Battery Energy Storage Systems in Different Countries for Arbitrage Services

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***Abstract*—This paper explores the feasibility and profitability of battery energy storage systems in different countries for arbitrage services. The study utilizes an improved algorithm designed to analyze and optimize battery energy storage systems deployment for energy arbitrage in diverse energy markets. The algorithm considers various factors such as energy prices, demand, battery cycling costs, and efficiency. The analysis focuses on quantifying the arbitrage profit in distinct countries, taking into account their unique energy market structures and electricity price dynamics. The conclusion drawn from this comprehensive study is that energy storage arbitrage facilitated by battery energy storage systems can indeed be profitable. This profitability, however, is contingent on the specific market conditions and regulatory frameworks in different countries. The findings of this paper underscore the potential of battery energy storage systems as a viable and lucrative solution for energy arbitrage, contributing significantly to the evolving discourse on energy storage and grid flexibility.**

Keywords—Battery energy storage systems, Energy arbitrage, Energy prices, Arbitrage profit, Rule-based algorithm

I. INTRODUCTION

Renewable energy (RE), battery energy storage systems (BESS), and arbitrage are all interconnected concepts that have gained significant traction in recent years [1]. As our world continues to face the dire consequences of climate change and the depletion of fossil fuels, the demand for sustainable, clean and efficient energy solutions has reached unprecedented heights [2], [3]. In this context, RE sources such as solar, wind and hydroelectric power have emerged as viable alternatives to traditional fossil fuels [4], [5]. However, the intermittent nature of these sources has given rise to the need for effective energy storage systems [6]. BESS have proven to be a key solution, facilitating the efficient management and use of RE [7] and not leading to a disruption in any services [8]. Furthermore, the systems have enabled a new realm of economic opportunities, particularly in the form of energy arbitrage which offers profit potential for investors [9], [10]. RE, harnessed from natural resources like sunlight, wind and water, offers a clean and sustainable alternative to traditional fossil fuel-based energy generation. As the technology behind RE sources continues to advance, their costs have decreased and their adoption rates have increased dramatically [11]. Governments and corporations around the world are increasingly investing in RE infrastructure, motivated by the desire to reduce greenhouse gas emissions, strengthen energy security and stimulate economic growth [12]. Despite the undeniable benefits of RE, its intermittent nature poses a significant challenge. Solar and wind power, for instance, are dependent on weather conditions which can vary greatly over time [13]. This variability can lead to fluctuations in energy supply, making it difficult to maintain a consistent and reliable energy grid. To address this issue, BESS have emerged as a critical component of modern energy infrastructure. These systems store energy generated during periods of high production and release it when demand is higher or production is lower, ensuring a steady and reliable power supply [14]. The growing adoption of BESS has given rise to new economic opportunities in the form of energy arbitrage [15]. Arbitrage, in the context of energy markets, refers to the practice of buying energy when prices are low and selling it when prices are high, capitalizing on price differentials to generate profit [16]. By utilizing BESS, investors can store RE during periods of low demand and abundant supply and then sell it during peak demand or when supply is constrained, thereby capturing the price differential. This not only contributes to the stability of the energy grid but also promotes the further adoption of RE sources by making them more economically attractive [17]. The interplay between RE, BESS and energy arbitrage has profound implications for the future of our energy landscape. As the world continues to shift away from fossil fuels and embraces sustainable energy solutions, these interconnected concepts will play an increasingly important role in promoting the widespread adoption of RE sources. At the same time, they offer significant profit potential for investors, further incentivizing the growth and development of clean energy infrastructure. As we move forward, understanding the intricate relationships between these concepts will be essential for navigating the complexities of our rapidly evolving energy ecosystem.

BESS have emerged as a crucial component of modern energy infrastructure, offering a wide range of technical advantages that facilitate the integration and efficient management of RE sources [18]. One of the primary benefits of BESS is their ability to provide grid stability and reliability by addressing the intermittency of RE sources such as solar and wind power [19]. Due to their inherent variability, these sources can result in fluctuations in power generation, leading to grid instability [20]. BESS help to mitigate this issue by storing excess energy during periods of high generation and releasing it when needed, ensuring a consistent and steady power supply [21], [22]. Furthermore, BESS offer rapid response times and high ramping rates which enable them to respond to sudden changes quickly and efficiently in energy demand or supply [23]. This characteristic is particularly valuable in maintaining grid frequency regulation and voltage support, as BESS can inject or absorb power within milliseconds, helping to preserve the overall stability and resilience of the energy grid. In addition, BESS can effectively accommodate the distributed nature of RE generation, allowing for the seamless integration of smaller, decentralized power sources into the grid which reduces the reliance on centralized fossil fuel-based power plants [24]. Another technical advantage of BESS is their ability to provide demand side management solutions such as peak shaving and load shifting [25]. Peak shaving involves using stored energy to meet periods of high demand, reducing the need for additional, often expensive, peaking power plants [26]. On the other hand, load shifting refers to the practice of shifting energy consumption from high-cost periods to lower cost periods, optimizing energy usage and reducing overall energy costs [27]. These demand side management capabilities not only enhance the efficiency and flexibility of the energy grid but also contribute to reduced greenhouse gas emissions by minimizing the need for fossil fuel-based power plants during periods of high demand.

In the context of energy markets, arbitrage plays a vital role in promoting market efficiency, enhancing grid stability and offering profit potential for investors [28]. By capitalizing on the price differentials that exist between different time periods or geographic locations, energy arbitrage helps to balance supply and demand dynamics and contributes to the overall stability of the energy grid [29]. The practice of buying low-cost energy, often generated during periods of low demand or abundant RE production and selling it when prices are higher due to increased demand or constrained supply, not only supports grid stability but also incentivizes the further adoption and development of RE sources by making them more economically attractive [30]. The importance of arbitrage is further magnified with the increasing integration of BESS into the energy infrastructure [31]. As BESS enable the efficient storage and release of energy, they facilitate the execution of arbitrage strategies by allowing investors to capitalize on the inherent price volatility in energy markets [32]. In turn, this helps in order to reduce price fluctuations and promote a more stable and predictable energy market, benefiting both consumers and producers. Moreover, the arbitrage can foster competition among energy suppliers, driving innovation and encouraging the adoption of more efficient and environmentally friendly energy generation technologies. This competitive pressure can come up with lower energy prices for consumers and stimulate economic growth by reducing overall energy costs for businesses and households. Additionally, the profit potential offered by energy arbitrage can attract investments into the energy sector particularly in RE and storage technologies, accelerating the global transition towards a sustainable energy future [33]. The aim of this paper is to develop an arbitrage strategy, by taking into account the charging and discharging schedule of a battery system based on production data and electricity prices, for BESS in a power plant. An improved algorithm has been designed to analyze and optimize battery energy storage systems deployment for energy arbitrage in diverse energy markets in different countries.

II. METHODOLOGY

A comprehensive approach for battery arbitrage in a power plant, aiming to maximize profits by optimizing the charging and discharging schedule of a battery system based on production data and electricity prices has been presented. In order to evaluate the efficiency of the proposed algorithm battery aging and the resulting profits calculated has also been considered. A power plant with a specific generation capacity and a battery energy storage system have been selected for this study. The power plant used in the study is a combination of energy sources with historical production data available for analysis. The BESS has a defined capacity, efficiency and charging/discharging rates that are essential for our battery arbitrage algorithm which has been developed in MATLAB to optimize the battery arbitrage process based on the collected production data and battery capacity. A simple flow diagram of the algorithm is given in Figure 1 and is used by using parameters which are given in Table 1.

TABLE I. INPUTS OF ALGORITHM

Parameters	Value
Reference Power Plant Installed Power	10 MW
Battery Capacity (Power/Energy)	10 MW/20 MWh
Minimum State of Charge	%10
Maximum State of Charge	%95
Efficiency of Inverter	%95
Battery Degradation Constant (Ka)	0.021

The algorithm aims to maximize profits by charging the battery during periods of low electricity prices and discharging it when prices are high. The algorithm also accounts for the relationship between battery aging and the charging/discharging cycles. As the battery undergoes more charge and discharge cycles, its capacity and efficiency decrease which may affect the overall profit maximization strategy.

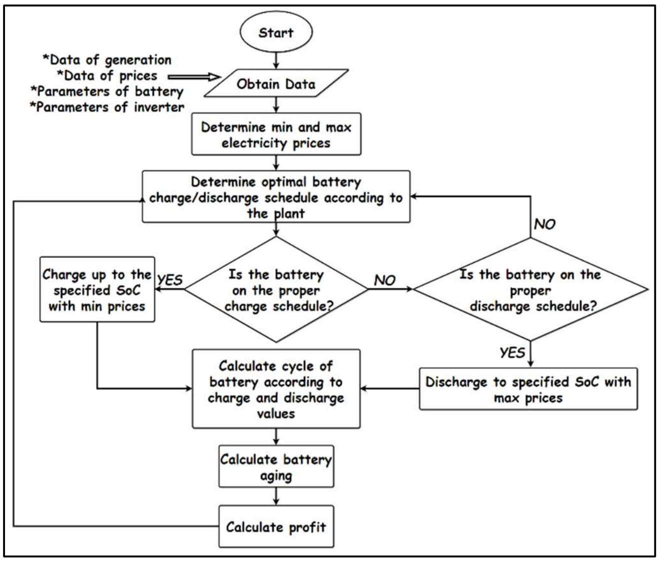

Fig. 1. Flowchart of the algorithm

The benefit can be defined as the revenue generated from selling energy at high electricity prices minus the cost of charging the battery during periods of low electricity prices.

The earnings calculation also takes into account the costs associated with battery degradation. The algorithm calculates profits by tracking revenue generated during discharge periods and subtracting the costs associated with charging the battery and battery degradation which has been calculated. This allows us to evaluate the efficiency of the arbitrage strategy and its impact on the overall profitability of the power plant.

III. ANALYSIS AND RESULTS

In this study, historical electricity market prices of Turkiye, Spain, France, and Portugal has been used to show the potential of arbitrage profit by BESS. The generation profile of a power plant that is shown Figure 2 has also been used. The prices of countries sourced from an open-source electricity market transparency platform is shown Figure 3. To determine potential revenue from the battery usage an analysis performed, and then the battery's aging computed in each scenario.

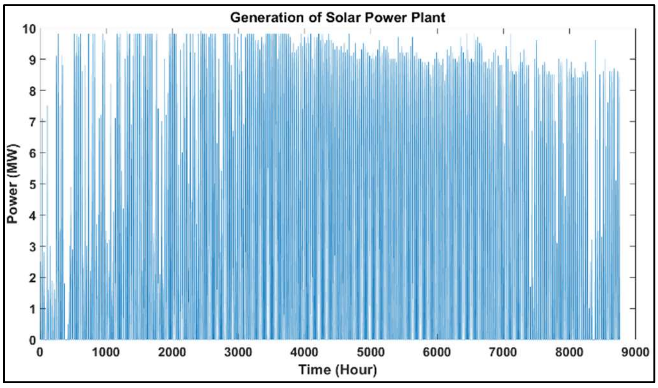

Fig. 2. Generation of solar power plant

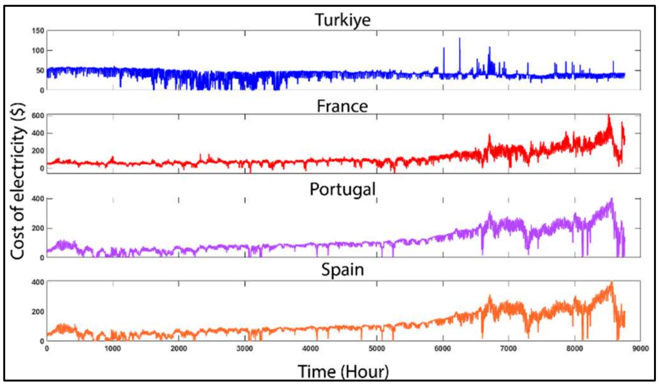

Fig. 3. Price of electricity according to countries

A. Scenario 1

In the present analysis, a scenario in which a solar power plant has ceased production has been considered. Under such circumstances all the energy that the plant produces is injected directly to the grid. As a result, the battery in this case will stay empty and will take the opportunity to arbitrage whenever possible. In the applied algorithm, specific periods are chosen for the battery to charge and discharge. The algorithm ensures that the battery charges when the electricity prices are at their lowest and discharges when the prices peak. This strategic operation of the battery is a way to take advantage of the fluctuating electricity prices thereby maximizing the profit from the arbitrage. In addition to these strategic operations, the algorithm also calculates the total cost of charging and discharging the battery. This is done by multiplying the amount of electricity used for charging or discharging by the respective electricity price during that period. The result of this calculation provides an insight into the total expenditure involved in the operation of the battery both when it is charging at a low price and discharging at a high price. Furthermore, the algorithm also takes into account the wear and tear of the battery. It calculates the battery's cycle which is the number of times the battery has gone through a complete charge and discharge and the battery's aging which is the decrease in its capacity over time. This is critical because the battery's capacity to store energy decreases as it ages affecting its efficiency and lifespan. These detailed analyses are visually represented in Figures 4 and 5 respectively.

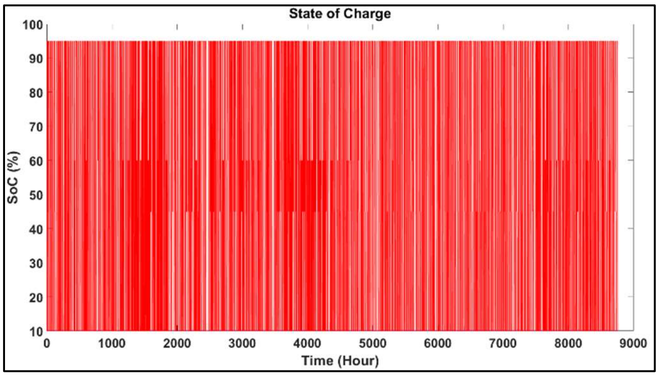

Fig. 4. Battery state of charge without excessive production

Figure 4 illustrates the state of battery charge when the energy storage system is not sourcing power from a power plant but solely purchasing electrical energy from the grid and subsequently selling it back. In this particular case, the battery energy storage system is engaged exclusively in energy arbitrage.

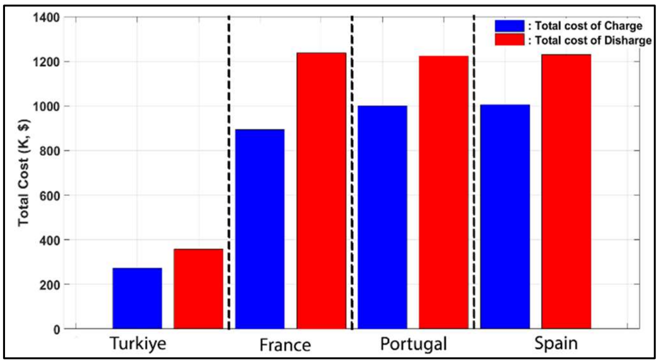

Fig. 5. Cost of arbitrage without excessive production

Figure 5 presents a comprehensive comparison between the total cost incurred in purchasing electrical energy from the grid and the total revenue gained from selling it back to the grid under this specific scenario. In this case, the battery cycle calculated by means of the developed algorithm is 390 and the battery aging is 1.2%.

B. Scenario 2

In the analysis considered as second scenario, the solar power plant has residual production, implying that any leftover energy produced by the plant is stored in the battery. As a result of this, the battery will not always be empty and available for arbitrage which means its operation will be more complex and will need to be handled strategically. The algorithm we have developed caters specifically to this situation. Specific periods are selected during which the battery is set to charge when electricity prices are at their cheapest and discharge when they are at their highest. These periods are carefully chosen to coincide with the times of residual energy production by the plant, ensuring that the most is made of the energy that would otherwise be wasted. To further understand the financial implications of this operation, the algorithm also calculates the total cost of charging and discharging the battery. It does this by taking into account the amount of electricity used for each operation and the respective electricity prices during those periods. By doing so, it provides a comprehensive understanding of the costs involved in operating the battery and how they interact with the gains from arbitrage. In addition to these cost calculations, the algorithm also factors in the wear and tear on the battery. It computes the battery's cycle - the number of complete charge and discharge operations it has undergone - and its aging which is the gradual decrease in its capacity over time due to repeated use. These factors are crucial to consider as they impact the battery's efficiency and lifespan which in turn affect its overall value and usefulness in the long term. The results of these intricate analyses are presented visually in Figures 6 and 7 respectively.

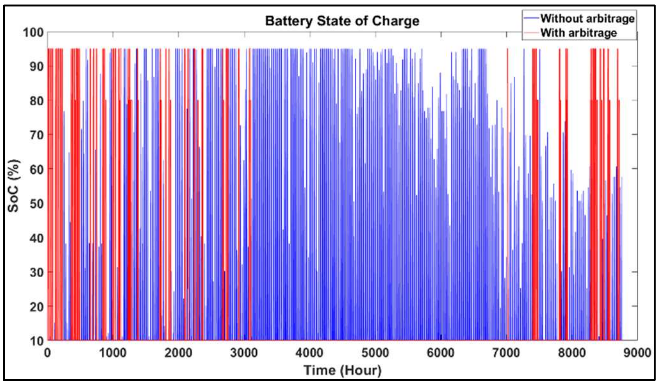

Fig. 6. Battery state of charge with excessive production

Figure 6 provides a visual representation of the battery energy storage system's operation, where the blue lines indicate periods of residual electrical energy storage from the solar power plant. In this scenario, the system is not engaged in arbitrage but instead satisfies the grid's energy demands as required. Conversely, the red line delineates periods of arbitrage, aiming to optimize battery usage and generate profit during times when the plant ceases production.

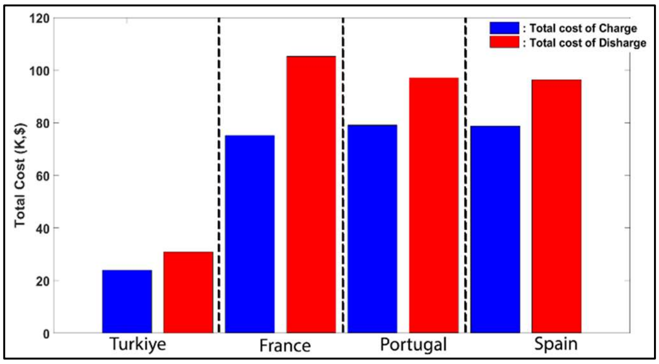

Fig. 7. Cost of arbitrage with excessive production

Figure 7 shows a detailed comparison of the overall cost of obtaining electrical energy from the grid with the total revenue gained by selling it back to the grid in this specific scenario. The battery cycle determined by the developed algorithm in this situation is 325 and the battery aging is 1.08%.

IV. CONCLUSION

We delve deeper into the implications of our findings and offer a more thorough discussion of their significance in the context of solar power plant operation and battery storage economics. Our study started with an examination of the production data from a solar power plant alongside the hourly electricity price data. This empirical evidence served as the foundation of our analysis.

Given this dataset we considered two distinct scenarios. The former is the solar power plant has ceased production completely. In this scenario, all energy from the plant goes directly to the grid, leaving the battery empty and available for arbitrage. The battery in this state could leverage price fluctuations in the electricity market, charging during periods of low prices and discharging when prices are high.

The latter scenario is one where there is residual production from the solar power plant. In this case any surplus energy generated by the plant would be stored in the battery. With the battery not always being empty, its availability for arbitrage is limited. To navigate these scenarios, we developed an algorithm that strategically determines the optimal periods for charging and discharging the battery based on the fluctuating electricity prices. Through this we aimed to maximize the benefits of arbitrage and calculate the potential profits that could be generated from such operations.

However, it's essential to note that battery operations are not devoid of costs. Beyond the direct costs associated with charging and discharging there are also indirect costs related to the battery's lifecycle and aging. The repeated use of a battery gradually decreases its capacity, affecting its efficiency and lifespan which in turn impacts the overall economics of the battery storage system. Our algorithm takes these factors into account, providing a more holistic understanding of the battery's operation in the context of solar power plant production. All in all, our analysis offers valuable insights into how a battery storage system can be efficiently and profitably operated in tandem with a solar power plant. It not only highlights the potential of battery storage for arbitrage but also underscores the importance of considering the costs associated with battery usage. These findings can serve as a valuable guide for energy operators and policymakers alike, paving the way for a more sustainable and economically viable energy future. Future research should focus on enhancing infrastructure of our algorithm and applicability by testing it across varied plants and battery configurations. Further, it should include complex market dynamics such as renewable energy certificates and demand response programs for a comprehensive economic evaluation. It is also vital to develop a more precise battery degradation model to understand the long-term effects of different operational strategies on battery lifespan and efficiency. Finally, a broader environmental impact analysis including lifecycle assessment of batteries and overall carbon footprint is necessary to truly understand the sustainability of these operations.

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