Participation of Battery Energy Storage in European Electricity Markets: Day-Ahead to Balancing

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***Abstract*—Battery energy storage systems (BESS) can provide fast, bidirectional flexibility and participate across multiple market layers. This paper develops and compares two optimization models for joint day-ahead energy and reserve market participation. The *strict* model requires the BESS to always be able to deliver the full reserve it offers, while the *intraday-correction* model allows reserve activation to be corrected on the intraday market. Using realistic day-ahead prices and representative reserve payments, we quantify how intraday correction changes optimal reserve offers, state-of-charge trajectories, and revenue composition. Results show that allowing intraday correction relaxes the effective energy constraint, increases feasible reserve provision in specific hours, and improves overall profitability.**

***Index Terms*—battery energy storage, multi-market participation, day-ahead market, intraday market, flexibility**

I. Nomenclature

A. Model parameters

$P^{\max}$	Rated battery power (MW)
$E^{\max}$	Energy capacity (MWh)
η^{ch}, η^{dis}	Charging and discharging efficiency
Δt	Time step length (h)
τ	Intraday correction delay (h)
α_t	Expected activation ratio (0–1) at time t
π_t^{DA}	Day-ahead energy price (EUR/MWh)
π^{RES}	Reserve capacity payment (EUR/MW)
π_t^{act}	Expected activation-related revenue term (EUR)

B. Optimization variables

P_t^{DA}	Day-ahead energy position at time t (MW)
R_t^u, R_t^d	Upward/downward reserve capacity at time t (MW)
P_t^{ch}, P_t^{dis}	Charging and discharging power at time t (MW)
SOC_t	State of charge at time t (MWh)
$P_t^{ID,u}$, $P_t^{ID,d}$	Intraday correction for upward/downward activation at time t (MW)

II. Introduction

Modern power systems are confronting simultaneous challenges of variable renewable generation, electrification of end uses, and tighter operational constraints, all of which increase the need for fast and scalable flexibility across time scales. The resulting requirement is not only to balance energy but also to manage uncertainty, ramps, and reserve availability with limited thermal backup. Flexibility therefore becomes a central planning and operational objective, and comprehensive reviews emphasize the central role of battery technologies and storage systems in enabling reliable, low-carbon power systems [1], [2]. Battery energy storage is uniquely positioned in this transition because it can both shift energy and deliver rapid bidirectional response, making it a key enabler for integrating renewables while maintaining reliability [3].

In market settings, battery storage can participate in multiple layers by arbitraging price differences in the day-ahead and intraday markets while also providing reserve capacity and activation services. Reviews of the evolving electricity market landscape emphasize that such participation couples energy and ancillary services decisions and requires careful management of state of charge, availability, and market timing to avoid infeasible or unprofitable offers [4], [5]. Recent work on the impacts of storage on power markets further highlights the importance of coordinated bidding across products and the role of market rules in shaping revenues [6]. Building on this context, this paper analyzes how a BESS should participate jointly in reserve and day-ahead markets and how intraday correction of reserve activation changes the optimal strategy.

A. Related Work

A large body of work studies co-optimization and bidding across energy and ancillary service products, typically for storage or flexible generation. Ramp-rate limitations and uncertain reserve activation have been incorporated explicitly when computing robust adjustable energy trading policies across day-ahead, intraday, and secondary reserve timescales [7]. In the applied aFRR context, Merten et al. develop an optimization-based bidding strategy for battery energy storage in the secondary control reserve market (aFRR) and evaluate revenue potential under realistic market rules [8]. Multi-market scheduling of battery storage within renewable portfolios has also been studied in [9], emphasizing day-ahead and ancillary market coordination. Recent work continues to emphasize that multi-market participation outperforms single-market strategies and that realistic intraday trading assumptions matter for implementable strategies [10].

Offering secondary frequency control creates stochastic energy deviations relative to an energy-market schedule; in European market designs, intraday trading provides a practical lever for balance-responsible parties to offset these deviations before real-time settlement. Merten et al. highlight the complexity of translating reserve activation into a feasible dispatch and bidding policy [8]. The storage-trading literature has begun to formalize joint strategies that combine reserve participation with continuous intraday trading to manage state recovery and opportunity costs [11].

Many studies quantify the value of stacking reserve revenues with energy-market scheduling while respecting SoC feasibility, efficiency losses, and cycling/degradation constraints. The aFRR-focused work of Merten et al. and related multi-market bidding formulations highlight the importance of activation modeling and intraday corrections for ex-post profitability [8], [11]. Broader work on integrated energy and reserve participation confirms that co-optimization yields value but depends on market rules and uncertainty [12], [13].

The literature establishes (i) the economic rationale for joint energy-and-reserve bidding and (ii) the need to model reserve activation and physical constraints in implementable strategies. However, there is limited work that explicitly designs an intraday trading layer whose primary purpose is to correct the energy deviation caused by aFRR activation under the rules of smaller European markets. This paper addresses that gap by proposing and comparing two market-consistent models: (1) a strict deliverability model and (2) an intraday-correction model with a two-hour correction delay. The case study focuses on a typical European market and product-specific requirements (minimum bid size, gate closure times, and settlement rules) can be swapped to analyze specific European market designs.

III. Market Structure and Participation Strategies

In this work, we consider the common European timeline for energy and balancing products:

- **Reserve market (RM):** hourly reserve schedules and price for capacity formation.
- **Day-ahead market (DAM):** hourly schedules and energy price formation.
- **Intraday market (IDM):** schedule updates closer to real time (continuous and/or auctions).
- **Operation:** Payments for activated reserve (Balancing energy)

Trading follows the timeline below. The day before, at 9:00, reserve is traded for the following day. A couple of hours later, at 12:00, day-ahead energy is traded. On the following day, real-time operation starts and the system operator may require reserve activation. This reserve must be available regardless of activation frequency. Upon activation, the BESS can participate in the intraday market according to the trading timeline. Here, we assume that activation happens in hour h. When that hour ends, the BESS owner knows the amount of energy activated and can correct the deviation by trading energy in hour $h+1$ and actually producing/consuming the traded energy in hour $h+2$. This process is depicted in Fig 1.

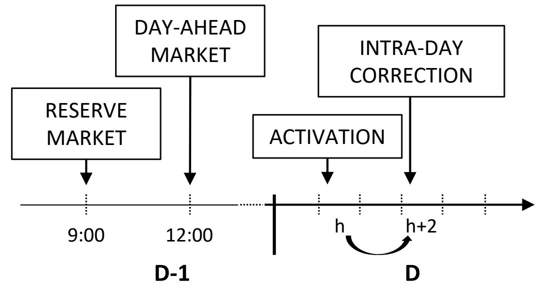

Fig. 1. Market clearing timeline for day-ahead, intraday, and balancing products.

This market structure is typical for many European electricity markets. In Fig 2, typical day-ahead price patterns are depicted. The clear cyclical nature of prices provides an opportunity for arbitrage that the BESS can exploit. These prices are adopted in the following optimization model. Since the focus of this paper is not exact profit analysis but rather a trading strategy demonstration, intraday prices are assumed to be the same as day-ahead prices.

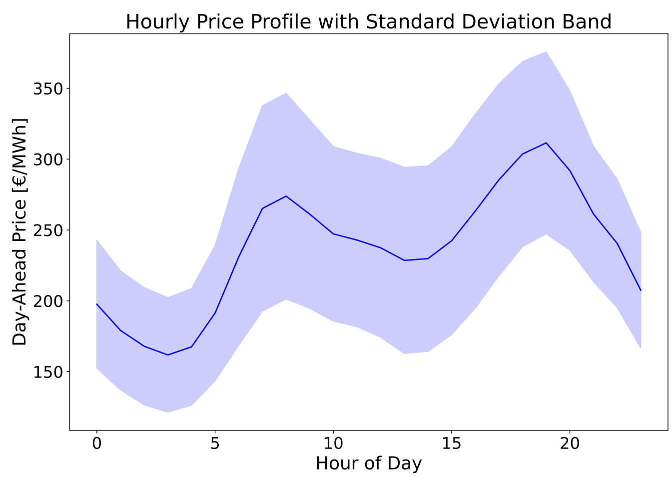

Fig. 2. Hourly day-ahead price profile (2022) used for the case study. The mean profile and dispersion motivate time-varying arbitrage opportunities.

IV. Optimization Models

We formulate two deterministic optimization models on hourly time steps. Let $t \in \mathcal{T}$ index the operating horizon. A positive power denotes discharge (sell), and negative denotes charge (buy). The BESS has rated power $P^{\max}$, energy capacity $E^{\max}$, and efficiencies η^{ch}, η^{dis}.

Following the market structure defined above, the objective of both models is the following:

$$\max \sum_{t \in \mathcal{T}} \Big(\pi_t^{DA} P_t^{DA} + \pi^{RES} (R_t^u + R_t^d) + \pi_t^{act} \Big), \quad (1)$$

The objective comprises three components: day-ahead profit, reserve capacity profit, and activation profit. In the strict model, π_t^{act} is computed directly from the activated reserve and the day-ahead price:

$$\pi_t^{act} = -\alpha_t^u \pi_t^{DA} R_t^d + \alpha_t^d \pi_t^{DA} R_t^u. \quad (2)$$

In the intraday-correction model, π_t^{act} depends on the day-ahead to intraday price spread after the correction delay:

$$\pi_t^{act} = -\alpha_t^u(\pi_t^{DA} - \pi_{t-\tau}^{DA})R_t^d + \alpha_t^d(\pi_t^{DA} - \pi_{t-\tau}^{DA})R_t^u. \quad (3)$$

It is important to emphasize that this model assumes an activation frequency determined by a random parameter α_t. Since it is out of the scope of the paper to examine activation patterns, a simple activation pattern is assumed.

The main constraints, common to both models, follow the technical capabilities of the BESS. To distinguish between charging and discharging operation, the following constraint is adopted.

$$P_t^{DA} = P_t^{dis} - P_t^{ch}, \quad \forall t \in \mathcal{T}. \quad (4)$$

Distinguishing between charging and discharging operation is necessary to properly represent charging and discharging efficiencies in the state-of-charge dynamics. These dynamics are defined in the following constraint:

$$SOC_t = SOC_{t-1} + \eta^{ch} P_t^{ch} \Delta t - \frac{1}{\eta^{dis}} P_t^{dis} \Delta t, \quad \forall t \in \mathcal{T}. \quad (5)$$

Finally, these variables need to be bounded:

$$0 \leq P_t^{ch}, P_t^{dis} \leq P^{\max} \quad (6)$$

$$0 \leq SOC_t \leq E^{\max} \quad (7)$$

It is important to emphasize that these constraints assume no activation in the operating stage and that operation is driven by day-ahead trading.

To take reserve trading into account, the model needs to ensure that there is enough capacity in both power and energy for the BESS. Power adequacy is ensured with the following constraints:

$$P_t^{DA} + R_t^u \leq P^{\max}, \quad P_t^{DA} - R_t^d \geq -P^{\max}, \quad \forall t \in \mathcal{T}. \quad (8)$$

Reserve must also be bounded:

$$R_t^u, R_t^d \geq 0. \quad (9)$$

Regarding the energy aspect of the BESS, two distinct approaches have been considered as follows.

A. Strict reserve deliverability model

The strict model assumes the BESS must always be able to deliver the full offered reserve, implying separate trajectories for full upward and full downward activation. Let SOC_t^u and SOC_t^d denote the hypothetical SoC trajectories under full upward and full downward activation. The constraints are:

$$P_t^{DA} + R_t^u = P_t^{dis,u} - P_t^{ch,u}, \quad (10)$$

$$P_t^{DA} - R_t^d = P_t^{dis,d} - P_t^{ch,d}. \quad (11)$$

$$SOC_t^u = SOC_{t-1}^u + \eta^{ch} P_t^{ch,u} \Delta t - \frac{1}{\eta^{dis}} P_t^{dis,u} \Delta t, \quad (12)$$

$$SOC_t^d = SOC_{t-1}^d + \eta^{ch} P_t^{ch,d} \Delta t - \frac{1}{\eta^{dis}} P_t^{dis,d} \Delta t. \quad (13)$$

These extreme trajectories of SOC must be constrained within the energy capacity of the BESS:

$$0 \leq SOC_t^u, SOC_t^d \leq E^{\max} \quad (14)$$

This enforces that the reserve offer is feasible under either extreme activation throughout the horizon. It is this strict requirement that limits the reserve profit and overall economic feasibility of BESS.

B. Intraday-correction model with two-hour delay

In the second approach, activation energy is corrected via intraday trades. We model this by allowing a recourse trade $P_t^{ID,u}$ (for upward activation) and $P_t^{ID,d}$ (for downward activation) τ hours after the activation, with $\tau = 2$ hours. The activation balance is:

$$P_t^{DA} + R_t^u - P_t^{ID,u} = P_t^{dis,u} - P_t^{ch,u}, \quad (15)$$

$$P_t^{DA} - R_t^d + P_t^{ID,d} = P_t^{dis,d} - P_t^{ch,d}, \quad (16)$$

and the recourse timing is enforced by

$$P_t^{ID,u} = R_{t-\tau}^u, \quad P_t^{ID,d} = R_{t-\tau}^d, \quad \forall t > \tau. \quad (17)$$

The SoC dynamics remain as in the strict model, but the intraday trades neutralize the energy impact of activation after two hours. The expected activation term in the objective then reflects the day-ahead to intraday price spread.

V. Case Study

We use hourly day-ahead prices from the regional market. Reserve capacity payments are modeled with a flat price representative of aFRR availability. Battery parameters are listed in Table I.

TABLE I
Battery parameters used in the case study.

Parameter	Symbol	Value
Rated power	$P^{\max}$	1 MW
Energy capacity	$E^{\max}$	10 MWh
Charging efficiency	η^{ch}	0.95
Discharging efficiency	η^{dis}	0.95
Intraday correction delay	τ	2 h

We evaluate two scenarios over a full year (8760 hours): (i) **Strict reserve deliverability**, and (ii) **Intraday correction** with a two-hour delay. The optimization is deterministic and uses expected prices and full activation, enabling direct comparison of the structural impact of intraday recourse. Full activation is unrealistic but serves only to demonstrate model capabilities.

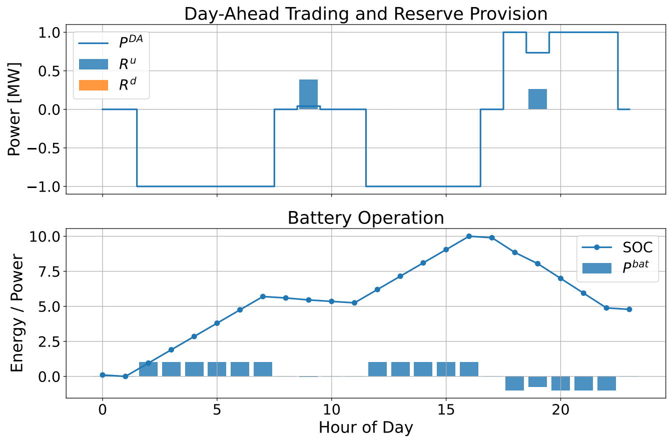

Fig. 3. Representative day under strict reserve deliverability.

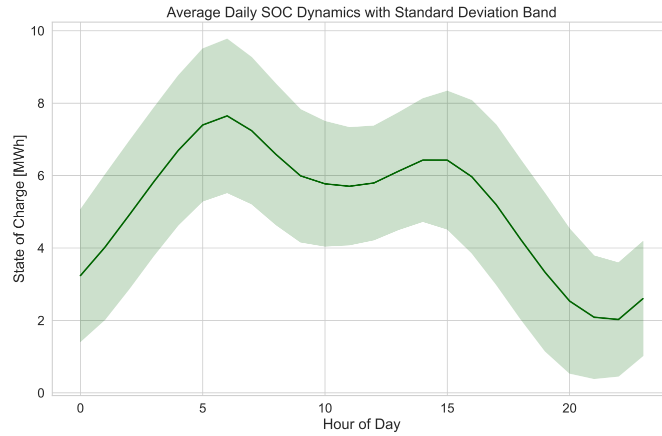

Fig. 5. Average daily SoC dynamics with variability under strict deliverability.

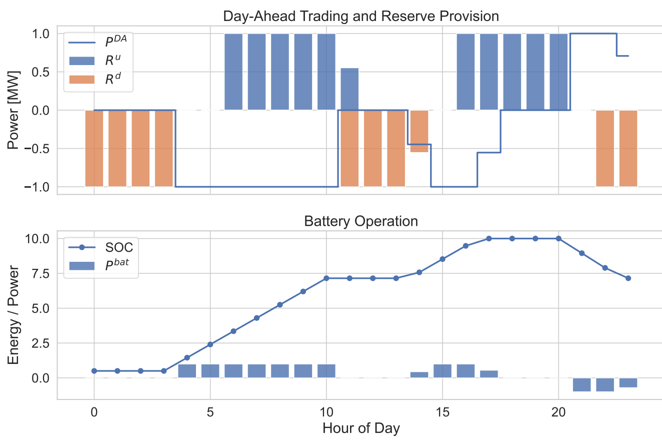

Fig. 4. Representative day with intraday correction (two-hour delay).

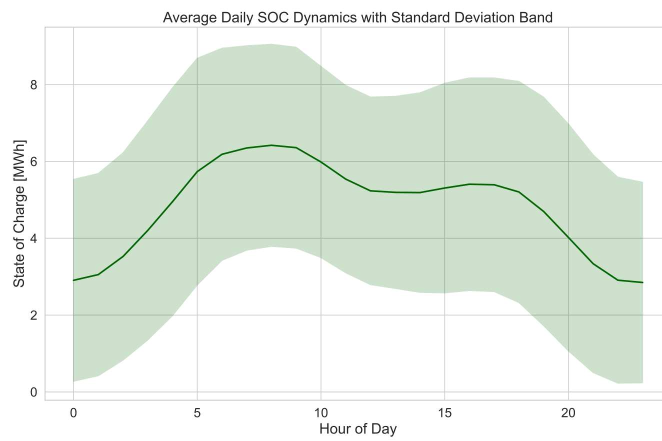

Fig. 6. Average daily SoC dynamics with variability under intraday correction.

VI. Results

Figures 3 and 4 compare a representative day of dispatch and reserve offers. Under strict deliverability, the battery limits reserve volumes during hours where full activation would violate SoC bounds. With intraday correction, the BESS can temporarily deviate and later rebalance, leading to higher reserve participation without violating energy constraints.

Figures 5 and 6 show average daily SoC profiles with variability bands. The strict model keeps SoC away from bounds to maintain deliverability for full activation, while the intraday-correction model allows deeper excursions and quicker recovery, reflecting the ability to rebalance after activation.

Heatmaps in Figs. 7 and 8 highlight the hours and seasons when reserve is offered. The intraday-correction model expands feasible reserve provision in price-scarce hours, particularly when SoC would otherwise need to be conserved for worst-case activation.

Figure 9 decomposes revenues into energy, reserve capacity, and activation-related components. Allowing intraday correction shifts revenue from conservative energy positioning to higher reserve capacity utilization and improved activation economics. It is important to emphasize that the assumption in this particular simulation is full activation ($\alpha_t = 1$). This assumption results in unrealistically high activation revenues. Hence, the result shown in Fig 9 cannot be used as a general conclusion but rather as an example of a trading strategy.

VII. Conclusion

This paper develops and compares two optimization-based trading models for BESS participation in day-ahead and reserve markets. The results demonstrate that permitting intraday correction two hours after activation materially alters reserve offers, SoC trajectories, and revenue composition. The strict deliverability model is conservative and tends to understate the value of reserve participation when intraday trading is available, while the intraday-correction model captures a more realistic operational pathway by allowing the battery to rebalance after activation. For Croatia and similar European markets, the feasibility of this strategy depends on intraday liquidity, gate closure times, and settlement rules. The two-hour delay assumption should be adapted to market-specific conditions, and future work could incorporate stochastic ac-

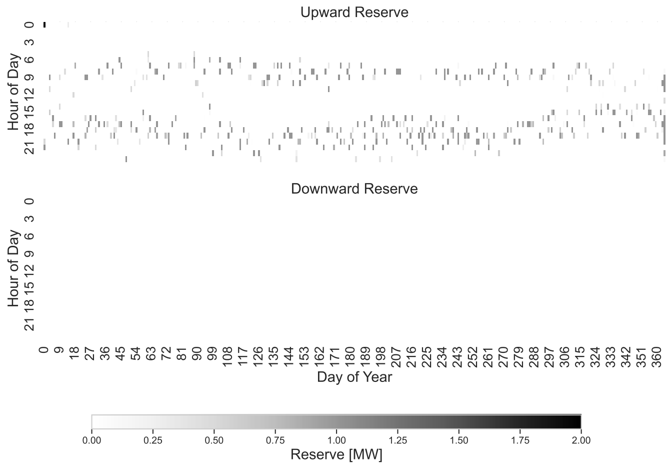

Fig. 7. Reserve offer heatmap under strict deliverability.

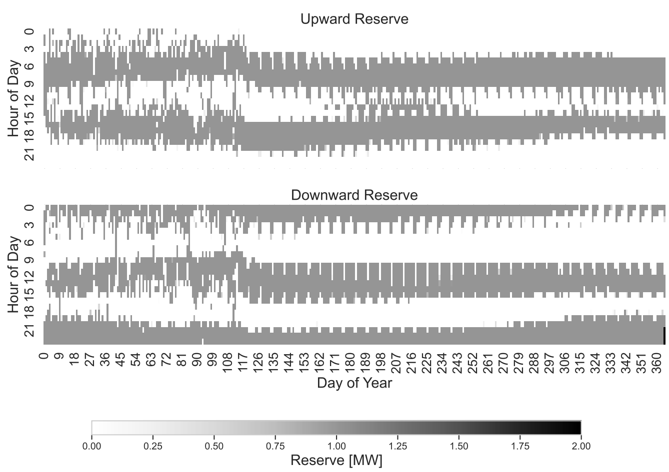

Fig. 8. Reserve offer heatmap under intraday correction.

tivation, intraday price uncertainty, and explicit degradation costs.

Funding

This research was funded by the project **FLEXSYS—Implementation of Flexibility Sources and Advanced Control Algorithms for Supporting Modern Power Systems with a High Share of Renewable Energy Sources**, IP-UNIST-05, funded by the European Union – NextGenerationEU. The views and opinions expressed are solely those of the author and do not necessarily reflect the official positions of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

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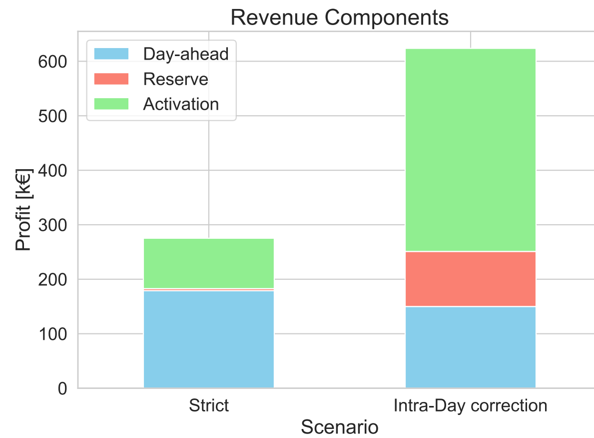

Fig. 9. Revenue decomposition across scenarios. Intraday correction increases reserve-related revenues while maintaining feasible energy scheduling.

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