (B) medium wind penetration (C) high wind penetration. Legends: 1 GW to 5 GW indicate the total storage capacities in day-ahead and real-time markets; No ES is a reference case in which the markets have no storage. Each trajectory represents the optimal consumer payment and carbon emission by varying storage ratios in day-ahead markets (with DA + RT participation) and real-time markets (with RT participation) under a specific wind and storage capacity. For example, in the purple curve in (B), 100% DA+RT (at the upper left end) indicates that all storage participants choose DA + RT participation with no storage in RT participation. Similarly, the label 0% DA + RT (at the lower right end) denotes that all storage participants choose RT participation. Note that these plots have the same x axis spacing, but the ranges differ.

payment in this study refers only to payment from the wholesale market, which takes up around 30% of the consumer's utility bill, while the rest arose from distribution grid-management and maintenance costs. Thus the payment price shown here is much lower than most utility bills in practice. We conduct Monte Carlo simulations by varying the ratio of energy storage participating in DA + RT participation from 0% to 100%, with the remaining storage participating only in real-time markets via RT participation. We record the resulting average consumer payment and carbon emission after market clearing.

Figure 4 displays the Pareto frontiers for different storage capacities and wind penetrations, illustrating the critical dependence of storage's ability to reduce consumer payment and carbon emissions based on the wind-penetration level in the power system. In the case of low wind penetration, all storage capacities result in an average generation cost reduction of approximately $25/MWh, as seen in Figure 4A. However, carbon-emission reduction is not significant in this case. Similar to our previous analysis, higher storage capacity leads to reduced system costs but increased carbon emissions in the absence of sufficient renewable capacity.

With increasing wind capacity, energy-storage participation in electricity markets shows clear and efficient Pareto frontiers, with higher storage capacity being more effective in reducing both carbon emissions and consumer energy bills. Figures 4B and 4C illustrate this trend, with higher storage capacity pushing Pareto frontiers toward the lower left of the plot. Storage shows a significant effect in reducing consumer payments. At 1 GW capacity, storage can reduce the payment by $34.8/MWh (48%) in the medium-wind scenario and $30.6/MWh (46.6%) in the high-wind scenario. At 5 GW capacity, the reduction amount increased to $41.7/MWh (57%) and $50.5/MWh (77%), respectively. Notably, the range of change in consumer payment is significantly higher than that of system generation cost, as shown in Figure 2. The driving factor is due to price spikes. Higher wind capacity introduces higher volatility in the system, which increases the occurrence of price spikes due to the more frequent dispatch of peaker unit generations. Although peaker units cause only small increments in generation cost, the impact on consumer payments is significant due to the marginal pricing principle in electricity pool markets, as their marginal fuel cost set the market-clearing price. Therefore, the participation of energy storage in real-time markets reduces the occurrence of price spikes and significantly lowers consumer payments.

Similar to our prior analysis, a higher ratio of storage in day-ahead markets is more effective in reducing carbon emissions, while storage participation in real-time markets is more effective in reducing consumer payments. However, the ratio needs to be carefully selected to achieve optimal outcomes. For example, in the case of high wind penetration with 5 GW storage capacity, as shown in Figure 4C, a ratio of 0.83 produces the optimal consumer payment and carbon emission of \$32.85/MWh and 0.0922 T/MWh. Changing the ratio to 1 can increase 52% consumer payment and 3% carbon emission simultaneously (to \$49.95/MWh and 0.0947 T/MWh). The ratio affects the trade-offs between affordability and sustainability. Solely pursuing the aim of carbon-emission reduction can greatly increase the energy bills for consumers. In the most significant case with high wind penetration and 5 GW storage capacity, as shown in Figure 4C, storage participation options can lead to a 53% change of consumer cost reductions, factored as maximum price difference of the curve normalized by the no-storage case, and 16% change of emission reductions, factored similarly based on the maximum-emission difference. Overall, the Pareto frontier analysis recommends having more storage participating in day-ahead markets to reduce carbon emissions, while having more storage only participating in real-time markets to reduce consumer costs.

Comprehensive analysis of different market participation options

In this section, we aim to provide a more comprehensive analysis of storage's contribution to decarbonization under different market participation options, i.e., DA, RT, and DA + RT, by considering four different factors: storage profitability, which describes how much profit can the storage earn per capacity unit; market-volatility mitigation, which describes how much storage can contribute to reducing market-price volatility; economics, which describes the total operating cost of the system; and sustainability, which describes the total carbon emission. We consider both a low storage capacity scenario (0.5 GW) and a high storage capacity scenario (2 GW), accompanied by low- and high-wind penetrations.

As shown in Figures 5A and 5B, our first finding is that DA+RT participation is superior to DA in nearly all aspects, and such superiority becomes more apparent as wind generation increases. This result aligns with our previous analysis of generation costs and carbon emissions. We also observe that RT and DA + RT participation options have similar scores at low wind penetration. However, under high wind penetration, RT participation outperforms DA + RT in the low storage capacity scenario, as shown in Figure 5B. In the high storage capacity scenario, as shown in Figure 5D, the two participation choices show trade-offs, in which DA+RT provides fewer carbon emissions. In contrast, RT provides lower generator operational costs and better market-volatility mitigation.

DISCUSSION

Our study shows that energy storage's market participation choices are crucial in balancing economic and sustainability objectives during power system decarbonization. Using an agent-based market simulation framework, we compare the impact of different storage market participation choices on generation cost, carbon emissions, and consumer payments in power systems. Our findings indicate that day-ahead and real-time markets have asymmetrical effects on generation costs and carbon

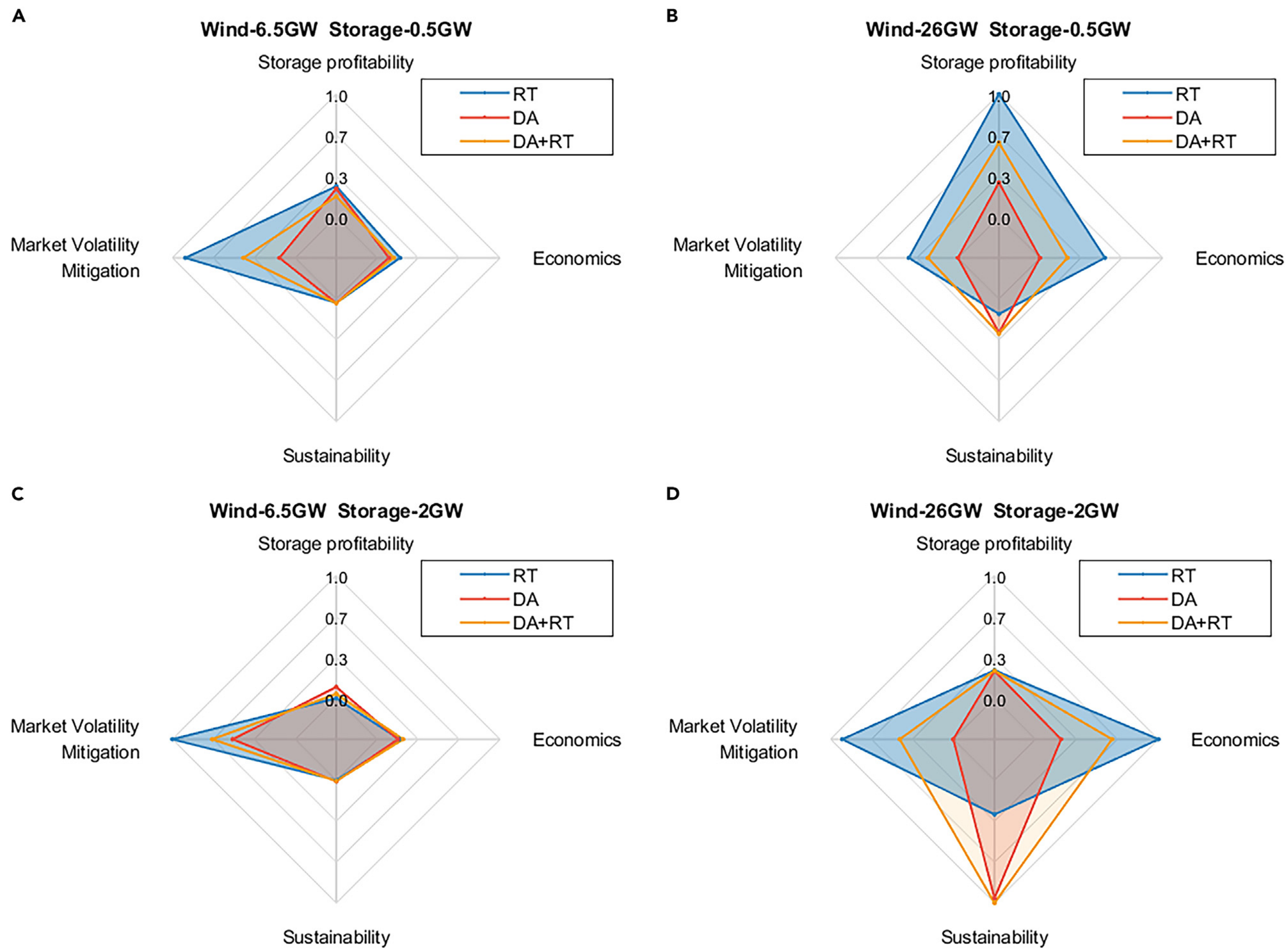

Figure 5. Comparison of DA, RT, and DA + RT participations under different wind scenarios and storage capacities
(A–D) (A) Low wind/low storage; (B) high wind/low storage; (C) low wind/high storage; (D) high wind/high storage. Here, the low/high storage indicates the storage capacity in markets is 0.5–2 GW, which accounts for about 4%–16% of load demand, respectively. Economics indicates electricity generation costs; storage profitability denotes storage arbitrage profits from the markets; sustainability reflects carbon emission; market volatility mitigation measures the standard deviation of real-time electricity prices for consumers. A low score for market volatility mitigation indicates that the real-time market has more price spikes and larger deviations, which makes the market riskier. The area of each participation choice on the radar plot represents the overall score. The score of each criterion is normalized between 0 to 1. Details of normalization can be found in supplemental information, where a score of 0 represents the worst outcome over all scenarios, and 1 represents the best.

emissions. Day-ahead market participation is most effective for utilizing storage to reduce carbon emissions, as higher storage capacity would reduce the capacity of committed generators. However, this approach increases system costs and market-price variability, as the system operator must dispatch peak generators more frequently to mitigate renewable fluctuations. Real-time market participation is more efficient for utilizing storage's flexibility to mitigate demand and renewable variability, which provides more system cost savings and more storage profits. However, the benefits saturate quickly as storage capacity increases. This problem arises from existing market designs that require storage to bid as a combination of generator and load. To fulfill this requirement, storage must design bids by speculating price predictions instead of based on physical costs. As the system-wide storage capacity increases, it becomes more difficult for storage to accurately predict market prices accounting for its own and peer storage's strategic actions. As a result, storage bids become more deviated from the system's actual conditions, leading to an increase in overall generation costs and carbon emissions.

Given the same total system-wide storage capacity, the consumer cost of electricity and carbon emissions vary significantly depending on storage market choices, i.e., the ratio of storage participating in day-ahead or real-time markets. These variations form Pareto frontiers, trading off economics and emissions, showing that deeper decarbonization requires a higher cost of electricity. In practice, storage participants may have different market preferences based on their risk preferences. For instance, some may prefer real-time markets for higher profit expectations, while others may opt for day-ahead markets for more stable returns. Moreover, regulatory requirements such as resource-adequacy or reserve-market obligations may also impact storage's decision on whether to participate in day-ahead, real-time markets, or both. For example, California mandates all utility-scale storage to bid into day-ahead markets to meet resource-adequacy requirements. However, data from the California ISO shows that some storage units submit unreasonably high bids in the day-ahead market to avoid being cleared, effectively reserving their capacity to arbitrage more volatile real-time prices.[41] These results underscore the significance of understanding storage participants' motives and market preferences and the impact of regulations and incentives on storage's market choices.

In conclusion, our study finds that existing electricity market designs are not well prepared for deep decarbonization, as the motives of storage participants can easily misalign with social welfare. Achieving decarbonization while maintaining affordable electricity requires careful coordination between energy-storage deployments, market participation strategies, and the growing renewable capacity to balance economic and decarbonization objectives. However, energy-storage owners in deregulated power systems prioritize revenue returns over other objectives. Our results show that price prediction accuracy is critical for storage to bid their opportunity values accurately into real-time markets. This suggests that intermediate markets between day-ahead and real-time, such as intra-day markets or coordinated day-ahead and real-time participation, could improve storage utilization by allowing participants to adjust their market positions and bids based on updated system conditions. Additionally, improved market design is necessary to better model storage's opportunity value in real-time market dispatches, such as incorporating look-ahead real-time dispatch or SoC-dependent bidding models. Finally, future power system operations should include mechanisms and incentives for storage to charge from renewable resources in dispatch optimization. While there are existing policies that incentivize storage to charge from co-located renewable generations,[42] there are currently no models for systematically matching storage with renewable sources in unit commitment and economic dispatch. Such models, coupled with decarbonization incentives, would be crucial for aligning economic and decarbonization goals in energy-storage market participation.

Lastly, our study is centered on the electricity pool market design, which aims to address the current challenge of integrating storage in North American markets, such as California. However, our findings also highlight the need for a systematic investigation of storage integration in other forms of market designs, especially in the European electricity market, where market participants have access to more trading options, such as intraday markets. This results in more sophisticated market participation strategies and, hence, a more complex analysis. Additionally, our simulation considers real-time market clearing at an hourly resolution, while many North American system operators have recently switched to sub-hourly real-time market clearings.[43] This settlement may increase storage's effectiveness in reducing system costs and increasing storage profits. Therefore, our real-time market estimation in case studies serves as a lower bound of storage performance in real-world real-time markets. Future studies must thoroughly understand

and facilitate storage's role in cost-efficient decarbonization in different market designs and clearing timeframes.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used ChatGPT version GPT-3.5 in order to enhance the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact Bolun Xu (bx2177@columbia.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

Original data for this paper, as well as the code used for simulation and analyses, are archived at a public repository.[44] These resources are also available on Github: https://github.com/Huskyseen/Storage_Market.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2023.05.014.

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AUTHOR CONTRIBUTIONS

Conceptualization, B.X., X.Q., and H.S. methodology, X.Q. and B.X. investigation, X.Q. and B.X. writing original draft, X.Q., B.X., I.L., H.S., and Y.G. writing—review and editing, X.Q., B.X., I.L., and Y.G. funding acquisition, B.X. resources, I.L., Y.G., H.S., and B.X. supervision, B.X., H.S., I.L., and Y.G.

DECLARATION OF INTERESTS

B. Xu is a technical advisor to Storylitcs, working on simulation modeling of grid-scale energy storage, and Sensai Analytics, working on data analytics and machine-learning solutions for grid-interactive batteries.

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