Analysis and Optimization of Battery Energy Storage Systems in Energy Markets

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***Abstract*— This article explores the optimization of Battery Energy Storage Systems (BESS) in energy markets, emphasizing their role in decarbonization by storing excess renewable energy and mitigating grid constraints. BESS enables energy transition by facilitating energy arbitrage, frequency regulation, and grid stabilization, essential for integrating variable renewable sources. Focusing on the UK energy market, the study highlights the favorable policies and investments driving BESS deployment. It examines revenue streams, including Day-Ahead and Intraday markets, ancillary services, and balancing mechanisms, particularly dynamic services like frequency regulation. Challenges such as gas market volatility and regulatory hurdles are also discussed. The proposed market optimization model simulates BESS operations, revealing consistent revenue potential influenced by market conditions and regulatory frameworks. The study underscores BESSs critical role in stabilizing grids, supporting renewables, and enhancing energy security while calling for further research on equipment degradation and broader impacts on energy systems and pricing.**

***Index Terms*-- Energy storage, Energy markets, Renewable energy integration, Ancillary services.**

I. INTRODUCTION

Mitigating Climate Change is an urgent global challenge due to its far-reaching effects, including rising temperatures, sea levels, and extreme weather events, all of which impact human health, biodiversity, and economies. Governments, public entities, and industries have prioritized addressing Climate Change, leading to significant investments in Renewable Energy Sources (RES) like solar, wind, hydro, and geothermal, as a means to reduce dependence on fossil fuels and lower greenhouse gas (GHG) emissions [1][2].

RES have minimal operational-phase emissions compared to fossil fuels, which continuously emit GHG during combustion [3]. However, integrating RES into the energy system introduces challenges due to their variability; generation depends on natural resource availability rather than consumer demand. This mismatch between generation and demand can stress the grid, leading to issues such as voltage and frequency instability, transmission problems, and the lack of dispatchability [4].

The traditional grid, designed for centralized power plants with one-way power flows and reduced flexibility, is increasingly incompatible with the rise of Distributed Energy Resources (DER) such as rooftop solar panels, wind farms, and electric vehicles. Modernization of the grid is essential to accommodate DER and ensure reliable energy delivery. Key modernization strategies include Demand Side Management, Smart Grid Technologies, and Energy Storage Systems (ESS).

Smart Grid Technologies enhance grid flexibility through advanced sensors, communication networks, and data analytics, optimizing the use of existing resources. ESS is a critical component of this transformation, storing the excess energy to be used according to system needs. ESS bridge the gap between variable RES generation and demand, improving grid stability, efficiency, and energy security.

ESS technologies include solutions like Pumped Hydroelectric Storage, Compressed Air Energy Storage, and BESS. These systems mitigate grid stress caused by RES variability, support the continued growth of renewable energy, and provide a promising investment opportunity for enterprises. As RES adoption accelerates, the development and integration of technologies like ESS are indispensable for ensuring a sustainable, reliable, and decarbonized energy future [5].

The case study concerns a BESS operating in the UK energy market. The UK has emerged as a leader in BESS deployment due to favorable government policies and substantial investments in renewable energy and storage technologies. The study delves into different revenue streams available for BESS, including the Day-Ahead and Intraday markets, ancillary services, and the balancing mechanism, with a special focus on dynamic services like frequency regulation. The study also identifies challenges such as gas market volatility, regulatory hurdles, and the need for further market integration.

The methodology includes a proposal of an optimization model for BESS operation in the electricity market, using the

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data of the UK energy markets such as the Day-Ahead and Intraday markets, and evaluates how balancing mechanisms and dynamic services contribute to profitability. The simulation results show that while BESS can generate consistent revenues, market conditions such as price fluctuations, the regulatory frameworks and the amount of revenue streams available can significantly impact the revenue performance.

II. LITERATURE REVIEW

BESS have been evolving very quickly and the same applies to its applications on several aspects of energy systems, particularly on the electricity markets. The literature shows some studies from this perspective, namely on how BESS can offer significant potential for participation in electricity markets, providing opportunities for energy arbitrage and ancillary services.

Studies have shown that BESS can generate profits by exploiting price volatility in energy markets across different regions [1]. Optimal sizing and scheduling of BESS are crucial for maximizing revenue, with participation in both energy and reserve markets yielding the best results [8]. The integration of BESS in energy communities can increase community income, though the impact on social welfare and fairness should be considered [9]. To fully leverage BESS potential, a thorough understanding of market regulations and mathematical modeling of various services is essential. This includes analyzing opportunities in ancillary services, day-ahead, and real-time markets, as demonstrated in the California Independent System Operator (CAISO) market study [10]. Article [11] proposes a bi-level optimization framework to investigate the optimal market operation strategies of price-maker battery energy storage systems in energy and ancillary services markets, considering battery degradation cost.

Building upon previous studies, this paper delves deeper into the specific role of government policies, market structures, and revenue streams for BESS, including dynamic services, balancing mechanisms, and the capacity market. It introduces an innovative optimization methodology tailored to the UK market, incorporating real-world factors such as market prices and operational constraints. The methodology is validated through simulations using real market data, providing actionable insights into effective market participation strategies. Unlike many reviewed studies that rely on artificial test systems or focus narrowly on specific BESS applications like energy arbitrage, this paper offers a comprehensive analysis of various market structures (e.g., Day-Ahead, Intraday, Dynamic Services). It further examines their interaction with BESS, addressing critical challenges such as the influence of gas price volatility on market performance.

III. EMPOWERING THE ENERGY TRANSITION: BESS IN MODERN ENERGY MARKETS

BESS have emerged as transformative solutions within energy markets, playing a critical role in enhancing grid stability and enabling the integration of renewable energy sources (RES). Their ability to both import and export energy positions them as significant contributors to energy market operations and decarbonization strategies.

A. Integration with Renewable Energy Sources

When paired with distributed energy resources (DER) such as photovoltaic (PV) plants or wind farms, BESS can store surplus energy during peak generation periods and release it during high demand or market opportunities. This capability helps address the variability of RES, mitigating grid issues like overvoltage and congestion while maintaining frequency within safe operational limits. By performing "peak shaving," BESS stabilize the supply-demand curve and reduce system operator constraints.

B. Challenges and Enablers

The economic viability of BESS is influenced by various factors, including DER penetration, government incentives, and technological advancements. Favorable policies, such as tax credits and subsidies, are essential for reducing initial investment costs and encouraging adoption. However, in many regions, BESS are restricted to self-consumption, limiting their potential for revenue generation. Allowing BESS to participate in energy auctions (Day-Ahead, Intraday, etc.) enables energy arbitrage, where energy is stored during low-cost periods and sold during high-demand, high-cost periods. This practice benefits both storage owners and grid operators [13].

C. BESS potential roles and benefits

BESS are uniquely suited for ancillary services due to their rapid response capabilities. They can address frequency regulation and voltage support needs almost instantaneously, unlike conventional power plants that require hours to respond. By providing reactive power and supporting stable voltage levels, BESS enhance overall grid reliability. Their ability to quickly absorb or release energy makes them critical for balancing intermittency from RES [14][12].

Beyond economic incentives for investors, BESS offer numerous advantages for grid management:

- Frequency regulation and voltage support, contributing to ensure stable grid operations by rapidly addressing fluctuations.
- Mitigating intermittency when paired with RES, improving reliability and dispatchability.
- Load shifting and peak shaving to reduce the need for costly peak power plants, lowering energy prices and operational stress.
- Capacity firming, delaying/avoiding the need for new energy facilities by optimizing existing capacity.
- Islanded operation, enabling localized energy independence, reducing grid complexity and serving as an emergency backup during outages.

D. Economic and Operational Impact

BESS contribute to reducing energy costs during peak periods and minimizing grid expansion. By alleviating stress on the grid, they simplify operations for system operators and enhance the resilience of energy systems.

ESS represent a vital component in modernizing energy markets, supporting renewable energy integration, and ensuring grid stability. Their flexibility in providing both energy and ancillary services positions them as indispensable tools for achieving decarbonization and energy transition goals. Continued policy development and technological innovation are key to unlocking their full potential.

IV. Methodology and Test Case

The optimization strategy considers the Day-Ahead Market (Hourly and Half-Hourly), Intraday Market, and Balancing Mechanism by utilizing publicly available market prices, to simulate the operation of a real-life BESS in the UK.

The algorithm combines these prices to determine the optimal bids for each Settlement Period throughout the day. As these markets primarily operate on a half-hourly basis, each day will be divided into 48 Settlement Periods (SP).

Key parameters were configured to align closely with those used in the real operation of the BESS, such as the number of daily cycles and State of Charge (SoC) limits. While alternative parameter values, such as maintaining the SoC between 20% and 80%, might be theoretically better for battery health, the simulation prioritized using realistic values to ensure more reliable and practical results.

The objective function aims to maximize profit from bids placed in the Day-Ahead Hourly and Half-Hourly Markets, Intraday Market, and Balancing Mechanism. Spot prices from the previous day, which are publicly available at the time of bidding, will be utilized. Day-Ahead and Intraday prices will be sourced from OFGEM, the regulator of electricity and gas markets in Great Britain [28], while Balancing Mechanism prices will be obtained from Elexon, the company responsible for managing the balancing and settlement of the wholesale electricity market in Great Britain [15].

$$max\ Profit = \sum_{i=1}^{48} \begin{aligned}(&-DA_H(i)\cdot Buy_{DAH}(i) \\ &+DA_H(i)\cdot Sell_{DAH}(i) \\ &-DA_{HH}(i)\cdot Buy_{DAHH}(i) \\ &+DA_{HH}(i)\cdot Sell_{DAHH}(i) \\ &-ID(i)\cdot Buy_{ID}(i) \\ &+ID(i)\cdot Sell_{ID}(i) \\ &-BM(i)\cdot Buy_{BM}(i) \\ &+BM(i)\cdot Sell_{BM}(i)\end{aligned} \quad (1)$$

Where:

- DAH(i): Spot Price for the Day-Ahead Hourly Market at the settlement period (SP) i
- BuyDAH(i), SellDAH (i): Buy and sell bids in MWh for the Day-Ahead Hourly Market at SP i
- DAHH(i): Spot Price for the Day-Ahead Half-hourly Market at SP i
- BuyDAHH(i), SellDAHH(i): Buy and sell bids in MWh for the Day-Ahead Half-hourly Market at SP i
- ID(i): Spot Price for the Intraday Market at SP i
- BuyID(i), SellID(i): Buy and sell bids in MWh for the Intraday Market at SP i
- BM(i): Spot Price for the Balancing Mechanism at SP i
- BuyBM(i), SellBM(i): Buy and sell bids in MWh for the Balancing Mechanism at SP i

It is important to note that the trading day does not run from 00:00 to 24:00 but instead spans from 23:00 on the previous day to 23:00 on the delivery day. This is because, for energy to be traded at 00:00, the nearest Settlement Period for Hourly markets will be at 23:00, and at 23:30 for Half-hourly markets. The BESS simulation was implemented with the following settings:

$$Cap = 27\ MWh \quad (2)$$

$$BidCap \in [0;\ 27]\ MWh \quad (3)$$

$$TradingCap = 2.7 \times Cap = 72.9\ MWh \quad (4)$$

$$TotalTrading = \sum_{i=1}^{48} \begin{aligned} &Buy_{DAH}(i) + Sell_{DAH}(i) \\ &+Buy_{DAHH}(i) + Sell_{DAHH}(i) \\ &+Buy_{ID}(i) + Sell_{ID}(i) \\ &+Buy_{BM}(i) + Sell_{BM}(i) \\ &\in [0;\ TradingCap]\ MWh \end{aligned} \quad (5)$$

$$InitialSOC = 0.05\ Cap \quad (6)$$

$$MinSOC = 0.05\ Cap \quad (7)$$

$$SOC_i = \begin{cases} InitialSOC, & for\ i = 1 \\ SOC_{i-1} + Buy_{DAH}(i) + Sell_{DAH}(i) \\ \quad +Buy_{DAHH}(i) + Sell_{DAHH}(i) \\ \quad +Buy_{ID}(i) + Sell_{ID}(i) \\ \quad +Buy_{BM}(i) + Sell_{BM}(i), & for\ i \in [2;48] \end{cases} \quad (8)$$

$$0 \le Buy_i \le BidCap, \quad i \in [1;48] \quad (9)$$

$$0 \le Sell_i \le BidCap, \quad i \in [1;48] \quad (10)$$

$$TotalTrading \le TradingCap \quad (11)$$

$$MinSOC \le SOC_i \le Cap, \quad i \in [1;48] \quad (12)$$

Where:

- Cap represents the available capacity of the BESS.
- SOC represents the State of Charge
- BidCap represents the Bidding Capacity for each SP and it can be adjusted according to the exploitation strategy, within the Cap limits.

- TradingCap is the trading capacity limit per day.
- TotalTrading is the sum of the total capacity traded in all the markets during the day, which must not exceed the trading capacity set for the day (TradingCap).

Equations (2)-(5) are the bounds imposed on the capacity and trading. The constraints (6)-(8) define the limits of the State of Charge (SOC) of the BESS operation. Although SOC is usually expressed as a percentage, capacity values will be utilized in the simulation.

If analyzing a single day in isolation, the most profitable setup would involve setting InitialSOC to 100% and MinSOC to 0%. However, considerations for battery health and long-term operational strategy must also be factored in. Starting the following day with an immediate need to buy energy might not be optimal, especially if the first Settlement Periods (SPs) are more favorable for selling.

The variable SOC(i) represents the State of Charge for each of the 48 SPs, monitoring the batteries' status throughout the day to ensure the simulation adheres to real-world constraints and minimizes equipment degradation. Fully discharge would significantly impact its State of Health (SOH) and is not advisable for long-term operation.

The BESS typically operates within state-of-charge (SOC) limits of 20% to 100%, balancing profitability with equipment maintenance. However, in specific situations, the lower SOC limit can be extended down to 5%. These limits were adopted in the simulation.

V. Results

This chapter focuses on analyzing the simulation results of BESS operations across various markets. The simulation examines the Day-Ahead (DA) Hourly and Half-Hourly Markets, the Intraday Market, and the Balancing Mechanism. While the actual BESS can also operate in Dynamic Services (DC, DR, DM), Firm Frequency Response, and the Capacity Market, these were not considered in this study.

The availability of market data influenced the scope of the analysis. Historical data for DA Hourly and Balancing Mechanism prices were publicly accessible online. However, obtaining historical data for DA Half-Hourly and Intraday prices proved more challenging, as comprehensive datasets required paid subscriptions from OFGEM and other sources, which were not feasible for this research. The analysis primarily relied on data from the Spring of 2024, when real-time data was accessible.

Despite these limitations, the study was able to explore diverse scenarios, including days with high DA Hourly Market Prices and days with negative DA Hourly Prices due to elevated renewable energy penetration. Additionally, cases were analyzed where Balancing Mechanism prices were consistently positive across Settlement Periods (SPs) and others where many SPs had negative prices.

To align with practical considerations and reduce exposure to unpredictable prices, a bid limit of 5 MWh was imposed. This restriction also reflected the results of prior studies and operational strategies.

A. *Day-Ahead and Intraday Markets*

The first analysis considered the BESS could only operate in the DA Hourly, Half-Hourly and ID Markets to make a first estimation of the possible profits.

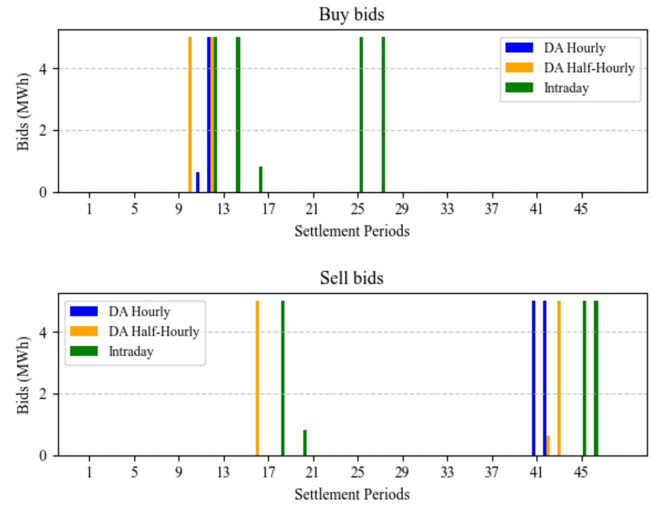

Figure 1. Bids from worst day on Day-Ahead and Intraday Markets

In this case, the profits between 48% and 81% of maximum potential, which corresponds to the situation of a perfect prices forecast. The implemented tool used prior day prices; naturally, an adequate forecasting tool would be employed in real-life operations.

B. *Including Balancing Mechanism (BM)*

The second set of tests incorporates the BM markets, which are defined by highly volatile prices driven by real-time grid imbalances, making precise predictions challenging. BM trades are executed near the delivery time, giving BESS assets a distinct advantage over generators that need longer lead times to activate. In this market, it is more practical to use the prices from the previous (SP) rather than the previous day's prices, as BM prices are influenced by the system's immediate conditions rather than the daily supply and demand patterns.

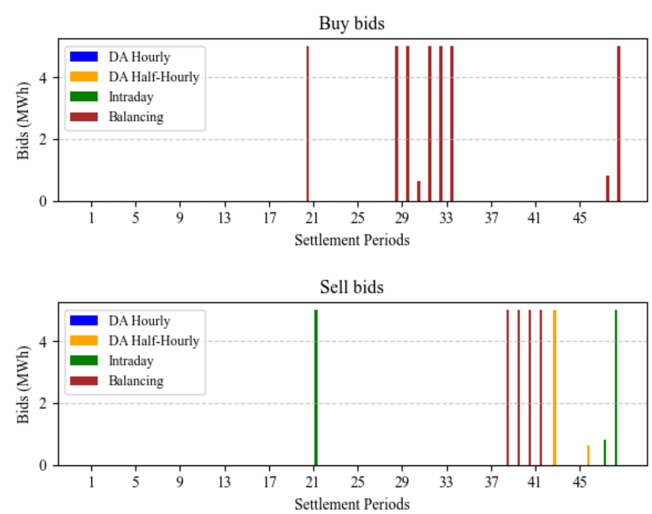

Figure 2. Bids of a day with the inclusion of the Balancing Mechanism

The revenue variability increased significantly with the BM inclusion. BM offered revenues between £1878 and £3930/day, representing 48% to 87% of the maximum possible profit. BM is a favorite of BESS due to real-time adaptability, more favorable prices and exclusion of slower generators.

C. Including Dynamic Services (DS)

These markets operate under regulatory pricing rules and require guarantees of capacity availability for grid stabilization.

Real-world operations, which combined Dynamic Services and other markets, generated average revenues of £3800/day, surpassing the simulation's £2749/day. This can be explained by two main factors. First, Dynamic Services provide a significant revenue flow, consistently exceeding £1000 per day and sometimes reaching over £3000, even without including other markets. Second, through Revenue Stacking, the BESS can earn from overlapping revenue streams. For example, the inclusion of Non-Physical Trading in the algorithm allows the asset to trade more capacity than it physically handles by combining buy and sell bids for the same delivery time and importing/exporting the difference. Similarly, current regulations permit overlapping Dynamic Services and other bids (e.g., DC and BM), enabling double rewards and maximizing revenue. These findings emphasize the importance of participating in Dynamic Services and diversifying revenue sources for optimal profitability.

VI. Conclusion

The study highlights the profitability of Battery Energy Storage Systems (BESS) in various energy markets, influenced significantly by the regulatory framework and market availability. Traditional markets like Day-Ahead (DA) and Intraday (ID) generated daily revenues up to £2600 for a 27 MW BESS. Including Balancing Mechanism (BM) and Dynamic Services increased this to over £6000, with potential to exceed £10,000/day when Capacity Markets are considered. Dynamic Services, particularly, provided consistent and substantial revenue.

The findings emphasize BESS's role in grid stability, renewable energy integration, and achieving Net Zero objectives. However, market saturation risks and declining ancillary market revenues pose challenges, potentially impacting both profitability and system safety. It suggests incentivizing BESS to prioritize grid-supportive services.

Concerns arise about how these changes might affect consumer energy prices, especially with increased fictional and competing transactions by market entities. Further research is required to assess long-term impacts on retail pricing and forecast reliability.

Future work should include larger data samples, accounting for equipment degradation in profitability models, and developing algorithms to balance risk and profit strategies. Additionally, studies on the economic viability of BESS investments and their influence on consumer energy prices are essential for understanding the broader implications of evolving energy markets.

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