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ADDRESSING THE CHALLENGES TO THE INTRODUCTION OF BATTERY ENERGY STORAGE SYSTEMS IN RENEWABLE ENERGY UTILISATION SYSTEMS

OBRAVNAVANJE IZZIVOV PRI UVEDBI SISTEMOV ZA SHRANJEVANJE ENERGIJE IZ OBNOVLJIVIH VIROV V SISTEME ZA IZKORIŠČANJE ENERGIJE

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Keywords: grid stability, electricity generation intermittency, green transition, environmental resilience, widespread deployment

Abstract

The transition to sustainable energy sources is integral to addressing climate change and ensuring long-term environmental resilience. Battery Energy Storage Systems (BESS) play a pivotal role in this transition, by mitigating the intermittency of renewable energy sources such as wind and solar power. However, the widespread deployment of BESS faces significant challenges, including high implementation costs, environmental impacts, grid stability concerns and battery lifecycle management issues. This paper investigates these challenges systematically through a comprehensive literature review methodology, synthesising insights from peer-reviewed articles, conference proceedings and technical reports. Common themes and recurring challenges related to BESS implementation are identified and categorised, encompassing technical, economic, regulatory and environmental factors. Furthermore, the effective mitigation strategies and solutions proposed in the literature are analysed and evaluated for their

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feasibility and applicability. The findings underscore the importance of innovative approaches, such as second-hand battery modules, sustainable production practices, the implementation of advanced operational strategies, and predictive maintenance algorithms, in enhancing the feasibility and efficacy of BESS integration. Additionally, policy incentives and collaborative efforts with utilities and grid operators are highlighted as crucial for promoting grid resilience and reliability. This research contributes to a nuanced understanding of the complexities inherent in advancing sustainable energy infrastructures, and provides valuable insights for policymakers, industry stakeholders, and researchers seeking to address the challenges of BESS deployment in renewable energy utilisation systems.

Povzetek

Prehod na trajnostne vire energije je sestavni del obravnave podnebnih sprememb in zagotavljanja dolgoročne okoljske odpornosti. Sistemi za shranjevanje energije iz baterij (BESS) igrajo ključno vlogo pri tem prehodu, saj zmanjšujejo prekinitve obnovljivih virov energije, kot sta vetrna in sončna energija. Vendar pa se široka uvedba BESS sooča s precejšnjimi izzivi, vključno z visokimi stroški izvajanja, vplivi na okolje, pomisleki glede stabilnosti omrežja in vprašanji upravljanja življenjskega cikla baterije. Ta članek sistematično raziskuje te izzive s pomočjo obsežne metodologije pregleda literature, ki združuje vpoglede iz strokovno pregledanih člankov, zbornikov konferenc in tehničnih poročil. Skupne teme in ponavljajoči se izzivi, povezani z izvajanjem BESS, so opredeljeni in kategorizirani, kar vključuje tehnične, ekonomske, regulativne in okoljske dejavnike. Poleg tega so učinkovite strategije za ublažitev in rešitve, predlagane v literaturi, analizirane in ovrednotene glede na njihovo izvedljivost in uporabnost. Ugotovitve poudarjajo pomen inovativnih pristopov, kot so rabljeni baterijski moduli, trajnostne proizvodne prakse, izvajanje naprednih operativnih strategij in algoritmov za napovedno vzdrževanje, pri izboljšanju izvedljivosti in učinkovitosti integracije BESS. Poleg tega so politične spodbude in sodelovanje z javnimi podjetji in upravljavci omrežij poudarjeni kot ključni za spodbujanje odpornosti in zanesljivosti omrežja. Ta raziskava prispeva k natančnemu razumevanju zapletenosti, ki je neločljivo povezana z napredovanjem trajnostnih energetskih infrastruktur, in zagotavlja dragocene vpoglede za oblikovalce politik, zainteresirane strani v industriji in raziskovalce, ki želijo obravnavati izzive uvajanja BESS v sistemih za uporabo obnovljive energije.

1 INTRODUCTION

The increasing global demand for electricity, coupled with the growing penetration of renewable energy sources like solar and wind, has led to a growing interest in energy storage solutions to address intermittency and variability in power generation. Battery energy storage systems (BESS) have emerged as one of the most promising technologies for storing excess energy during periods of high generation, and discharging it during times of high demand or low generation. BESS offer various advantages, including fast response times, scalability, modularity, and the ability to provide ancillary services such as frequency regulation and voltage support. Despite their benefits, however, the widespread adoption of BESS in energy systems faces a multitude of challenges, including high initial costs, the associated negative impact on the environment, adjustment to the intermittent nature of the renewable energy sources, and managing the lifespan and performance of the components of the system. Additionally, integrating BESS into the existing energy infrastructure requires addressing technical issues such as compatibility with grid systems, optimal siting, control and management strategies, and grid stability considerations.

Understanding and mitigating these challenges are crucial for maximising the effectiveness and economic viability of battery energy storage systems in modern energy systems and achieving broader energy transition goals.

With that said, the primary aim of this research paper is to examine prominent impediments and drawbacks associated with the deployment of BESS within renewable energy utilization infrastructures systematically. Additionally, this paper seeks to analyse prospective resolutions to these challenges comprehensively, encompassing diverse methodologies for their amelioration. Finally, it aims to explicate varying strategies and approaches aimed at mitigating the identified negative aspects, thereby fostering a nuanced understanding of BESS integration, and facilitating informed decision-making in energy system optimisation endeavours.

2 METHODS

Energy storage systems form somewhat of an emerging field in the Electricity sector, which, despite being under the spotlight for the better part of the last decade, were only given the research and development emphasis required sporadically. To address this issue, this article employs a methodology based on a comprehensive literature review, to identify and investigate the challenges associated with the implementation of BESS to propose effective mitigation strategies to these challenges, and facilitate a more knowledgeable and well-informed approach to their adoption and introduction.

This includes an extensive research conducted across multiple reputable academic databases and a detailed analysis of different peer-reviewed articles, conference proceedings, feasibility studies, technical reports and legislation published between 2012 and 2023. Keywords such as "battery energy storage systems," "energy storage challenges," and "mitigation strategies" were utilised in various combinations, to ensure extensive coverage of the literature. The inclusion criteria comprised relevance to the research topic, publication in peer-reviewed journals or reputable conference proceedings, and alignment with the scope and objectives of the present study.

Common themes, patterns, and recurring challenges related to BESS implementation in energy systems are identified by reviewing and synthesising the selected literature. This is followed by applying thematic analysis techniques to categorise the identified challenges into distinct domains, such as technical, economic, regulatory and environmental factors. To address the identified challenges, the proposed mitigation strategies and solutions presented in the literature are analysed and evaluated systematically based on their feasibility, effectiveness and applicability. Ultimately, a comparative analysis was conducted to identify the consensus among the different studies, and to highlight the variations in perspectives and approaches across the various analysed sources.

3 MATERIALS

In contemporary society, the transition towards sustainable energy sources, such as wind and solar power, has emerged as an imperative strategy to mitigate the adverse impacts of climate change and ensure the long-term viability of environmental ecosystems. Concurrently, the development of effective energy storage solutions has become paramount to facilitate peak shaving and accommodate dynamic consumption patterns, thereby harmonising the adoption of renewable energy with the prevailing societal lifestyles and consumption habits, while fortifying energy resilience for future contingencies. Furthermore, it is essential to understand the impact of energy storage systems on electricity production in wind and solar power generation systems. Fig. 1 illustrates the electricity production dynamics in systems reliant on wind and solar power, elucidating the effects of omitting energy storage systems on overall production stability and efficiency.

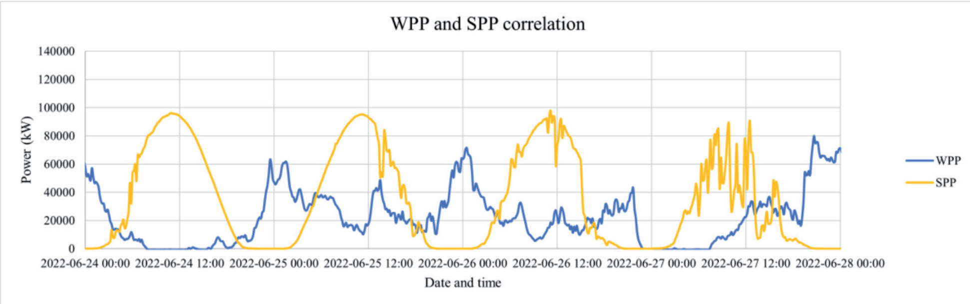

Figure 1: *Wind power plant [WPP] and solar power plant [SPP] production for a sample time period [1]*

Real-world applications demonstrate that regions with different renewable energy profiles face distinct challenges. For instance, areas with high solar irradiance, such as the state of California in the United States of America, tend to have surplus energy during the day, while regions known to utilise wind energy, like the United Kingdom, face different, almost unpredictable fluctuations when using this renewable source, due to variable wind patterns.

The US state of California is a leader in combining solar energy with BESS. In fact, battery storage is the fastest-growing resource in the California Independent System Operator (CAISO) balancing area (Fig. 2) [2], and batteries accounted for approximately 8.3% of load from hours-ending 10 to 13 in 2023, reducing the need to curtail or export surplus solar energy at very low prices.

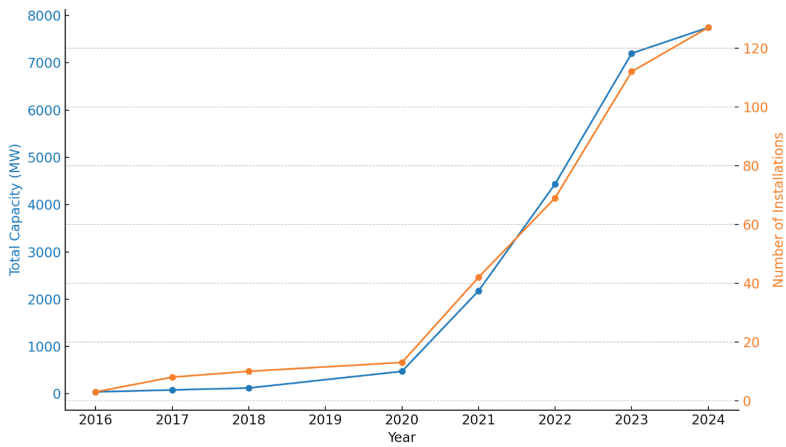

Figure 2: *Installed utility BESS for the 2016-2024 timeframe, in the CAISO balancing area*

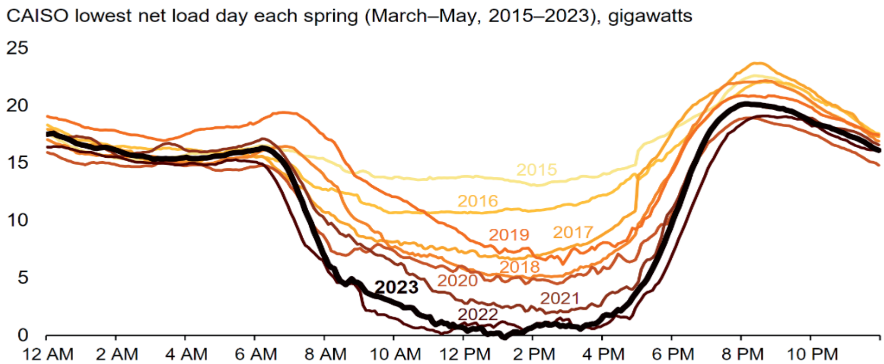

Figure 3: *CAISO lowest net load day, each spring for the March-May timeframe of 2015-2023, in gigawatts, representing the so-called California's duck curve [3]*

The intermittency of the solar energy, however, reveals a pronounced daily generation pattern characterised by peak energy production during midday, followed by a steep decline in output as the sun sets. This results in significant overgeneration during sunny days, often leading to curtailment or negative pricing, as the excess solar energy surpasses demand, while simultaneously creating challenges for grid stability, due to the rapid ramp-up required from alternative energy sources, such as batteries, to meet the evening demand [3]. California is projected to require around 50 GW of battery energy storage to meet its 2045 greenhouse gas reduction goals [4], which would also help in managing the duck curve phenomenon.

On the other hand, wind energy patterns generally show that higher wind speeds can often be expected during nighttime and early morning hours, typically aligning with lower electricity demand. Conversely, wind speeds can be lower during the afternoon, when electricity demand is often higher. In such cases, it is crucial to understand the demand pattern that the remaining local or regional power stations will have to meet, in case energy storage is not available. Fig. 4 shows a correlation of electricity demand and wind generation in the British and Irish markets, as part of the United Kingdom (UK), showing substantial space for improvement. Total wind generation in the UK increased by 18% to a record 75.4 TWh between 2019 and 2020; within it, offshore wind generation rose by over 27% to 40.7 TWh, surpassing onshore wind at 34.7 TWh (Table 1).

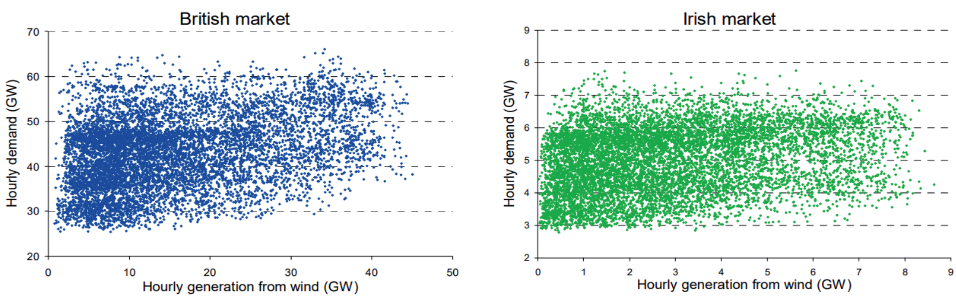

Figure 4: *Correlation between hourly wind generation and hourly electricity demand, on the British market (left) and Irish market (right) [5]*

Table 1: *UK's electricity generation from renewable sources since the year of 2020 [6]*

Type of renewable energy	**2000**	**2010**	**2018**	**2019**	**2020**
Onshore wind (TWh)	0.9	7.2	30.4	31.8	34.7
Offshore wind (TWh)	-	3.1	26.5	32.0	40.7
Solar PV (TWh)	-	0.0	12.7	12.6	13.2
Hydro (TWh)	5.1	3.6	5.5	5.9	6.8
Landfill Gas (TWh)	2.2	5.2	3.9	3.6	3.5
Other Bioenergy (TWh)	1.7	7.0	31.1	33.7	35.8
Total (TWh)	9.9	26.2	110.0	119.5	134.6

Given that renewable electricity accounted for a record 43.1% of electricity generated in the UK during 2020, it is important to note that large grid energy storage can help in stabilising the integration of renewable energy sources, by removing the variability and intermittency associated with wind farm plants, too [7]. Although the UK Government has stated that grid-scale BESS enable the UK to use electricity more flexibly and decarbonise the energy system in a cost-effective way, in 2023 the electricity output from battery storage on the grid scale was equivalent to only 1,018 GWh (Table 2).

Table 2: *Electricity output from energy storage facilities [8]*

Storage type	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Pumped storage (GWh)	2,872	2,498	1,838	1,567	1,893	1,991	1,823
Battery storage – grid scale* (GWh)	0	36	82	113	94	195	1,018
Other energy storage (GWh)	0	0	0	0	0	0	0
Total (GWh)	2,873	2,534	1,920	1,680	1,987	2,185	2,841
*Data include grid-scale battery storage, excluding small "behind the meter" batteries, such as those in domestic or commercial properties.							

The burgeoning demand for energy storage systems (ESS) mirrors the escalating adoption of sustainable energy technologies [1]. However, the utilisation of an ESS necessitates a surplus of generated power to ensure its practical functionality. Forecasts indicate a significant upscaling in the deployment of BESS [9] in the forthcoming years, underscoring the growing significance of these technologies in the energy landscape.

Critical to the effective integration of energy storage systems into existing infrastructures are the challenges inherent in their implementation. An understanding of these challenges is pivotal for achieving optimal efficiency and cost-effectiveness, while upholding the stringent environmental and social imperatives associated with climate change mitigation and sustainability endeavours.

4 RESULTS

Based on the performed research, the results section delineates four common challenges encountered in the implementation of BESS:

4.1 Cost of implementation

The initial capital outlay required for implementing battery energy storage systems often represents a substantial financial commitment, depending mainly on the power capacity of the system. This upfront investment encompasses various elements, such as the cost of battery modules, inverters, control systems, installation and site preparation. As the main component of a BESS, the cost of battery modules can vary significantly in price, depending on factors such as technology type, energy capacity and performance characteristics. When compared with technologies for energy storage with a similar level of popularity in the industry, battery energy storage systems are shown to be unprofitable in multiple studied scenarios, but they are still considered a valuable addition to the energy system [1].

4.2 Environmental Impact

Addressing environmental concerns related to battery production, disposal and recycling is increasingly important for sustainable BESS deployment, which should also involve managing the impacts. Production of batteries entails resource extraction and manufacturing processes that contribute to habitat destruction, pollution and emissions [10]. Furthermore, improper disposal of batteries at the end of their life cycle can release hazardous substances into the environment, causing harm [11].

4.3 Tailoring BESS to the intermittent nature of the energy source and stability of the grid

The general incorporation of renewable energy sources into the power grid, such as integrating wind and solar power plants, and simultaneous maintenance of constant and reliable power delivery despite fluctuations in supply and demand, presents challenges, owing to their intermittent characteristics. Moreover, managing the produced surplus electrical energy by using BESS poses additional challenges in power electronics integration and storage-system technology for investors, given the considerable impact of their variable output [12,13]. Additionally, differences in the scale of implementation influence the challenges associated with integrating BESS significantly. In a micro-grid setting, the challenges are related to managing local generation and consumption dynamics, as well as ensuring grid stability on a smaller scale. In large-scale integration, challenges arise from coordinating the interactions between multiple energy sources and addressing grid-level stability concerns across a broader geographical area.

4.4 Lifecycle Management

Managing the lifespan and performance degradation of batteries over time, including monitoring and maintenance, is essential for maximising BESS efficiency, but can be arduous. Battery degradation impacts the profitability of grid-level energy storage systems significantly, with a reduction in revenue of 12-46%, depending on the degradation model and end-of-life criteria [14].

5 DISCUSSION OF PROPOSED MITIGATION STRATEGIES

Following a better and more comprehensive understanding of the complexities inherent in advancing sustainable energy infrastructures and the most common challenges associated with the introduction of BESS in renewable energy utilisation systems, the proposed mitigation strategies to these challenges are as follow:

5.1 Cost of implementation

When assessing the profitability and feasibility of investing in BESS, investors should duly account for the ancillary financial benefits inherent to such systems. Beyond direct revenue streams, the financial viability of BESS investments is augmented by the multifaceted economic advantages they afford. BESS deployment contributes to optimising energy asset utilisation, enhancing grid reliability, and facilitating the integration of renewable energy sources, thus fostering a more resilient and sustainable energy infrastructure. Acknowledging and quantifying these ancillary financial benefits are imperative for evaluating the investment potential and overall profitability of BESS implementation in renewable energy utilisation systems comprehensively. These benefits encompass, but are not limited to, arbitrage, revenue increase of central generation capacity, revenue increase of ancillary services, transmission and distribution deferral, peaking plant capital saving, increased revenue from renewable energy sources, and reduced reliability-related and power quality-related financial losses [15].

Certain solutions, such as using second-hand battery modules, can help mitigate upfront costs and improve the financial feasibility of BESS projects. Second-hand battery modules, sourced from electric vehicles, consumer electronics, or decommissioned stationary storage systems, offer a practical alternative to purchasing new batteries for BESS applications. Investors can find suitable used batteries through various channels, including battery recycling facilities, online marketplaces, or partnerships with manufacturers and suppliers. Repurposing electric vehicle batteries in secondary applications can reduce initial costs, with government support being the most important trigger for battery reuse [16]. By giving these batteries a second life in BESS applications, investors could also contribute to environmental conservation and the promotion of a circular economy [17].

5.2 Environmental Impact

Sustainable practices throughout the battery life cycle, including responsible mining, clean production methods, and circular economy initiatives, are crucial considerations for environmental sustainability in BESS deployment. Prioritising the use of environmentally sustainable materials, investing in research and development of recycling technologies to recover valuable materials from spent batteries, and promoting circular economy principles in battery manufacturing and disposal processes, are potential approaches to mitigating the negative impact on the environment.

While the recycling of Li-ion batteries helps prevent the shortage of critical minerals from a mass flow perspective, from an environmental perspective, the currently available technologies lead to significant consumption of energy and higher air emissions than the primary production [18]. The most obvious environmental benefit of BESS is lengthening the battery's lifespan by postponing recycling (or, even worse, landfill), and ensuring the most efficient use of individual components. At some point, the batteries should still be recycled, however, reusing is preferable, since it exhausts the currently available resources. When discussing the environmental benefits, the fact that repurposing batteries reduces the need for new batteries in BESS goes without saying, but, additionally, it saves on raw materials. Compared to the effective use of original materials and manufacturing, repurposed batteries add a separate life cycle to the manufactured battery, by extending the effective useful lifespan of a battery pack by a decade when repurposed for stationary use [19].

5.3 Tailoring BESS to the intermittent nature of the energy source and stability of the grid

Implementing advanced forecasting and predictive modelling techniques can help in anticipating renewable energy generation patterns, allowing BESS to store excess energy effectively during periods of high generation and discharge during times of low generation. Namely, the intermittency can be addressed through programming of advanced management systems and incorporating balancing algorithms, enabled by specific regulatory components within the storage system, such as a controller and a scheduler [1]. This entails crafting a meticulously designed operational strategy that is not only efficient, but also finely attuned to the unique characteristics and requirements of the individual system in question, which can be achieved through astute task definition, resulting in optimisation of the system's performance as a cohesive unit. In a BESS with such an operational strategy, a scheduler determines actions for the upcoming hour, based on factors such as market prices, energy storage status, and anticipated power production over the next two hours. Upon calculating the optimal power allocations for fuel cells and grid interactions at the beginning of each hour, these Directives are conveyed to a controller. The controller's role is to maintain the prescribed values provided by the scheduler to the best of its ability, while ensuring that the system`s components operate within their specified parameters. While the scheduler relies on informed projections, should the demands exceed feasibility, the controller intervenes to safeguard the system`s integrity. In essence, the scheduler and the controller operate on different time scales, to facilitate the optimal technical and economic performance of the BESS.

The technologies and operational principles vary widely for different cases of implementation, leading to a significant diversification in the range of energy storage products available. Specifically, whereas one method may excel in evening out annual fluctuations, another might be better suited for meeting brief periods of high power demand. Therefore, it becomes crucial to have a fundamental understanding of the available technology, but also take into consideration the specifications of the renewable energy utilisation system.

Prior to modelling the operational strategy and the system's forecast model, a comprehensive evaluation of the integration scale is of great importance, considering variables such as local demand profiles and grid infrastructure. Moreover, a meticulous assessment of technical prerequisites and grid specifications is imperative, to facilitate the seamless and efficacious implementation of the BESS within the energy framework. The implementation of a deep learning-based peak forecasting model can outperform state-of-the-art techniques by 11-32%, yielding annual savings of $496,320 for a 4 MWh battery in certain microgrids [20]. At the same time, battery technologies are shown to be exceptionally good for grid-level large-scale electrical energy storage, due to their modularisation, rapid response, flexible installation and short construction cycles [21].

As an additional measure, focusing policy incentives on innovation in energy storage and grid management can tackle the issue of electricity grid management of the intermittent renewable energy sources [22]. Furthermore, participation in demand response programmes to provide grid stability services, and collaboration with utilities and grid operators to enhance grid resilience and reliability, is of great essence.

5.4 Lifecycle Management

To address this obstacle, one approach is to create predictive maintenance algorithms and monitoring systems. These tools can monitor battery performance, devise strategies to optimise battery usage and prolong the lifespan, and establish plans for environmentally compliant recycling and disposal at the end of the battery's life. By implementing a battery degradation model and a rolling look-ahead operational optimisation strategy, battery cycle life can be extended effectively and profits can be enhanced within the real-time electricity market [23]. Taking into consideration that reducing frequent charge-discharge cycles and high discharge currents can extend battery life [24], an effectively designed operational model has the potential to enhance battery life cycle management and optimise utilisation by timing the accumulation and release of energy strategically.

6 CONCLUSION

The analysis reveals that, while BESS offer significant potential for mitigating intermittency in power generation and facilitating the integration of renewable energy sources, several key hurdles must be overcome to realise their full benefits. The high initial costs of implementing BESS pose a substantial barrier to widespread adoption. However, innovative solutions, such as utilising second-hand battery modules, can help mitigate these upfront expenses and improve the financial feasibility of BESS projects. Furthermore, addressing the environmental impacts of battery production, disposal and recycling, is paramount for BESS' sustainable deployment. Additionally, tailoring BESS to the intermittent nature of renewable energy sources and grid stability considerations is essential for effective integration. Implementing advanced forecasting and operational strategies, along with focusing on grid management innovations, can help address these challenges and optimise BESS performance. Finally, effective lifecycle management of batteries is crucial for maximising BESS efficiency and longevity. Developing predictive maintenance algorithms and monitoring systems can help optimise battery usage and extend the lifespan, thereby enhancing profitability within the real-time electricity market.

While this study provides a comprehensive review of existing literature and research papers, it is important to acknowledge certain limitations. Firstly, reliance on secondary sources may introduce biases or methodological limitations. Furthermore, the findings and conclusions drawn from the review are dependent on the quality and reliability of the sources reviewed, which may vary across different studies. The scope of this review may not encompass all relevant research, and the inclusion of diverse examples from different markets introduces variability. Additionally, examining how other investors are addressing the challenges identified in this research, as well as identifying any new or more pressing challenges that may have emerged since the completion of this study, would contribute to a more comprehensive understanding of the topic.

Finally, this review does not include the policies and regulations segment required to support or incentivise the introduction of BESS on a larger scale. Being a somewhat new technology, many countries lack an overall proactive approach in the legislative segment, passing regulations only reactively, or once a challenge is exposed for the Energy sector. Some of the topics that the current legislation offers little to no answers to are the reliable physical integration of the new electricity generation infrastructure, and the overall system functioning, continuous improvement of the grid, but also plans for new investments and revitalisations of the distribution network and the implementation of advanced concepts like smart grids, vehicle-to-grid technologies and energy storage systems.

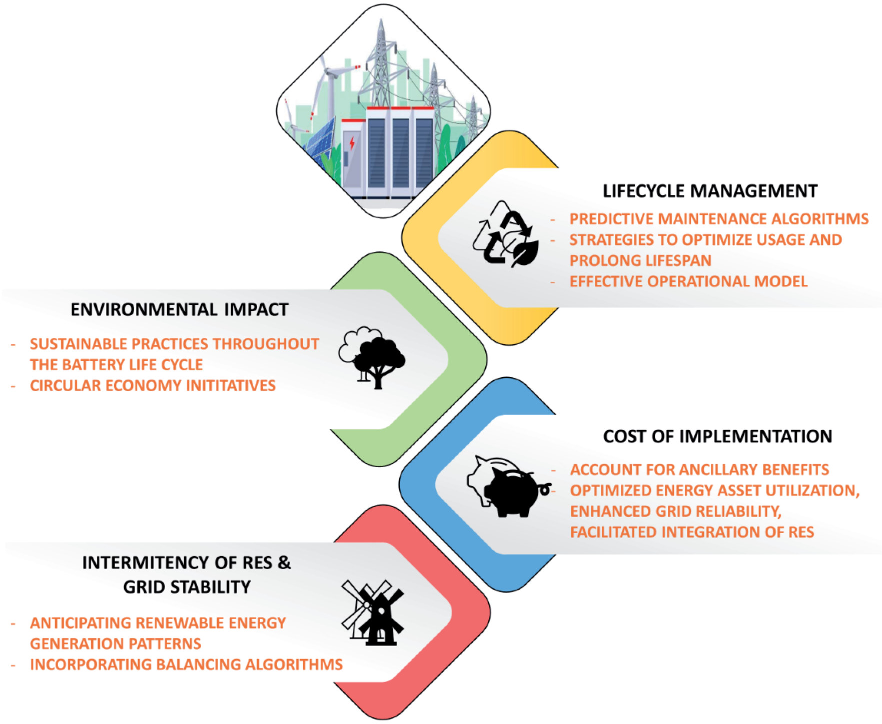

Figure 5: *Challenges and mitigation strategies to address the introduction of BESS*

As a point for future work, future endeavours that would cover any of the abovementioned remarks, would enhance the depth and breadth of knowledge in this field, thereby informing more effective strategies and solutions on the matter of the introduction of BESS.

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