energies

Review

Battery Electric Storage Systems: Advances, Challenges, and Market Trends

Alessandro Saldarini *, Michela Longo, Morris Brenna and Dario Zaninelli

Department of Energy, Politecnico di Milano, 20156 Milan, Italy; michela.longo@polimi.it (M.L.); morris.brenna@polimi.it (M.B.); dario.zaninelli@polimi.it (D.Z.)
* Correspondence: alessandro.saldarini@polimi.it

Abstract: The increasing integration of renewable energy sources (RESs) and the growing demand for sustainable power solutions have necessitated the widespread deployment of energy storage systems. Among these systems, battery energy storage systems (BESSs) have emerged as a promising technology due to their flexibility, scalability, and cost-effectiveness. This paper aims to provide a comprehensive review of the diffusion and deployment of BESSs across various applications, analyzing their impact on grid stability, renewable energy integration, and the overall energy transition. The paper examines the key drivers and challenges associated with BESS adoption, as well as market trends influencing their proliferation. Through an analysis of empirical data, this study aims to shed light on the current state of BESS diffusion. Finally, this research contributes to the knowledge base surrounding battery storage technology and provides insights into its role in achieving a sustainable and reliable energy future.

Keywords: battery energy storage system; frequency regulation; market trends; renewable energy integration; utility-scale applications

check for updates

Citation: Saldarini, A.; Longo, M.; Brenna, M.; Zaninelli, D. Battery Electric Storage Systems: Advances, Challenges, and Market Trends. *Energies* **2023**, *16*, 7566. https://doi.org/10.3390/en16227566

Academic Editor: Shimoi Norihiro

Received: 10 October 2023
Revised: 7 November 2023
Accepted: 10 November 2023
Published: 14 November 2023

1. Introduction

1.1. Motivation

As the world faces an increasingly urgent climate crisis, it is imperative to drastically reduce greenhouse gas (GHG) emissions from the transportation and energy sectors. Decarbonization and the transition to electricity are two key aspects in the fight against climate change [1]. In that context, impacts on the environment, effects on climate change, and air pollution have attracted international attention with the Paris Agreement on Climate Change [2]. The Paris Agreement adopted in December 2015 aims to align current policies and attitudes to achieve climate neutrality by the end of the century. In the context of the climate challenge, battery energy storage systems (BESSs) emerge as a vital tool in our transition toward a more sustainable future [3,4]. Indeed, one of the most significant aspects of BESSs is that they play a key role in the transition to electric transport and reducing GHG emissions. Furthermore, BESSs represent one of the keys to unlocking the potential of renewable energy sources (RESs) while reducing dependence on fossil fuels. These storage systems allow us to capture energy produced from renewable sources during periods of abundance and store it during periods of low demand [5]. This ability to mitigate the intermittency of renewable sources is critical for ensuring a continuous and reliable energy supply. Furthermore, BESSs are crucial for achieving decarbonization goals in the transportation and industrial sectors by contributing to the replacement of internal combustion vehicles with electric vehicles (EVs) powered by renewable energy [6–8]. Under the base scenario, more than 34 million different types of EVs are expected to be sold by 2030 [9,10].

Various battery technologies are used for energy storage systems (ESSs); an overview of these technologies can be found in Ref. [11]. Common technologies include lead–acid, lithium-ion, nickel–cadmium, nickel–metal hydride, and sodium–sulphur batteries. Each technology has its own characteristics and benefits, including energy density, durability, safety, and cost. The BESSs mainly utilize lithium-ion batteries as a means of storing energy, offering significant advantages in terms of efficiency, scalability, and operational flexibility [12,13].

Additionally, BESSs are extensively employed within power distribution systems to enhance grid management. This strategic integration of BESS technology into distribution networks serves to bolster grid reliability, flexibility, and efficiency. These systems act as a buffer, capable of rapidly responding to fluctuations in supply and demand. During times of peak energy consumption, BESSs can supply additional electricity to mitigate strain on the grid, preventing blackouts or brownouts. Conversely, during periods of generation, surplus energy can be stored in the BESSs for later use. This load-balancing capability is instrumental in ensuring a stable and dependable power supply to consumers [14,15]. By strategically deploying BESSs in locations with high energy demand or congestion, utilities can reduce transmission and distribution (T&D) losses and optimize energy flow. These systems help mitigate the need for costly infrastructure upgrades by efficiently managing and storing electricity, ensuring that it is used when and where it is most needed.

1.2. Contributions

The main objective of this manuscript is to explore and illustrate the power grid services provided by BESS installed at both the front of the meter (FTM) and behind the meter (BTM) levels of the electric transmission grid. These services play a key role in the efficient and reliable management of electricity, contributing significantly to the transition to a more sustainable energy system. In summary, this document offers a comprehensive and informative resource for understanding the multifaceted role of BESS in modern energy systems, their technical aspects, and their promising contributions to sustainability and resilience. In detail, the main contributions of this document are the following:

1. Comprehensive Coverage: The document provides a thorough and comprehensive overview of BESSs and their diverse applications, addressing a wide range of scenarios, from power savings and grid stability to renewable energy integration and microgrid solutions. Furthermore, before proceeding with the comparison between lithium-ion batteries and solid-state batteries, it is essential to conduct a detailed analysis of lithium-ion batteries, emphasizing the various chemical technologies.
2. Technical Insights: It offers valuable insights into the implementation of BESSs for every type of application, such as minimum cycles per year, power and energy ranges, C-rate considerations, and the best-suited battery chemistry for each application. For example, in the context of a grid stability application, the technical insights highlight the necessity for a high C-rate to rapidly release stored energy during grid disturbances. They also outline the preferred battery chemistries for this application, emphasizing the importance of lithium iron phosphate batteries for their enhanced safety and durability.
3. Renewable Integration: The document underscores how BESS facilitates the seamless integration of RESs into the grid, optimizing energy supply–demand dynamics and supporting sustainability goals.
4. Market Trends: The document analyses current and projected market trends for both FTM and BTM applications, offering valuable data and insights for stakeholders in the energy sector. For example, in the field of FTM applications, the document discusses the ongoing trend of increasing investment in large-scale BESS projects, such as those associated with utility-scale renewable energy integration. It highlights that this trend is driven by a combination of government incentives, renewable energy targets, and the need for grid stabilization, paving the way for substantial growth in the energy storage sector.

1.3. Paper Organization

The remainder of this paper is organized as follows: the next Section 2 presents a literature review that aims to examine the main studies associated with the BESS. Section 3 explains the BESS architecture and battery chemistry. Section 4 highlights the available technologies for BESS, differentiating FTM applications from BTM ones. Subsequently, in Section 5, a wide range of BESS services are represented. Section 6 covers the market trends for applications. Finally, the paper is concluded in Section 7.

2. Literature Review

This section provides a comprehensive review of the existing literature on BESS. The BESSs have garnered considerable attention in recent years due to their pivotal role in achieving sustainable and resilient energy systems. This review synthesizes key findings from a wide range of sources to elucidate the current state of BESS technology, examine the challenges that persist, and identify emerging trends in this dynamic field.

In order to prolong the battery lifetime, ensure the device's safety and monitor the voltage and energy levels of each cell, a battery monitoring system (BMS) is a necessity. Regarding this, the paper [16] provides an overview of the present state-of-the-art in BMS modelling and highlights the need for advanced models to fully harness the potential of BMS. Meliala et al. [17] primarily focus on elucidating the hardware architecture of a sophisticated BMS. This BMS is designed to provide users with the capability to monitor precise data related to various aspects, including actual cell voltage levels, temperatures within the battery modules, and a wide array of status information on the health status of individual cells. Energy management systems (EMSs) and optimization methods are required to utilize energy storage effectively and safely as a flexible grid asset that can provide multiple grid services. The EMS needs to be able to accommodate a variety of use cases. Byrne et al. [18] provide a brief history of grid-scale energy storage, an overview of EMS architectures, and a summary of the leading applications for storage.

One of the notable advancements in BESS technology is the evolution of battery chemistries. Rechargeable batteries exhibit a broad spectrum of characteristics, encompassing efficiency, charging behaviour, longevity, and cost. This paper [19] conducts a comparative analysis, focusing on the two primary contenders for stationary energy storage: the lead–acid battery and the lithium-ion battery. A meticulous cost analysis underscores the cost-effectiveness of lithium-ion batteries, particularly when considering the total number of charge/discharge cycles they endure. In addition, Saini et al. [20] focus their research on identifying the most suitable battery chemistry across different technologies, using a simulation-based study. Lithium-ion batteries have emerged as the dominant choice due to their high energy density, long cycle life, and relatively low self-discharge rates. Finally, Del Valle et al. [21] show how multiple lithium-ion batteries undergo a comprehensive analysis through various tests aimed at assessing critical performance parameters for BESS applications. To achieve these objectives, several testing protocols are developed, which encompass internal resistance assessments, constant power cycling tests, rapid charging methodologies, and performance evaluations conducted under both kinetic and thermodynamic conditions.

BESSs enhance the reliability and resilience of the electricity grid in several ways. Regarding this, Galvan et al. [22] discuss the challenges and benefits of incorporating microgrids into the power distribution system, especially with regard to efficiently managing distributed energy resources, including BESSs. They demonstrate how to enhance the resilience of the power distribution system against natural disasters through BESS. It is important to acknowledge that uncertainties related to variables like renewable energy generation, load, and energy prices can significantly impact the optimal operation of BESSs. In response to this challenge, the authors in [23] introduce an adaptive robust optimization approach. This approach aims to effectively address degradation in the management of BESS charging and discharging, even in the presence of uncertainties. Instead, Hamidi et al. [24] delve into the exploration of integrating wind power, photovoltaic (PV) solar power, and BESSs into microgrid-based charging stations (CSs). The proposal includes the incorporation of second-life lithium-ion batteries into this system, which would serve the dual purpose of acting as an energy buffer and supplying emergency power in the event of a grid disconnection. Regarding this, Li et al. [25] have introduced a two-stage optimization approach for effective planning of distributed generation (DG) while taking into account the incorporation of energy storage. Their experimental findings show that this method outperforms existing approaches and that when energy storage is integrated, DGs can reliably operate at their intended capacities with a likelihood of at least 60%. Similarly, Medghalchi et al. [26] have introduced an innovative method to assess the integration of solar PV and wind turbines coupled with BESS. Their goal is to reduce the weighted average cost of energy while ensuring a set fraction of RESs. This system optimizes the capacity of PV, wind turbines, batteries, electrolyzers, hydrogen tanks, and fuel cells concurrently, addressing a complex and intricate optimization problem.

Zyryanov et al. [27] provide an overview of the primary drivers and current application areas of BESS within power systems. The paper delves into approaches aimed at addressing various pressing issues, such as equipment selection, power system structure organization, operational mode maintenance, energy quality enhancement, and the preservation of stability and reliability within power systems through the utilization of BESS technology. In addition, in the work by Stecca et al. [28], various facets of the integration of BESSs into distribution grids are thoroughly examined. The study encompasses an investigation into the diverse functionalities that a grid-connected BESS can offer, followed by an analysis of its sizing, optimal placement within the distribution network, and the control strategies associated with its operation.

The study of Benini et al. [29] examines the potential for a BESS to participate in the Italian balancing market (BM) by providing balancing services. The paper introduces a strategy for formulating both downward bids and upward offers within the market. This strategy is based on the timing of the BM sessions and focuses on selling the stored energy until the remaining energy level reaches a predetermined minimum threshold. Subsequently, the approach involves submitting purchase bids to recharge the battery when necessary. Nonetheless, the emerging energy storage market faces a significant challenge in terms of transparency, with frequently unrealistic assumptions about prices and battery specifications. In response to this concern, Figgener et al. [30] offer a comprehensive study providing detailed insights into the markets for various storage systems in Germany. This includes home storage systems, industrial storage systems, and large-scale storage systems, aiming to provide clarity and accurate information to bridge the gap between market expectations and reality. Instead, as regards the world market, Telaretti et al. [31] provide an overview of the state-of-the-art in electrochemical storage systems. Furthermore, a description of the main BESS technologies used in stationary applications is carried out, and the main trends are also identified, with reference to the main electrochemical technologies currently spread in the main world markets.

Table 1 summarizes the relevant reviews regarding the different topics that will be covered in the manuscript. In summary, the literature review highlights a significant surge in interest in BESS applications in recent years, with a predominant focus on the benefits these systems can bring to the electrical grid. However, a notable gap in the literature pertains to predicting market trends. In the context of this article, in addition to providing in-depth insights into the specifics of each application and service offered by BESSs, an attempt has been made to outline a possible outlook for the future market. This study aims to bridge the gap between existing research and the need to understand how BESS adoption may evolve in the coming years, thus contributing to more informed and strategic planning in the field of energy storage technologies.

Table 1. Summary of Referenced Topics and Publications.

Topic	Title	Year	Reference
BMS	Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications.	2014	[16]
	Energy Management and Optimization Methods for Grid Energy Storage Systems.	2018	[18]
	Active Battery Management System for Home Battery Energy Storage.	2020	[17]
Lithium ion chemistry	Comparison of lead-acid and lithium-ion batteries for stationary storage in off-grid energy systems.	2016	[19]
	Analysis of Advanced Lithium-Ion Batteries for Battery Energy Storage Systems.	2018	[21]
	Cloud Energy Storage Based Embedded Battery Technology Architecture for Residential Users Cost Minimization.	2022	[20]
Services	EV charging station integrating renewable energy and second-life battery.	2013	[24]
	Optimal distributed generation planning in active distribution networks considering integration of energy storage.	2018	[25]
	Analysis of Energy Storage Systems Application in the Russian and World Electric Power Industry.	2020	[27]
	A Comprehensive Review of the Integration of Battery Energy Storage Systems into Distribution Networks.	2020	[28]
	Networked microgrids with roof-top solar PV and battery energy storage to improve distribution grids resilience to natural disasters.	2020	[22]
	Charging Management of Chemical Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) Batteries, Considering Battery Degradation Effects under Uncertain Operation in Multi-energy Systems.	2020	[23]
	A novel hybrid optimization framework for sizing renewable energy systems integrated with energy storage systems with solar photovoltaics, wind, battery and electrolyzer-fuel cell.	2023	[26]
Market Trends	Stationary battery systems in the main world markets: Part 1: Overview of the state-of-the-art.	2017	[31]
	Participation of Battery Energy Storage Systems in the Italian Balancing Market: Management Strategies and Economic Results.	2018	[29]
	The development of stationary battery storage systems in Germany—A market review.	2020	[30]

3. BESS Architecture

The architecture of a BESS refers to the overall design and configuration of the system components that enable the storage and distribution of electrical energy. A well-designed architecture is essential for the efficient and safe operation of the BESS. The architecture of a typical BESS can be described as follows:

- At the heart of a BESS are the battery modules, which are interconnected to form a larger battery pack. These modules are typically composed of multiple individual battery cells, arranged in series and parallel configurations to meet the system's voltage and capacity requirements.
- The battery management system (BMS) is responsible for monitoring and controlling the performance of the battery modules. It ensures the proper charging and discharging of the batteries, monitors their state of charge (SoC), state of health (SoH), temperature, and voltage levels, and protects the batteries from overcharging, overdischarging, and thermal issues. The BMS also manages the balancing of cells within each module to ensure uniform performance and longevity of the battery pack [32–34]. It ensures the safe and efficient operation of the battery pack. Alongside technological advancements, the BMS sector faces significant challenges. Cost management remains a priority as energy storage systems become increasingly widespread and competitive in the market. BMS costs must remain affordable to enable the widespread adoption of these systems. Furthermore, interoperability and standardization are fundamental issues, as the diversity of BMS technologies can hinder the interconnection and compatibility of various energy storage systems. Current research focuses on solutions to

improve interoperability and create shared standards for BMS. Other emerging challenges include the management of critical resources and materials required for battery production. In this context, research into new BMS technologies aims to maximize resource efficiency and reduce environmental impact. These challenges and opportunities underscore the importance of ongoing discussion on recent developments and challenges in the BMS sector, as this is crucial for the future of energy storage systems.

- The power conversion system (PCS) is a fundamental component within a BESS and plays a crucial role in ensuring the effective operation of the system as a whole. The PCS consists of several key elements, including inverters, transformers, and control circuits. Inverters are responsible for converting the direct current (DC) electrical energy stored in batteries into alternating current (AC) that can be used by electrical devices or injected into the electrical grid. This step is crucial, as it enables the BESS to be interoperable with other energy sources and support grid balancing. Transformers play an important role in adjusting the voltage of the converted energy to the specific requirements of the load or the grid. Additionally, the control circuits of the PCS efficiently manage the charging and discharging operations of the batteries, ensuring that the batteries are kept within safe voltage and temperature limits. The interaction of the PCS with the BMS is critical since the BMS provides information to the PCS about the state of the batteries and optimal operating conditions. This bidirectional communication between the PCS and the BMS is essential for maintaining battery performance and lifespan. Moreover, in a grid-connected BESS, the PCS can perform grid support functions, such as frequency regulation and voltage control, to ensure the stability of the electrical system. The authors in this paper [35] analyse the relationship between the BESS design scheme and the PCS.
- The energy management system (EMS) is a central control unit that monitors and optimizes the overall operation of the BESS. It collects real-time data from the BMS and power conversion system, analyses the energy storage requirements, and determines the most effective strategies for charging and discharging the batteries. The EMS can be programmed to prioritize different objectives, such as maximizing self-consumption of renewable energy, participating in grid services, or optimizing economic returns [36,37].
- To enable seamless integration with the electrical grid and RESs, a BESS typically incorporates communication interfaces and protocols [38]. These allow for real-time monitoring, control, and communication with other grid-connected devices, such as renewable energy systems or smart grid infrastructure. Communication capabilities enable remote monitoring of system performance, diagnostics, and software updates.
- Safety Systems: A BESS is housed in an enclosure designed to protect the components from environmental factors and ensure safety. The enclosure provides physical support, thermal management, and protection against fire, shock, and other hazards. Safety systems, such as fire suppression systems, smoke detectors, and emergency shutdown mechanisms, are also incorporated to mitigate potential risks [39].

Overall, the architecture of a BESS, schematized in Figure 1, is designed to efficiently store and release electrical energy, manage power conversion, and ensure the safety and reliability of the system. Furthermore, it enables grid stabilization, load management, and participation in grid services, contributing to the decarbonization and resilience of the electrical grid. BESS architecture can be customized based on the specific needs of residential, commercial, industrial, or utility-scale applications.

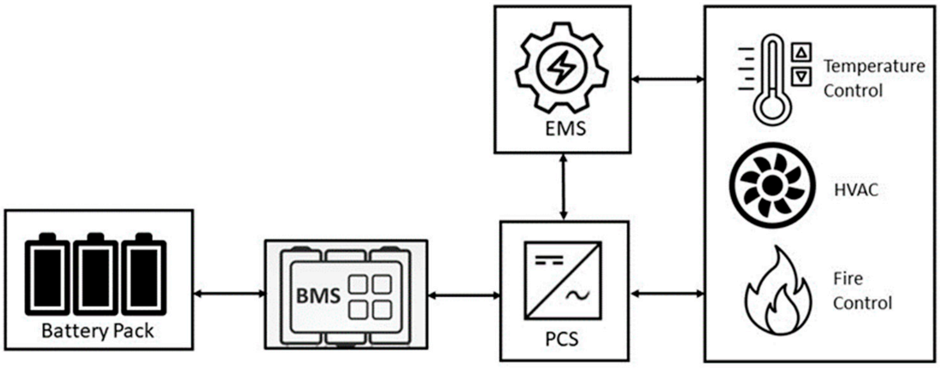


Figure 1. BESS architecture scheme.

3.1. Lithium-Ion Battery Chemistry

BESSs can incorporate various battery types such as lithium-ion, lead–acid, nickel–cadmium batteries, and others. Lithium is the lightest among the other metals, with the greatest electrochemical potential which can allow the largest specific energy per weight (3.86 Ah/g and 7.23 Ah/cm^3) [40]. This property permits the expression of high specific energy density, but only if other electrolyte materials with high standard oxidation potential are used. Another advantage is that lithium-ion batteries are characterized by an almost flat discharge profile, within a range of 10% to 90% of SoC, which perfectly matches with a traction application, where the discharge and the power delivered need to be as constant as possible to avoid fluctuations in the power delivered to the motors. But lithium-ion batteries are not free of problems. Indeed, they require a protective circuit and degrade at high temperatures and high voltages. In addition, fast charging is not possible at freezing temperatures (<0 °C) [41]. However, their great advantages, which can be summarized as high specific energy and high load capacity with power cells, are their long cycle and increased durability (almost no need for repair). They are characterized by higher size, low internal resistance, relatively short charging time, and low self-discharge [42]. These properties determine their suitability for different applications such as EVs, power plants, and ESSs. Multiple varieties of lithium-ion batteries are in existence, each distinguished by its characteristics, as exemplified in Table 2.

As lithium-ion battery technology continues to evolve and become more cost-effective [43], it is likely to drive further innovation and adoption in various sectors, contributing to a more sustainable and environmentally friendly future. Additionally, research in the field of battery technology is expected to yield even more breakthroughs in the coming years.

Table 2. Comparison of the characteristics of the different types of lithium batteries.

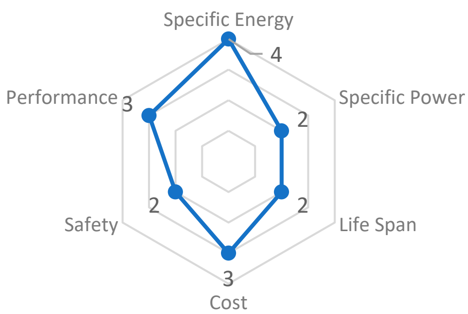
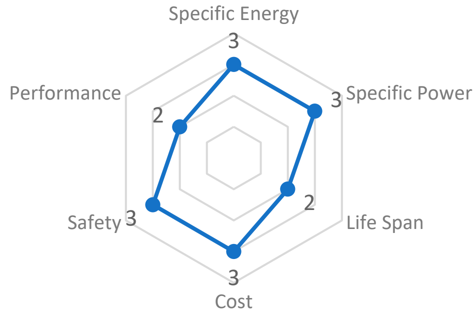
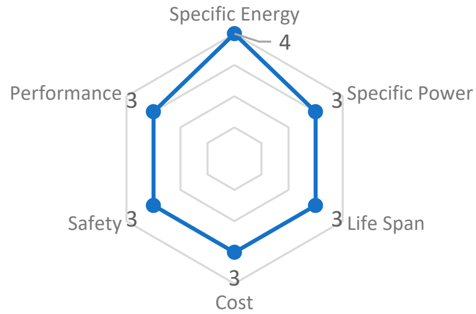
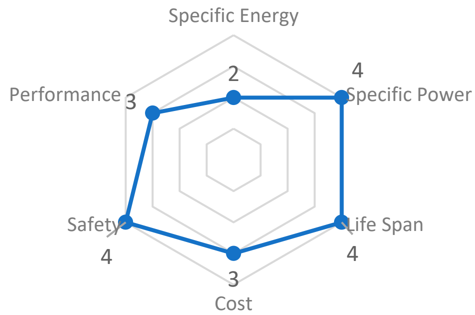
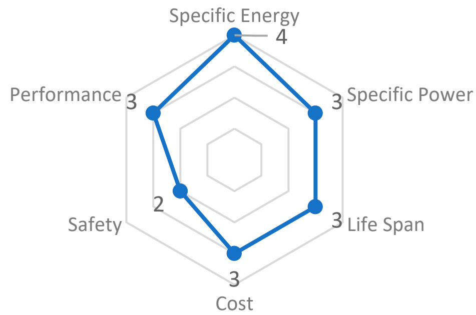
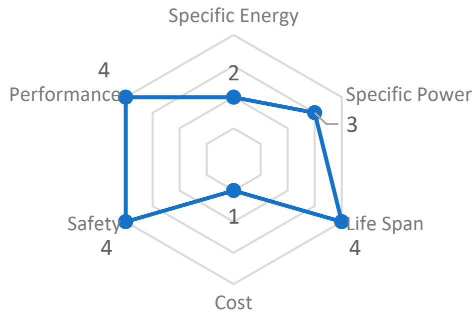
Lithium Cobalt Oxide—LCO batteries have high specific energy but shorter life, lower thermal stability, and defined load abilities. Modern designs include nickel, manganese, and/or aluminium to improve longevity and cost [44].	

Table 2. *Cont.*

<table>
<tr><td>Lithium Manganese Oxide—LMO batteries offer higher thermal stability and safety but have a lower capacity compared to LCO batteries. They are often combined with nickel manganese cobalt oxide (NMC) for increased specific energy and extended life [45].</td><td>
</td></tr>
<tr><td>Lithium Nickel Manganese Cobalt Oxide—NMC batteries combine nickel, manganese, and cobalt to achieve a balance between specific energy and stability. They are commonly used in power tools, EVs, and electric propulsion systems [46].</td><td>
</td></tr>
<tr><td>Lithium Iron Phosphate—LFP batteries offer good electrochemical performance, low resistance, and increased safety. They have a lower specific energy but have a longer cycle life and thermal stability [47].</td><td>
</td></tr>
<tr><td>Lithium Nickel Cobalt Aluminium Oxide—NCA batteries provide high specific energy, relatively good specific power, and longer life. They are used in specific applications but have higher costs and lower safety compared to other chemistries [48].</td><td>
</td></tr>
<tr><td>Lithium Titanate—LTO batteries replace graphite at the anode and offer advantages such as safety, excellent discharge properties at low temperatures, and high thermal stability. However, they have a lower specific energy and higher costs compared to other lithium-ion systems [49].</td><td>
</td></tr>
</table>

In the context of a scientific text discussing lithium battery technologies, it is essential to provide a comprehensive overview of the key parameters that define these technologies.

Table 3 below presents a comparison of various lithium battery technologies, focusing on crucial parameters such as specific energy, energy density, cycle life, discharge rate, nominal voltage, and price. It should be noted that the prices mentioned in the table are as of 2023. This overview allows for an understanding of the distinctive characteristics of each of the technologies and provides a basis for assessing their applications in various sectors, from energy storage to EVs.

Table 3. Comparison of Key Parameters for Various Lithium Battery Technologies.

	LCO	LMO	NMC	LFP	NCA	LTO
Specific energy [Wh/kg]	200	150	220	170	250	70
Energy density [Wh/l]	400	350	500	350	550	177
Cycle life	500–1000	300–700	2000	>4000	1000	15,000–20,000
Discharge rate	1C	1C, 10C	2C/3C	1C/3C	2C/3C	4C/8C
Rated voltage	3.6	3.7	3.6	3.2	3.6	2.4
Price [$/kWh]	~123 [50]	~95 [51]	~112 [51]	~100 [51]	~120 [51]	~160 [51]

3.2. Characteristics of Solid-State Batteries

In the field of battery technologies, the comparison between traditional lithium-ion batteries and the newer solid-state batteries is becoming a subject of increasing interest and research. Traditional lithium-ion batteries, based on liquid electrolytes, have dominated the market for decades but come with limitations in terms of safety, efficiency, and cycle life. On the other hand, solid-state batteries offer a promising alternative by utilizing solid electrolytes, eliminating the risks of leakage, and providing higher energy density. This comparison takes an in-depth look at key parameters such as safety, specific energy, efficiency, and cycle life, offering a comprehensive overview of the characteristics of both technologies. The choice between the two depends on the specific requirements of the application and the need to maximize safety, efficiency, and performance in the context of energy storage [52]. As depicted in Table 4 [53], solid-state batteries feature a solid electrolyte, offering higher energy density and cost-effectiveness, along with a significantly reduced weight and smaller physical footprint. Importantly, they are characterized by enhanced safety with a minimal risk of explosion or fire when compared to lithium-ion batteries, which employ liquid or gel-based electrolytes and are known to carry a higher safety risk [54].

Table 4. Comparison Between Solid-State and Lithium-Ion Batteries.

	Solid-State	Lithium-Ion
Electrolyte	Solid	Liquid/Gel
Energy density [Wh/kg]	500–550	260–270
Cost [$/kWh]	80–90	151
Weight (80 kWh) [km]	158	500
Size	Smaller	Larger
Safety	Low risk of explosion or fire	Risk of explosion or fire

In conclusion, the comparison between traditional lithium-ion batteries and emerging solid-state batteries highlights the transformative potential of the latter in the field of energy storage. While lithium-ion batteries have long been the dominant technology, they present challenges related to safety, efficiency, and cycle life due to their liquid electrolytes. Solid-state batteries, on the other hand, offer a compelling alternative by employing solid electrolytes, thus eliminating the risk of leakage, and achieving higher energy density. The choice between these two technologies ultimately hinges on the specific demands of the application, with solid-state batteries presenting a promising avenue for those seeking to maximize safety, efficiency, and performance in the context of energy storage. This evolving landscape of battery technologies signifies a pivotal shift towards more sustainable and secure energy storage solutions.

3.3. Comparison of BESS with Other Energy Storage Technologies

BESS can be compared to other energy storage technologies in terms of cost-effectiveness, scalability, and environmental impact. The comparison (Table 5) shows that the optimal choice may vary depending on specific use cases and technologies.

Table 5. Comparison of Energy Storage Technologies.

	BESSs (Lithium-Ion)	Pumped Hydro Storage	Compressed Air Energy Storage	Flywheel Energy Storage
Cost-Effectiveness	Relatively cost-effective	Cost-effective for large-scale, geography-dependent applications	Can be cost-effective for large-scale applications	Competitive for short-duration applications
Scalability	Highly scalable	Limited scalability due to geographic constraints	Moderately scalable; geological requirements may limit deployment	Limited scalability due to energy capacity
Environmental Impact	Concerns about resource extraction; improving with sustainable chemistry and recycling	Minimal ongoing	Moderate due to energy-intensive compression and expansion; can be mitigated with RES use	Environmentally friendly; no hazardous materials; long lifespan; highly recyclable

In summary, BESSs are versatile and scalable, making them suitable for various applications, but their environmental impact can be a concern. The choice of energy storage technology depends on specific project requirements, such as capacity, duration, location, and environmental considerations. Each technology has its advantages and limitations, and the optimal choice will vary based on the specific use case and priorities.

4. Available Technologies for BESS

BESSs are coming out as one of the potential ways to enhance system flexibility because of their inherent ability to absorb, maintain, and then re-inject power. Based on the North American energy-saving association, market applications are typically distinguished as FTM or BTM:

- FTM batteries are integrated into distribution or transmission networks or in connection with a production property. They allow applications needed by system operators, such as auxiliary services or system load reductions.
- BTM batteries are connected behind the electricity meter of commercial, industrial, or residential customers, mainly with the aim of reducing electricity bills through demand-side management.

4.1. FTM BESS Concept

BESSs at the application scale (in FTM) have begun to change power generation, transmission, and distribution systems. These batteries are arranged in modules or containers to form a scalable and flexible system. Their overall capacity can range from several to hundreds of MWh. The primary purpose of an FTM BESS is to store excess electricity generated during periods of low demand or high renewable energy production. This stored energy can then be discharged during times of high demand or low renewable energy generation. By doing so, the BESS helps to balance the supply and demand of electricity on the grid, ensuring a stable and reliable power supply. One of the key advantages of an FTM BESS is its fast response time. It can rapidly charge or discharge electricity within milliseconds, making it well-suited for providing frequency regulation services. When grid frequency deviates from the nominal value, the BESS can inject or absorb power instantly to stabilize the frequency. FTM BESSs are also capable of delivering high power output when needed. This allows them to provide peak shaving services by supplying additional power during periods of high demand, reducing the strain on the grid and avoiding the need for expensive peaker plants. To ensure the safe and efficient operation of an FTM BESS, it is equipped with sophisticated control systems. These systems monitor grid conditions, battery status, and demand patterns in real-time, allowing for intelligent and optimized operation. The BESS can be remotely controlled and managed to respond to grid operator commands or market signals. Overall, an FTM BESS plays a crucial role in modernizing and optimizing the electrical grid. By providing grid-level storage and flexibility, it helps to enhance grid stability, reliability, and efficiency while supporting the integration of RESs into the power system, Table 6.

Table 6. Applications of FTM BESSs and Their Benefits.

Applications	Note
Utility-Scale Energy Storage	Large-scale FTM BESSs are integrated into the electrical grid at substations. They provide various grid services, such as frequency regulation, voltage support, and energy arbitrage.
Renewable Integration	FTM BESSs are paired with renewable energy. They store excess energy generated during periods of low demand or high renewable output and release it during peak demand or when renewable generation is low, helping to balance the grid.
Grid Ancillary Services	FTM BESSs are used to provide grid ancillary services like frequency response, spinning reserves, and black start capabilities. These services help maintain grid stability and can be dispatched quickly to address fluctuations in supply and demand.
T&D Upgrade Deferral	FTM BESSs can defer the need for expensive upgrades to T&D infrastructure by providing localized grid support and reducing strain on existing infrastructure.
Islanded Microgrids	FTM BESSs can be a part of islanded microgrid systems, where they act as the primary source of power during grid outages or in remote areas were connecting to the main grid is not feasible.

The general power flow in an FTM BESS is illustrated in the provided Figure 2 [55]. This diagram demonstrates how energy is typically transferred within the BESS, including charging from external sources and discharging to the grid or other applications.

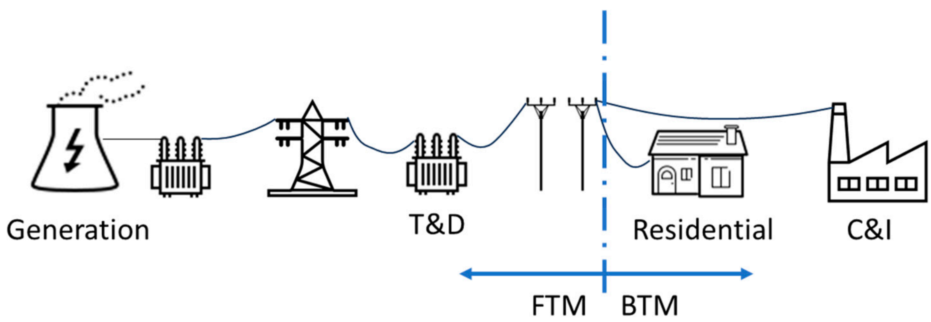


Figure 2. Energy storage market segments: BTM vs. FTM.

4.2. BTM BESS Concept

A BTM BESS is an energy storage system located on the customer's side of the electrical meter. It is designed to provide various benefits to the customer, such as reducing electricity costs, increasing energy independence, and improving resilience, Table 7. A BTM BESS typically consists of a bank of batteries, often utilizing lithium-ion technology, although other battery chemistries can also be used. The capacity of the BESS can vary depending on the customer's needs, ranging from kWh for residential applications to several MWh for commercial and industrial installations. The primary purpose of a BTM BESS is to store electricity during periods of low demand or when electricity prices are low. The stored energy can then be used during times of high demand or when electricity prices are high, reducing the customer's reliance on grid power and helping to minimize peak demand charges. Furthermore, a BTM BESS can provide backup power during grid outages or blackouts. By having a reliable source of stored energy, critical loads or the entire premises can continue to operate, ensuring uninterrupted power supply for essential functions such as medical equipment, refrigeration, or security systems; this enhances the resilience of the customer's electricity supply. BTM BESSs are often integrated with renewable energy systems, such as solar panels. This maximizes the self-consumption of renewable energy and reduces the need to rely on grid power.

Table 7. Applications of BTM BESSs and Their Benefits.

Applications	Note
Residential Settings	BTM BESSs are commonly installed in residential homes. Homeowners use these systems to store excess electricity, then use it when electricity demand is high or during power outages. This helps reduce electricity bills and provides backup power.
Commercial Buildings	Many businesses and commercial properties install BTM BESSs to manage their electricity consumption effectively. These systems help reduce peak demand charges, provide backup power during outages, and enhance overall energy efficiency.
Industrial Facilities	Industrial facilities often employ BTM BESSs to smooth out electricity demand and reduce utility costs. These systems can be used for load shifting and power quality improvement in manufacturing processes.
Microgrid	Some communities and businesses deploy microgrids with BTM BESSs to enhance energy resilience, especially in remote or isolated areas. These systems can operate independently or in conjunction with the main grid.

The total power flow in an industrial plant including a BTM BESS and BTM PV system is illustrated in Figure 3. It demonstrates how the BTM BESS interacts with the power grid to optimize energy usage, providing energy when needed, storing excess energy, and reaping economic benefits associated with electricity prices. This contributes to more efficient and resilient energy management within the system.

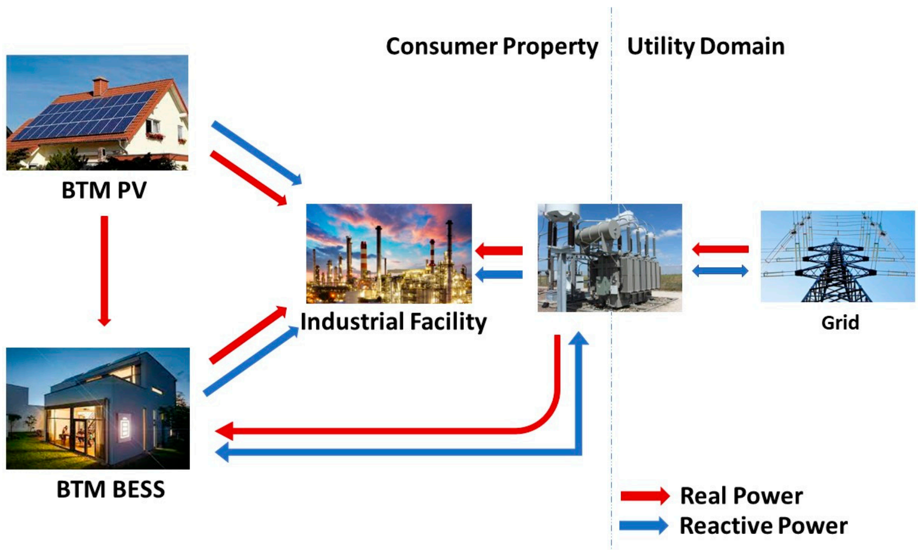


Figure 3. Power Flow in a facility containing BTM BESS.

5. BESS Services

BESSs offer a wide range of services to improve the efficiency, resilience and sustainability of the energy system; they are illustrated in Table 8. The utilization and benefits of BESSs can be categorized into five distinct groups: bulk energy, auxiliary services, network support (T&D system), renewable energy integration, and customer energy management services.

Table 8. Energy Storage Services per Segment.

Segment	Services	Use Case/Application
Front-of-the-meter (Utility Scale)	Bulk Energy Services	Electric supply capacity Electric energy time shift
	Ancillary Services	Frequency regulation Voltage support Black start Spinning reserve
	Grid Support (T&D)	Transmission services (upgrade deferral and congestion relief) Distribution services (upgrade deferral and voltage support)
	Renewable Energy Integration	Renewable capacity firming
Behind-the-meter (End-user Scale)	Customer Energy Management Services	Peak shaving Power upgrade deferral Time-of-use energy cost management Maximizing/optimizing self-production Renewable integration Back-up power Power Quality Compensation of the reactive power Energy independence EV fast charging

5.1. Bulk Energy Services

A BESS within the realm of bulk energy services offers two significant advantages. Firstly, it enhances versatility by strategically storing excess energy, subsequently deploying it during peak demand hours to capitalize on price differentials [56]. Traditionally, production systems are dimensioned according to projected peak demand, which can lead to cost inefficiencies due to potential overestimation. Generator installation costs are directly correlated with their nominal rating and are often influenced by peak demand scenarios. As a result, a BESS serves as a valuable solution to mitigate this challenge, permitting the provision of supplementary energy capacity during peak demand and thereby reducing the necessity for deploying high-capacity production systems [57].

- Electric Supply Capacity (a)

Supply capacity refers to the maximum amount of electricity that a distribution network operator (DNO) must ensure, essentially representing the peak power possible from the network. Within this framework, a BESS can effectively delay or reduce the need to invest in new-generation plant capacity or acquire additional capacity from the electricity market [58]. In the event of an extended power outage or system shutdown, the reset process must initiate from pre-selected generating units capable of self-starting. The customary range for the minimum number of annual cycles in the operation of a BESS for this application typically spans from as few as 5 cycles to as many as 100 cycles per year.

- Electric Energy Time-Shift (Arbitrage) (b)

BESSs employed in a time shift application are designed to harness cost-effective electricity during off-peak periods and release it when electricity prices surge [59]. These BESSs, tailored for temporal energy displacement, can be strategically situated either within or in proximity to power plants or at various points within the network, including locations near energy demand centres. Numerous pivotal technical considerations come to the forefront in this context. Notably, the minimum cycling frequency per year often surpasses 250 cycles, signifying the substantial operational resilience and versatility of these systems.

Furthermore, the reutilization of second-life batteries can yield significant practical benefits, particularly in the realm of stationary energy storage applications, where their capabilities can be harnessed effectively. The size and duration of these systems can vary depending on the specific application, ranging from smaller-scale deployments, such as PV or small wind farms, to larger installations catering to energy arbitrage in connection with substantial wind farms or PV power plants.

The parameters and values associated with the electrical supply capacity and electricity time-shift application are shown in the following Table 9.

Table 9. Bulk Energy Service Specifications.

Parameter	Value (a)	Value (b)	Note
Power range [MW]:	1–500	1–500	Electric supply system
Energy range [MWh]:	1–1000	1–1000	Greater than 1 h service to the grid
C-rate:	0.1–1	0.1–1	Favourable power–energy ratio
Chemistry:	NCM—NCA—LFP	NCM—NCA—LFP	High energy density is required to reduce the occupied space
2nd life:	Yes	Yes	Not required hard performance

5.2. Ancillary Services

Ancillary services are defined as services that support the transmission of electricity from the place of production to the customer or help maintain its usability throughout the system. On a larger scale, ancillary services are generators or other service providers that are networked and able to rapidly increase output in three main categories: potential reserves, regulation, and flexibility. This section will provide an explanation of the most popular auxiliary services allowed by BESSs as presented in Table 8.

- Frequency Regulation (a)

This function serves as a program for balancing grid frequency. Traditional power plants often prove less suitable for this specific application, as rapid fluctuations in power output can lead to substantial wear and tear [60,61]. From a technical point of view, several important considerations emerge. Often, the minimum number of cycles per year ranges between 250 and 10,000 cycles, an indicator of the versatility and operational robustness of these systems. In addition, frequency regulation demands swift responsiveness, exceptional high-rate performance, substantial power capacity within the BESS, and a charging/discharging rate exceeding a C-rate of 1. Consequently, the preference leans towards NCM or NCA battery chemistries renowned for their attributes, including rapid response times and high-power capabilities. The use of second-life batteries is not recommended since high performance is required.

- Voltage Support (b)

On-load tap changers, step voltage regulators, and shunt capacitors represent common voltage regulators used in traditional distribution systems. However, these conventional regulators may not efficiently address voltage regulation within fast and nonlinear dynamics. This is where the rapid dynamic response of a BESS becomes pivotal, as it can effectively mitigate major voltage fluctuations through its charge and discharge capabilities. Network operators are tasked with the responsibility of maintaining network voltage within prescribed limits [62]. Voltage support holds particular significance during peak hours when power lines and transformers experience their highest levels of utilization. The estimated nominal time required for voltage support stands at approximately 15 min, allowing the grid to stabilize and potentially initiate a systematic reduction in load. High energy and power density are imperative attributes for effective voltage support applications. The utilization of second-life batteries is generally discouraged by the rigorous demands and high-performance expectations associated with voltage regulation.

- Black Start (c)

During the startup phase, large generators require an external power source to initiate critical functions before commencing electricity generation for the grid. In typical operational scenarios, this external power is sourced from the grid. However, in the aftermath of a system disruption, when the grid is unable to provide this essential power, generators must undergo a "black start" procedure, necessitating the use of on-site power supplies such as diesel generators [63]. An on-site BESS can also serve this critical function and obviate the need for conventional black start generators, thereby avoiding the associated costs of fuel consumption and GHG emissions. Given that system outages are infrequent events, an on-site BESS can offer additional benefits, stepping in to provide essential services in the event of a blackout failure [64].

- Spinning, Non-Spinning Reserves (d)

In the realm of electrical power systems, a specific storage capacity is typically allocated to ensure system performance and availability in the event of unexpected production capacity disruptions [65]. This storage capacity is known as:

✓ Spinning Storage: it refers to capacity that is directly connected and synchronized with the network, capable of swiftly responding to compensate for production or transmission interruptions. Spinning reserves represent the primary backup source utilized in the event of a power outage.
✓ Non-Rotating Storage: it is connected to the network but operates asynchronously. It can typically be brought online within 10 min, serving as a valuable resource for uninterrupted loads. Examples include offline or block generation capacity.
✓ Supplementary Storage: it becomes available within an hour and typically serves as a backup for both rotating and non-rotating storage resources. Supplementary reserves come into play after all rotating reserves are operational.

Critical technical factors within these storage categories encompass a variety of aspects. For instance, the minimum cycling frequency per year typically resides in the range of 20 to 50 cycles, an essential metric that affects the durability and effectiveness of the BESS. Moreover, the provision of spinning reserves demands exceptional high-rate performance, substantial power capacity from the BESS, and a C-rate that surpasses a certain predefined threshold. These considerations are fundamental when evaluating and implementing energy storage solutions within these specific categories.

Table 10 describes the values associated with ancillary service applications.

Table 10. Ancillary Service Application Specifications.

Parameter	Value (a)	Value (b)	Value (c)	Value (d)
Power range [MW]:	1–40	1–40	5–50	10–100
Energy range [MWh]:	2.5–40	0.1–10	1–50	2.5–100
C-rate:	1–4	1–5	1–4	1–4
Chemistry:	NCM—NCA —Solid State	NCM—NCA —Solid State	NCM—NCA —Solid State	NCM—NCA —Solid State
2nd life:	No	No	No	No

5.3. Grid Support (T&D)

BESSs have assumed a pivotal role in grid support and power T&D. These systems provide a versatile and efficient solution to address the challenges of the modern electrical infrastructure. Their ability to store energy when it is abundant and release it when it is needed makes them a key component in energy supply and demand management and contributes significantly to the stability and efficiency of modern power grids.

- Transmission and Distribution Congestion Relief (a)

During peak periods of electricity demand, it is not uncommon for transmission lines to lack the necessary capacity to provide the most cost-effective energy delivery to all connected loads. This congestion on the transmission lines can lead to increased energy costs. BESSs strategically placed within the power grid play a crucial role in mitigating congestion-related costs and expenses [66]. In this context, BESS installations are typically positioned downstream of the densely populated segments of the transmission system. From a technical standpoint, several factors merit consideration. Notably, these systems are engineered with a specific target for the minimum number of charge and discharge cycles per year, typically falling within the range of 50 to 100 cycles. It is important to highlight that the discharge periods required to alleviate transmission congestion do not follow a uniform distribution throughout the year. In some instances, merely a few hours of support may be necessary annually to address congestion concerns. This underscores the remarkable flexibility and efficiency of BESSs in effectively managing peak demand and ensuring the cost-effective delivery of energy.

- Transmission and Distribution Upgrade Deferrals (b)

The infrastructure for transmitting and distributing electricity in the power grid must be designed to meet peak demand, which often occurs during just a few hours each year. As the projected growth in peak electricity demand surpasses the capacity of the existing grid, substantial investments are usually required to upgrade equipment and expand infrastructure [67,68]. However, the deployment of BESSs offers an effective means to delay or even circumvent the necessity for new grid investments. BESSs can store energy during periods of lower demand and then discharge it during peak demand hours, thus alleviating congestion and enhancing the overall utilization of T&D assets. From a technical perspective, several crucial considerations come into play. First and foremost, these systems are meticulously designed with a specific focus on achieving a minimum number of charge and discharge cycles per year, typically falling within the range of 10 to 50 cycles. Additionally, to effectively address the substantial power density demands associated with grid peak periods, it becomes imperative to employ BESSs based on advanced technologies such as LFP or solid-state. These considerations underscore the pivotal role that BESSs can fulfil in elevating the efficiency, adaptability, and resilience of the power grid, all while mitigating the necessity for costly infrastructure upgrades.

Table 11 lists the parameters and values associated with transmission and distribution congestion relief/upgrade deferral applications.

Table 11. Transmission and Distribution Congestion Relief/Upgrade Deferral Specifications.

Parameter	Value (a)	Value (b)	Note
Power range [MW]:	1–100	10–100	Transmission, distribution grid system
Energy range [MWh]:	1–400	20–800	From 1 h to 8 h
C-rate:	0.25–1	0.1–0.5	Favourable power-energy ratio
Chemistry:	LFP– Solid State	LFP– Solid State	Suitable for applications requiring high power density
2nd life:	Yes	Yes	Not required hard performance

5.4. Renewable Energy Integration

The integration of RESs into the existing power grid has emerged as a pivotal objective in the global transition towards sustainable and clean energy systems. However, the inherent variability and intermittency of RESs, such as solar and wind power, pose significant challenges to the grid's stability and reliability. BESS has emerged as a transformative technology, offering a versatile and effective solution to address these challenges and facilitate the seamless integration of renewable energy resources [69].

- Renewable Firm Capacity or Peaking Capacity

System operators bear the responsibility of ensuring an adequate production capacity to reliably meet electricity demand, particularly during periods of high or peak demand.

Typically, these peak demand periods are met with higher-cost electricity generators. However, considering the shape of the load curve, BESSs can also play a pivotal role in securing ample peak production capacity. By strategically pairing variable renewable energy (VRE) resources with BESSs, system operators can enhance the ability of these resources to align with peak demand, consequently boosting system capacity and reliability [70]. Capacity firming, a widely adopted practice, serves the purpose of stabilizing the grid in the context of variable wind and solar resources. Its application offers several advantages to the electricity network, including:

✓ Optimization of Generation Profiles: capacity firming optimizes the generation patterns of renewable sources, ensuring consistent and reliable power output.
✓ Reactive Power Support: capacity firming facilitates the supply and exchange of reactive power to support RESs, enhancing their performance and grid stability.
✓ Balancing Load Currents: it assists in balancing load currents and compensating for imbalances that might not always be accommodated by RESs.

Critical technical considerations for the implementation of capacity firming utilizing BESSs include achieving a targeted minimum number of cycles per year, which typically ranges from 10 to 50 cycles. This requirement is closely tied to the substantial power density demanded and specific C-rate limitations inherent in capacity firming applications, as shown in Table 12. Consequently, the adoption of battery technologies such as LFP or solid-state is paramount for the effective execution of capacity firming objectives.

Table 12. Renewable Firm Capacity or Peaking Capacity Specifications.

Parameter	Value	Note
Power range [MW]:	1–500	Utility-scale PV, on-shore or off-shore wind farms
Energy range [MWh]:	1–1000	2–4 h service to the grid
C-rate:	0.1–1	Favourable power–energy ratio
Chemistry:	NCM—NCA	High energy density is required to reduce the occupied space
2nd life:	Yes	Not required hard performance

5.5. Customer Energy Management Services

BES technologies possess diverse intrinsic characteristics that determine their suitability for specific applications and their ability to provide distinct services to electrical systems. These characteristics include discharge time (ranging from seconds to hours) and power rating (from kilowatts to megawatts). Currently, lithium-ion batteries have gained prominence despite their higher initial cost when compared to lead–acid batteries. This popularity stems from their longer lifespan and greater efficiency. As a result, lithium-ion accumulators have become the prevalent choice for stationary battery installations in buildings. However, not all lithium-ion batteries are identical. Different applications demand specific battery types:

✓ Lithium-Cobalt Dioxide Accumulators: These are favoured for applications such as cell phones and EVs, where a compact, lightweight battery with high energy and power density is essential.
✓ Lithium Iron Phosphate Accumulators: These are well-suited for building applications, where weight and size are less critical, and longevity takes precedence.
✓ NCM Batteries: By incorporating nickel and manganese, originally designed for cell phones, NCM batteries have been adapted for use in buildings, offering a balance between energy density and cost-effectiveness.

In terms of services provided by BESSs, the primary growth drivers, especially BTM applications, are expected to be new PV installations. As PV installations continue to expand, battery storage systems are likely to play a pivotal role in enhancing grid resilience, optimizing energy usage, and ensuring a stable supply of electricity to meet the evolving needs of consumers and the grid.

- Peak Shaving (a)

Peak shaving involves the utilization of energy storage by end-users (utility customers) to effectively manage and reduce their overall electricity expenses. Customers charge the storage systems during off-peak time periods when retail electricity prices are at their lowest. Subsequently, they discharge the stored energy during on-peak time-of-use (TOU) periods when higher retail energy prices come into effect. This program bears similarities to electric time shifting; however, it is important to note that the pricing structure differs significantly. In peak shaving, the electricity price is determined based on the customer's specific retail tariff, whereas electric time shifting primarily relies on wholesale electricity prices as the predominant factor [71]. Critical technical considerations for peak shaving encompass the achievement of a targeted minimum number of cycles per year, which typically ranges from 50 to 250 cycles. The battery system covers power ranges from 10 kW to 1 MW and energy capacities ranging from 10 kWh to 6 MWh. Flexibility is a strength, as it offers variable durations from 1 h to 6 h to meet specific needs. Furthermore, it promotes sustainability and responsible resource usage with the possibility of a "second life" EV battery. This means that batteries can be reused in other applications after their automotive life.

- Power Upgrade Deferral (b)

The expansion of T&D networks should align with the pace dictated by demographic and economic factors [72]. It is imperative to conduct load growth forecasting and strategic planning for the augmentation or installation of new feeders. Research studies, as exemplified by [73], have underscored that intermittent energy production can potentially postpone the necessity for substantial network upgrades, thereby deferring significant associated costs. Critical technical considerations for addressing these challenges revolve around achieving a targeted minimum number of cycles per year, frequently falling within the range of 50 to 250 cycles. The deployment of BESSs within this specified range equips utilities and grid operators with the capability to efficiently manage load growth, alleviating the immediate necessity for extensive network expansions. This optimization of resource utilization not only leads to cost savings but also enhances grid resilience, thereby mitigating the challenges posed by evolving energy demands and grid stability. The battery system encompasses a power range, from 10 kW to 2 MW, and an energy range spanning from 10 kWh to 4 MWh, ensuring it can handle extended service to the grid, exceeding 1 h. This system employs LFP and NMC, with LFP emphasizing high operational safety while having slightly lower energy density compared to NMC.

- Time-of-use Energy Cost Management (c)

Power savings strategies can be employed by end-users to effectively lower their overall electrical service costs, primarily by reducing their electricity demand during peak periods designated by the utility company. To avoid incurring high demand charges, it is essential to curtail the load during the entire demand charge period, which typically falls within specific hours on days (e.g., 11:00 a.m. to 5:00 p.m.). To alleviate the burden of high demand costs, BESSs are employed. The stored energy is subsequently discharged to supply power to the load during times when demand charges are in effect [74]. Critical technical considerations for the implementation of power savings through energy storage revolve around achieving a targeted minimum number of cycles per year, which frequently falls within the range of 50 to 500 cycles. These strategies empower end-users to actively manage and optimize their electricity consumption patterns, aligning them with cost-saving opportunities. The battery system is designed to cater to a wide range of customers, including residential, commercial, and industrial users, with a power range spanning from 10 kW to 1 MW. It offers a flexible energy range of 10 kWh to 4 MWh, with the capability to provide power for durations ranging from 1 h to 4 h. Operating within a C-rate range of 0.25 to 1, it ensures an advantageous power-to-energy ratio. This system employs a combination of LFP and NMC chemistry, with a specific emphasis on high power density.

- Maximizing/Optimizing Self-production (d)

When a diesel generator is already in place, whether serving as an emergency power source or an off-grid energy supply, the integration of a BESS represents a valuable expansion. This is because a storage system extends the uninterrupted runtime of the generator and reduces the frequency of inefficient starts and cold runs, leading to reduced fuel consumption and lower maintenance costs. Moreover, when coupled with renewable electricity generators such as solar panels or wind turbines, the storage system enhances overall system efficiency. During times when the RES is unavailable, the electricity is first drawn from the storage system. Only when the storage system is depleted does the diesel generator activate. This approach significantly reduces the diesel generator's running time and maximizes the utilization of solar- and wind-generated electricity. Critical technical considerations for the seamless integration of a battery storage system with an existing diesel generator include achieving a targeted minimum number of cycles per year, frequently within the range of 50 to 700 cycles. The specified battery system is tailored for commercial and industrial customers, with a power range ranging from 50 kW to 250 kW and an energy range of 25 kWh to 500 kWh. It utilizes NMC chemistry, which is preferred over LFP for its high energy density characteristics.

- Renewable Integration (e)

Innovative energy storage solutions play a pivotal role in facilitating the seamless integration of RESs while ensuring cost-effectiveness. These solutions will be instrumental in helping the European Union (EU) achieve its ambitious carbon offset targets by 2050 as outlined in the European Green Deal, all the while bolstering European energy security. BESS technology plays a vital role in this context, offering the ability to provide energy or absorb energy to offset fluctuations in RE production and changes in electrical loads [75].

BESS technology offers several advantages over conventional electricity generation methods:

✓ Partial Load Operation: BESSs can effectively operate at partial load with minimal performance degradation, enhancing overall system efficiency.
✓ Rapid Response: BESSs can swiftly respond to varying electrical loads, adapting to changing conditions in real-time.
✓ Load Following Capability: BESSs are well-suited for both load following down (matching load reductions) and load following up (meeting increased demand) by either charging or discharging energy as needed.
✓ Grid Variability Smoothing: BESS technology plays a crucial role in mitigating grid variability associated with fluctuations in renewable energy generation.

Critical technical considerations for the implementation of BESSs encompass achieving a targeted minimum number of cycles per year, frequently within the range of 50 to 500 cycles. These considerations underscore the remarkable versatility and effectiveness of BESSs in grid stabilization, optimizing the integration of RESs and advancing sustainability, aligning with the European Union's green energy objectives. The specified battery system is suitable for residential and commercial PV systems as well as small wind farms. It offers a versatile power range, spanning from 10 kW to 1 MW, and an energy range from 10 kWh to 4 MWh. This flexibility allows it to support services ranging from just a few minutes to up to 4 h of operation.

- Back-up Power (f)

As the costs associated with BESSs continue to decline, fresh opportunities for cost-effective technology deployment, often linked with RESs, are becoming increasingly accessible. Simultaneously, the frequency and intensity of natural disasters are on the rise. Consequently, an expanding number of companies are opting for BESSs as a versatile energy solution. This choice is driven by the recognition that traditional backup power solutions, such as diesel generators, may prove insufficient, especially during extended and large-scale disasters. One of the primary limitations of diesel generators is their reliance on on-site diesel fuel delivery, which typically takes only a few days [76]. To circumvent these limitations and ensure reliable backup power during critical situations, the preference is shifting toward the utilization of BESSs. Key technical considerations for the deployment of BESSs to enhance disaster resilience encompass achieving a targeted minimum number of cycles per year, which frequently falls within the range of 10 to 200 cycles. By choosing to implement a BESS, organizations can significantly bolster their disaster resilience, establishing a dependable and sustainable backup power source that is not dependent on fuel deliveries and is less susceptible to maintenance-related failures. This transition aligns perfectly with the increasing emphasis on robust and sustainable energy solutions, especially in regions susceptible to natural disasters. The specified battery system offers a power range from 10 kW to 500 kW and an energy range from 10 kWh to 1000 kWh. Its versatility allows for applications ranging from brief seconds to extended hours of operation.

- Power Quality (g)

Electric power quality services encompass the utilization of BESSs to safeguard customer loads downstream, ensuring their resilience against short-term events that can adversely affect the quality of power supplied to these loads [77]. Poor electricity quality can manifest in various ways, including:

✓ Voltage Magnitude Fluctuations: This includes short-term voltage jumps or drops, as well as long-term fluctuations or reductions in voltage levels.
✓ Frequency Variations: Changes in the initial frequency at which the power is delivered.
✓ Low Power Factor: Indicating an excessive phase difference between voltage and current, resulting in inefficient power transfer.
✓ Harmonics: The presence of current or voltage components at frequencies other than the primary frequency, causing distortion.
✓ Service Interruptions: These can occur at any time, ranging from fractions of a second to a few seconds.

Key technical considerations for the deployment of BESSs to enhance power quality encompass achieving a targeted minimum number of cycles per year, often falling within the range of 10 to 200 cycles. The discharge duration necessary to address power quality issues typically spans from a few seconds to several minutes. On-site BESSs play a pivotal role in effectively managing and rectifying disturbances in municipal electricity quality, ensuring a stable and high-quality power supply to downstream loads.

- Compensation of the Reactive Power (h)

Prior to the widespread use of high-capacity batteries, the management of power factor compensation and voltage support in T&D predominantly relied on equipment such as switch capacitor banks, transformer switches, and rotary machines. However, advancements in energy storage technology have enabled dynamic control of these critical network management functions using fast BESSs. These systems can also effectively manage reactive power [78]. When the BESS's DC/AC converter does not generate the entire apparent power required, the control unit calculates the available reactive power. If the reactive power absorbed at the measuring point exceeds a predefined threshold value, the BESS system steps in to provide the difference between the reactive power supplied by the grid and the threshold value. Key technical considerations for the implementation of BESSs in power factor compensation and voltage support applications encompass achieving a targeted minimum number of cycles per year, frequently falling within the range of 10 to 400 cycles. These technical considerations underscore the pivotal role of BESS technology in elevating the efficiency and effectiveness of power factor compensation and voltage support within T&D networks. The specified battery system is tailored for commercial and industrial customers, offering a power range ranging from 50 kW to 500 kW and an energy range from 50 kWh to 150 kWh. This system is engineered to deliver rapid power in seconds to minutes, making it ideal for applications where instant service is crucial.

- Energy Independence (i)

Microgrids are energy systems designed to balance distributed energy generation with demand within predefined operational parameters. Their primary purpose is to ensure sustainable and secure energy services, often in situations where a traditional grid is unavailable, such as on remote islands. Microgrid projects can be initiated for various reasons, and the factors driving their deployment can vary significantly from one project to another [79]. Key characteristics and technical considerations of microgrids include:

✓ Energy Source Integration: Microgrids typically incorporate solar PVs as a primary energy source, but they can integrate other renewable energy assets like wind turbines. This diversity contributes to their resilience and sustainability.

✓ Grid Interactivity: Microgrids can be designed to interact with the national electricity market (NEM) or operate as fully independent systems, providing flexibility in how they connect with broader energy networks.

✓ Customization: Microgrid solutions are highly customizable to suit specific needs, ensuring the highest levels of quality, safety, and performance in line with the unique requirements of each deployment.

Regarding energy storage within microgrids, there are key technical considerations to keep in mind, which frequently include achieving a minimum number of cycles per year, typically ranging from 10 to 400 cycles. Microgrids represent versatile solutions that assume a crucial role in bolstering energy resilience and security, especially in areas where conventional grid infrastructure is either limited or unreliable. Their capacity to seamlessly integrate RESs and incorporate energy storage serves to ensure the provision of efficient and sustainable energy services within such environments. The specified battery system allows for versatile applications, with the capability to provide power for durations ranging from just a few minutes to several hours. Additionally, this battery system is designed for the use of second-life batteries, offering opportunities for reuse in other applications. It does not require hard performance specifications, emphasizing adaptability and sustainability.

- EV Fast Charging (j)

The increasing adoption of EVs poses challenges to local power distribution networks, as many EV users require high-capacity quick charging that can strain existing connections. To alleviate this strain and enhance the efficiency of electrical loads, BESSs can be strategically deployed near areas with high EV usage. The application of BESSs in the power grid offers various advantages, including the provision of auxiliary services for distribution system operators (DSOs) and transmission system operators (TSOs). Previous research has explored two main approaches to mitigate the impact of EV adoption on networks and charging costs:

✓ BESS Integration with Residential RES: This approach involves deploying BES systems in households in conjunction with RESs, particularly PV, to support EV charging. The goal is to reduce the impact of EVs on household voltage and power quality while minimizing charging costs [80].

✓ BESS Coordination at Public Charging Stations: This approach focuses on optimizing BESS deployment at public CSs, considering cost reduction opportunities for BES systems. The aim is to mitigate the impact of EV adoption on network infrastructure and charging costs [81,82].

Technical considerations for the implementation of BESSs in these applications often encompass achieving a minimum number of cycles per year, typically falling within the range of 10 to 400 cycles. The primary objective of these studies and applications is to minimize the costs related to EV charging while simultaneously mitigating the impact of widespread EV adoption on electrical networks. Such endeavours play a pivotal role in the development of a more sustainable and efficient EV charging infrastructure, addressing the dual goals of cost-effectiveness and network sustainability.

Table 13 lists the parameters and values associated with customer energy management services, offering a comprehensive overview of key technical specifications.

Table 13. Comparison of Customer Energy Management Services.

	Power Range [kW]	Energy Range [kWh]	C-Rate	Chemistry	Second Life
(a)	10–1000	10–6000	0.1–1	LFP—NMC	Yes
(b)	10–2000	10–4000	0.5–1	LFP—NMC	Yes
(c)	10–1000	10–4000	0.25–1	LFP—NMC	Yes
(d)	50–250	25–500	0.1–2	NMC	Yes
(e)	10–1000	10–4000	0.25–4	LFP—NMC	Yes
(f)	10–500	10–1000	0.5–1	LFP—NMC	No
(g)	10–1000	10–350	1–3	NCM—NCA	No
(h)	50–500	50–150	1–3	NCM—NCA	No
(i)	0.1–10	0.2–20	0.1–1	LFP—NCA—NMC	Yes
(j)	100–300	20–300	1–5	NCM—NCA	Yes

6. Market Trends

The European energy landscape is undergoing a significant transformation, driven by the increasing adoption of advanced energy storage solutions, particularly battery-based technologies. One of the driving forces behind this transformation is the lucrative revenue opportunities presented by European frequency control markets. These markets have recognized the value of integrating cutting-edge technologies like batteries due to their rapid response capabilities, making them exceptionally well-suited to ensure grid stability. Notably, in Western Europe, a collective effort involving six countries has resulted in the provision of 3 GW of frequency control reserves, often referred to as frequency containment reserves (FCRs) [83,84]. These reserves play a crucial role in maintaining grid stability and ensuring the reliable operation of the electricity network. As of now, the participating nations include Germany, which leads the pack with a substantial 603 MW of FCR capacity, followed closely by France with 561 MW. The Netherlands, Switzerland, Austria, Belgium, and Denmark are also actively involved, collectively adding their contributions of 74 MW, 68 MW, 62 MW, 47 MW, and 30 MW, respectively. Moreover, the future looks promising, as both Spain and Poland are anticipated to join this endeavour in the coming years, further enhancing the grid's resilience. Germany, in particular, stands out as a frontrunner in this initiative, with its impressive 87% share of the existing FCR capacity and ambitious plans to add an additional 209 MW in the near future, solidifying its commitment to grid stability and renewable energy integration. The varying growth of the BESS market is primarily attributed to two key factors that significantly differ by region, namely government policies (incentives) and environmental concerns. The first offers a range of incentives, including subsidies, tax deductions, and benefits, to encourage the installation and use of BESSs, while the latter incentivizes regions that place a strong emphasis on environmental sustainability, as they view the BESS approach as a key solution to contribute to a cleaner environment. For example, Germany has proactively promoted the adoption of BESS technology through a series of significant incentives, including benefits for self-consumption of self-generated energy and financial support for the installation of home batteries [85]. In the United Kingdom, on the other hand, an innovative approach has been adopted by offering time-differentiated electricity tariffs. This strategy has driven the growth of BESS installations in both residential and commercial settings, allowing them to intelligently manage stored energy [86]. The insights presented in Figure 4 shed light on the predominant applications of large-scale ESSs in Europe during the year 2019. These applications stand as integral components in the operation of the European electricity grid, underscoring the strategic significance of energy storage in several key aspects.

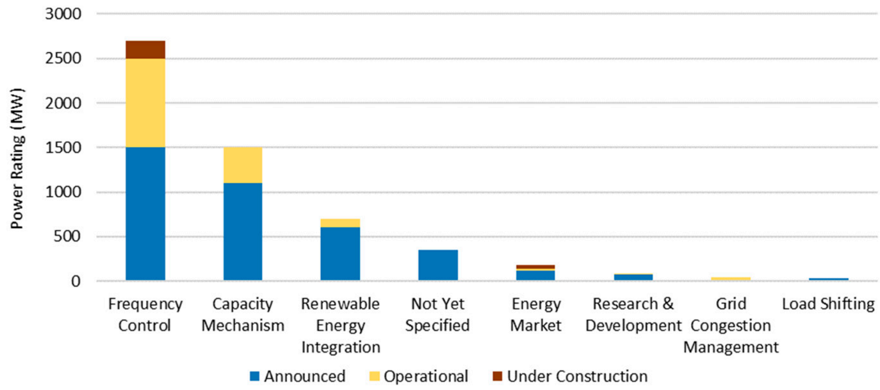


Figure 4. Most common applications for European large-scale energy storage systems (2019).

The utility-scale BESS market is poised for remarkable growth looking ahead to 2030, Figure 5. This growth trajectory is undeniably significant, considering the substantial increase projected from 10 GWh in mid-2017 to 45 GWh in the reference case and a more robust 74 GWh in the doubling case by 2030. The variations between the high and low estimates in the reference and doubling cases are primarily attributed to the extent of storage deployment across different applications. Key uncertainties in these projections include factors such as the average battery pack size in 2030 on a global scale and the composition of EVs deployed by that year. This uncertainty includes considerations like the size of EVs and whether falling battery costs will result in larger batteries to extend driving ranges. For this reason, these uncertainties are factored into the high and low case scenarios. However, what is truly striking is the potential for even more substantial expansion, as the most optimistic scenario paints a picture of capacity ranging from 81 GWh to a staggering 187 GWh by the year 2030. Figure 5 shows a representation of the cumulative volume of BESSs anticipated for this critical year, showcasing the immense potential and evolving landscape of utility-scale BESS solutions in the energy industry's future [87].

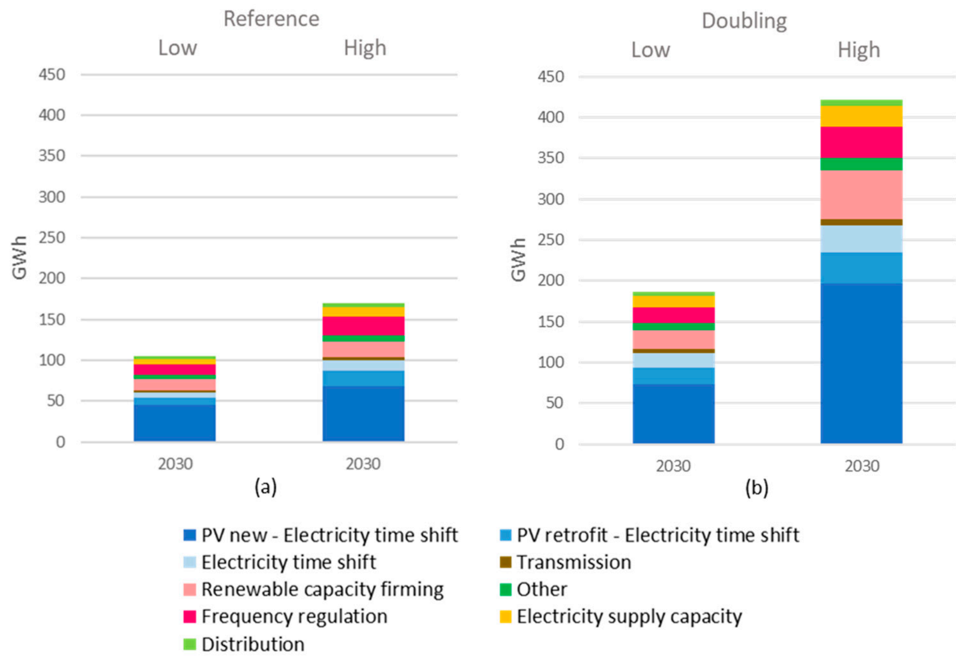


Figure 5. BESS capacity growth in stationary applications by main-use case, 2017–2030. (**a**) Reference scenario, (**b**) Doubling scenario.

Within the utility-scale applications, the primary use case for BESSs is the time-shift of electricity. By 2030, the reference case (Figure 5a) envisions the deployment of 45 GWh to

75 GWh of BESS capacity for electricity time-shifting operations, constituting approximately 60% to 62% of the total capacity. In the doubling case (Figure 5b), these figures rise to a range of 115 GWh to 269 GWh, accounting for 62% to 64% of total capacity.

In the reference case, the next prominent main-use application is frequency regulation, where the rapid response capabilities of batteries make them an ideal solution. In 2030, this application is projected to account for 15 GWh to 23 GWh of storage capacity. In the doubling case, the next significant main-use case after electricity time-shifting is renewable capacity firming, with storage capacity ranging from 24 GWh to 57 GWh. The remaining use cases for storage are estimated to contribute to the overall capacity, with 24 GWh to 41 GWh expected in 2030 in the reference case. These include renewable capacity firming, electricity supply reserve capacity, and various other services. In the doubling case, frequency regulation is the leading main-use case, accounting for 20 GWh to 42 GWh of storage capacity, followed by electricity supply reserve capacity and transmission, distribution, and other services, with 9 GWh to 21 GWh and 14 GWh to 32 GWh, respectively. These projections highlight the diverse range of applications and the substantial growth potential of BESS in utility-scale settings by 2030.

An in-depth analysis of the European energy storage market has been conducted, focusing on the estimated market volumes from 2020 to 2030, specifically in terms of GWh installed in various BTM applications, Figure 6 [88].

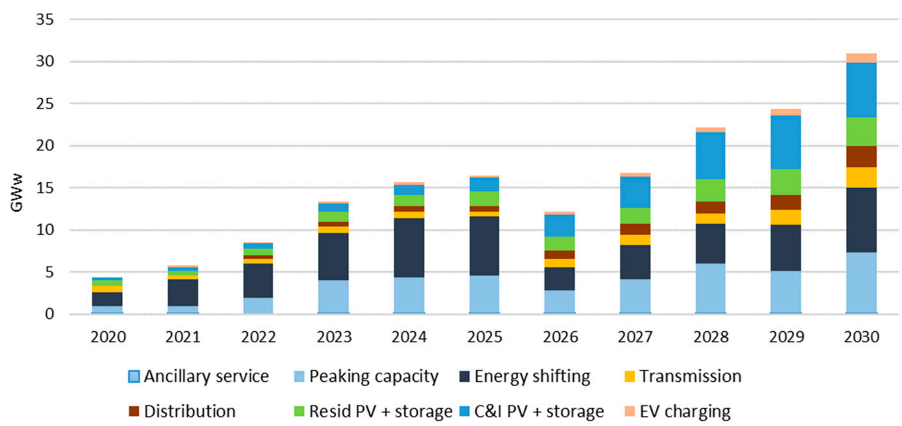


Figure 6. EU projected annual deployments by BTM applications, 2020–2030.

This Figure 6 reveals a general growth trajectory for most years, indicating a sustained and upward trend in energy storage adoption across Europe. However, a notable exception is projected for the year 2026, where a temporary slowdown in deployment is anticipated. The dip in energy storage deployment in 2026 is attributed to a specific factor: a reduction in the projections of power plant retirements. According to Bloomberg New Energy Finance (BNEF) models, it is expected that fewer power plants will retire during this period. This reduction in plant retirements impacts the overall energy storage landscape, as power plant retirements often create opportunities for energy storage deployment to compensate for the loss of generation capacity. While the projected slowdown in 2026 is a noteworthy observation, it is important to view it within the broader context of the overall growth trend in energy storage deployment across the decade from 2020 to 2030. This comprehensive approach allows stakeholders to gain a deeper understanding of how the energy storage market is expected to evolve in Europe over the coming decade.

When examining the year 2030 as the central focus of our analysis, the provided Figure 7 offers a comprehensive portrayal of the GWh installed across various applications within the domain of BESS [88]. Within this illustrative landscape, a striking contrast in the installed GWh becomes evident when comparing FTM and BTM applications.

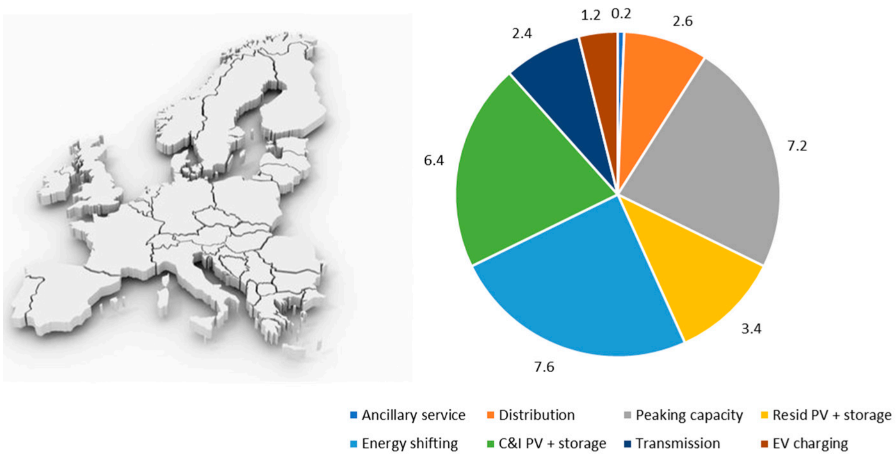


Figure 7. EU projected installations by BTM applications, 2030.

In the domain of BTM applications, two distinct categories stand out, boasting substantial installed GWh capacities. The peaking capacity commands a significant share of the installed GWh capacity, surpassing the 7 GWh mark. It assumes a pivotal role in the orchestration of grid operations, offering the swift deployment of stored energy during periods characterized by heightened electricity demand. The other application is energy shifting, which also boasts an installed capacity exceeding 7 GWh. Energy shifting is instrumental in the management of energy resources, enabling the storage of surplus energy during periods of low demand or excess renewable generation. It facilitates the subsequent discharge of stored energy during times of elevated demand or when renewable generation ebbs, contributing to optimized energy supply–demand dynamics.

In contrast, within the realm of BTM applications, two specific categories emerge as distinctive luminaries, exhibiting substantial installed GWh capacities: the commercial and industrial applications are one, commanding a formidable estimated installed capacity of 6.4 GWh. Commercial and industrial entities are increasingly embracing the integration of solar PV systems with battery storage to enhance energy efficiency and cost savings. The other application category is residential PV, which is notable for its estimated installed capacity of 3.4 GWh. Within residential settings, the integration of battery storage with PV systems assumes a pivotal role in augmenting the self-consumption of solar-generated energy and fortifying energy resilience. These findings encapsulate the envisaged distribution of BESS capacity across diverse applications by the year 2030. They underscore the burgeoning role of energy storage across multifarious sectors, encompassing grid management, seamless integration of renewable energy sources, and the enhancement of energy efficiency for commercial, industrial, and residential end-users.

7. Conclusions

In this exploration of BESS, we have examined various aspects, including their applications, technical considerations, and market trends. The evolving landscape of BESS presents both opportunities and challenges that require a strategic approach from stakeholders in various sectors. A key takeaway from this analysis is the remarkable versatility of BESS, spanning from large-scale utility deployments to residential and commercial applications at the BTM level. BESS's ability to store surplus energy during high generation periods and discharge it during peak demand contributes to grid stability. In addition, BESS serves as a reliable backup power source, outperforming traditional diesel generators and ensuring uninterrupted power during critical situations.

Market trends indicate a promising future for BESS, with significant growth expected in both FTM and BTM applications. Looking ahead to 2030, the energy storage landscape is poised for transformation.

This study reveals a dynamic and promising landscape where advanced technologies, renewable energy integration, and strategic deployment strategies are key to unlocking

BESS's full potential. As we navigate the challenges and opportunities of the energy transition, BESS stands as an innovative and resilient solution, ready to power a sustainable future. These findings underscore the critical importance of ongoing research, development, and collaboration in the energy storage field. It is essential to increase investment in battery research, as this will allow researchers to develop safer, more efficient and long-lasting batteries. In parallel, strengthening regulations on battery management and recycling is equally crucial. These regulations will foster the creation of a battery recycling industry, reducing electronic waste and helping to ensure a sustainable supply of materials for battery production. Finally, the implementation of tax incentives for the installation of energy storage systems represents a significant step. These incentives can reduce upfront costs for consumers, incentivizing the widespread adoption of energy storage systems, which in turn will help reduce peak grid loads and improve the overall stability of the energy system. For future work, in light of the current preliminary stage of research, it is necessary to intensify research efforts in improving the performance of solid-state batteries by mitigating internal resistance and facilitating faster charging. This recommendation not only identifies a fundamental research area but also underscores the pressing need for innovative materials to overcome current challenges in batteries. In conclusion, with concerted efforts, we can harness the power of BESS to drive positive change in our energy systems, benefiting society, the environment, and the economy.

Author Contributions: Conceptualization, A.S. and M.B.; methodology, A.S.; formal analysis, A.S. and M.L.; investigation, A.S.; resources, A.S.; writing—original draft preparation, A.S. and M.L.; writing—review and editing, M.L.; supervision, D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage System
BM	Balancing Market
BMS	Battery Management System
BNEF	Bloomberg New Energy Finance
BTM	Behind the Meter
CS	Charging Station
DC	Direct Current
DG	Distributed Generation
DNO	Distribution Network Operator
DSO	Distribution System Operator
ESS	Energy Storage System
EMS	Energy Management System
EU	European Union
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FTM	Front of the Meter
GHG	Greenhouse Gas
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LTO	Lithium Titanate
NCA	Lithium Nickel Cobalt Aluminium Oxide
NEM	National Electricity Market
NMC	Lithium Nickel Manganese Cobalt
PCS	Power Conversion System

PV	Photovoltaic
RES	Renewable Energy Sources
SoC	State of Charge
SoH	State of Health
T&D	Transmission and Distribution
TOU	Time-Of-Use
TSO	Transmission System Operator
VRE	Variable Renewable Energy

References

1. Vatalis, K.I.; Avlogiaris, G.; Tsalis, T.A. Just transition pathways of energy decarbonization under the global environmental changes. *J. Environ. Manag.* **2022**, *309*, 114713. [CrossRef] [PubMed]
2. Horowitz, C.A. Paris Agreement. *Int. Leg. Mater.* **2016**, *55*, 740–755. [CrossRef]
3. Hannan, M.A.; Al-Shetwi, A.Q.; Begum, R.A.; Ker, P.J.; Rahman, S.A.; Mansor, M.; Mia, M.S.; Muttaqi, K.M.; Dong, Z.Y. Impact assessment of battery energy storage systems towards achieving sustainable development goals. *J. Energy Storage* **2021**, *42*, 103040. [CrossRef]
4. Psarros, G.N.; Papathanassiou, S.A. Electricity storage requirements to support the transition towards high renewable penetration levels—Application to the Greek power system. *J. Energy Storage* **2022**, *55*, 105748. [CrossRef]
5. Letcher, T.M. Global warming, greenhouse gases, renewable energy, and storing energy. In *Storing Energy*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 3–12. [CrossRef]
6. Lipu, M.S.H.; Mamun, A.A.; Ansari, S.; Miah, M.S.; Hasan, K.; Meraj, S.T.; Abdolrasol, M.G.; Rahman, T.; Maruf, M.H.; Sarker, M.R.; et al. Battery Management, Key Technologies, Methods, Issues, and Future Trends of Electric Vehicles: A Pathway toward Achieving Sustainable Development Goals. *Batteries* **2022**, *8*, 119. [CrossRef]
7. Jafari, M.; Botterud, A.; Sakti, A. Decarbonizing power systems: A critical review of the role of energy storage. *Renew. Sustain. Energy Rev.* **2022**, *158*, 112077. [CrossRef]
8. Hoeft, F. Internal combustion engine to electric vehicle retrofitting: Potential customer's needs, public perception and business model implications. *Transp. Res. Interdiscip. Perspect.* **2021**, *9*, 100330. [CrossRef]
9. Ballinger, B.; Stringer, M.; Schmeda-Lopez, D.R.; Kefford, B.; Parkinson, B.; Greig, C.; Smart, S. The vulnerability of electric vehicle deployment to critical mineral supply. *Appl. Energy* **2019**, *255*, 113844. [CrossRef]
10. Speirs, J.; Contestabile, M.; Houari, Y.; Gross, R. The future of lithium availability for electric vehicle batteries. *Renew. Sustain. Energy Rev.* **2014**, *35*, 183–193. [CrossRef]
11. Šimić, Z.; Topić, D.; Knežević, G.; Pelin, D. Battery energy storage technologies overview. *Int. J. Electr. Comput. Eng. Syst.* **2021**, *12*, 53–65. [CrossRef]
12. Hidalgo-León, R.; Siguenza, D.; Sanchez, C.; León, J.; Jácome-Ruiz, P.; Wu, J.; Ortiz, D. A survey of battery energy storage system (BESS), applications and environmental impacts in power systems. In Proceedings of the 2017 IEEE Second Ecuador Technical Chapters Meeting (ETCM), Salinas, Ecuador, 16–20 October 2017; pp. 1–6. [CrossRef]
13. Hannan, M.A.; Wali, S.B.; Ker, P.J.; Abd Rahman, M.S.; Mansor, M.; Ramachandaramurthy, V.K.; Muttaqi, K.M.; Mahlia, T.M.I.; Dong, Z.Y. Battery energy-storage system: A review of technologies, optimization objectives, constraints, approaches, and outstanding issues. *J. Energy Storage* **2021**, *42*, 103023. [CrossRef]
14. Duerr, S.; Ababei, C.; Ionel, D.M. Load Balancing with Energy Storage Systems Based on co-Simulation of Multiple Smart Buildings and Distribution Networks. In Proceedings of the 2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), San Diego, CA, USA, 5–8 November 2017; pp. 175–180. [CrossRef]
15. Gusev, Y.P.; Subbotin, P.V. Using Battery Energy Storage Systems for Load Balancing and Reactive Power Compensation in Distribution Grids. In Proceedings of the 2019 International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM), Sochi, Russia, 25–29 March 2019; pp. 1–5. [CrossRef]
16. Lawder, M.T.; Suthar, B.; Northrop, P.W.; De, S.; Hoff, C.M.; Leitermann, O.; Crow, M.L.; Santhanagopalan, S.; Subramanian, V.R. Battery Energy Storage System (BESS) and Battery Management System (BMS) for Grid-Scale Applications. *Proc. IEEE* **2014**, *102*, 1014–1030. [CrossRef]
17. Zich, J.; Jandik, J. Active Battery Management System for Home Battery Energy Storage. In Proceedings of the 2020 21st International Scientific Conference on Electric Power Engineering (EPE), Prague, Czech Republic, 19–21 October 2020; pp. 1–4. [CrossRef]
18. Byrne, R.H.; Nguyen, T.A.; Copp, D.A.; Chalamala, B.R.; Gyuk, I. Energy Management and Optimization Methods for Grid Energy Storage Systems. *IEEE Access* **2018**, *6*, 13231–13260. [CrossRef]
19. Keshan, H.; Thornburg, J.; Ustun, T.S. Comparison of Lead-Acid and Lithium Ion Batteries for Stationary Storage in Off-Grid Energy Systems. In Proceedings of the 4th IET Clean Energy and Technology Conference (CEAT 2016), Institution of Engineering and Technology, Kuala Lumpur, Malaysia, 14–15 November 2016; p. 30. [CrossRef]
20. Saini, V.K.; Seervi, A.; Kumar, R.; Sujil, A.; Mahmud, M.A.; Al-Sumaiti, A.S. Cloud Energy Storage Based Embedded Battery Technology Architecture for Residential Users Cost Minimization. *IEEE Access* **2022**, *10*, 43685–43702. [CrossRef]

21. del Valle, J.A.; Ansean, D.; Viera, J.C.; Antuna, J.L.; Gonzalez, M.; Garcia, V. Analysis of Advanced Lithium-Ion Batteries for Battery Energy Storage Systems. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–6. [CrossRef]
22. Galvan, E.; Mandal, P.; Sang, Y. Networked microgrids with roof-top solar PV and battery energy storage to improve distribution grids resilience to natural disasters. *Int. J. Electr. Power Energy Syst.* **2020**, *123*, 106239. [CrossRef]
23. Aghamohamadi, M.; Abdar, A. Charging Management of Chemical Lithium Nickel Cobalt Aluminum Oxide ($LiNiCoAlO_2$) Batteries, Considering Battery Degradation Effects under Uncertain Operation in Multi-Energy Systems. In Proceedings of the 2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Jaipur, India, 16–19 December 2020; pp. 1–6. [CrossRef]
24. Hamidi, A.; Weber, L.; Nasiri, A. EV Charging Station Integrating Renewable Energy and Second-Life Battery. In Proceedings of the 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain, 20–23 October 2013; pp. 1217–1221. [CrossRef]
25. Li, Y.; Feng, B.; Li, G.; Qi, J.; Zhao, D.; Mu, Y. Optimal distributed generation planning in active distribution networks considering integration of energy storage. *Appl. Energy* **2018**, *210*, 1073–1081. [CrossRef]
26. Medghalchi, Z.; Taylan, O. A novel hybrid optimization framework for sizing renewable energy systems integrated with energy storage systems with solar photovoltaics, wind, battery and electrolyzer-fuel cell. *Energy Convers. Manag.* **2023**, *294*, 117594. [CrossRef]
27. Zyryanov, V.; Kiryanova, N.; Korotkov, I.; Nesterenko, G.; Prankevich, G.; Rudiuk, I. Analysis of Energy Storage Systems Application in the Russian and World Electric Power Industry. In Proceedings of the 2020 Ural Smart Energy Conference (USEC), Ekaterinburg, Russia, 13–15 November 2020; pp. 106–109. [CrossRef]
28. Stecca, M.; Elizondo, L.R.; Soeiro, T.B.; Bauer, P.; Palensky, P. A Comprehensive Review of the Integration of Battery Energy Storage Systems into Distribution Networks. *IEEE Open J. Ind. Electron. Soc.* **2020**, *1*, 46–65. [CrossRef]
29. Benini, M.; Canevese, S.; Cirio, D.; Gatti, A. Participation of Battery Energy Storage Systems in the Italian Balancing Market: Management Strategies and Economic Results. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–6. [CrossRef]
30. Figgener, J.; Stenzel, P.; Kairies, K.P.; Linßen, J.; Haberschusz, D.; Wessels, O.; Angenendt, G.; Robinius, M.; Stolten, D.; Sauer, D.U. The development of stationary battery storage systems in Germany—A market review. *J. Energy Storage* **2020**, *29*, 101153. [CrossRef]
31. Telaretti, E.; Dusonchet, L. Stationary Battery Systems in the Main World Markets: Part 1: Overview of the State-of-The-Art. In Proceedings of the 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Milan, Italy, 6–9 June 2017; pp. 1–5. [CrossRef]
32. Spoorthi, B.; Pradeepa, P. Review on Battery Management System in EV. In Proceedings of the 2022 International Conference on Intelligent Controller and Computing for Smart Power (ICICCSP), Hyderabad, India, 21–23 July 2022; pp. 1–4. [CrossRef]
33. Rajendran, G.; Vaithilingam, C.A.; Misron, N.; Naidu, K.; Ahmed, M.R. A comprehensive review on system architecture and international standards for electric vehicle charging stations. *J. Energy Storage* **2021**, *42*, 103099. [CrossRef]
34. See, K.W.; Wang, G.; Zhang, Y.; Wang, Y.; Meng, L.; Gu, X.; Zhang, N.; Lim, K.C.; Zhao, L.; Xie, B. Critical review and functional safety of a battery management system for large-scale lithium-ion battery pack technologies. *Int. J. Coal Sci. Technol.* **2022**, *9*, 36. [CrossRef]
35. Liu, M.; Cao, X.; Cao, C.; Wang, P.; Wang, C.; Pei, J.; Lei, H.; Jiang, X.; Li, R.; Li, J. A Review of Power Conversion Systems and Design Schemes of High-Capacity Battery Energy Storage Systems. *IEEE Access* **2022**, *10*, 52030–52042. [CrossRef]
36. Lee, D.; Cheng, C.-C. Energy savings by energy management systems: A review. *Renew. Sustain. Energy Rev.* **2016**, *56*, 760–777. [CrossRef]
37. Reihani, E.; Sepasi, S.; Roose, L.R.; Matsuura, M. Energy management at the distribution grid using a Battery Energy Storage System (BESS). *Int. J. Electr. Power Energy Syst.* **2016**, *77*, 337–344. [CrossRef]
38. Hänsch, K.; Naumann, A.; Wenge, C.; Wolf, M. Communication for battery energy storage systems compliant with IEC 61850. *Int. J. Electr. Power Energy Syst.* **2018**, *103*, 577–586. [CrossRef]
39. Conzen, J.; Lakshmipathy, S.; Kapahi, A.; Kraft, S.; DiDomizio, M. Lithium ion battery energy storage systems (BESS) hazards. *J. Loss Prev. Process. Ind.* **2023**, *81*, 104932. [CrossRef]
40. Wong, D.N.; Wetz, D.A.; Mansour, A.M.; Heinzel, J.M. The Influence of High C Rate Pulsed Discharge on Lithium-Ion Battery Cell Degradation. In Proceedings of the 2015 IEEE Pulsed Power Conference (PPC), Austin, TX, USA, 31 May–4 June 2015; pp. 1–6. [CrossRef]
41. BU-410: Charging at High and Low Temperatures. Available online: https://batteryuniversity.com/article/bu-410-charging-at-high-and-low-temperatures#:~:text=Lithium%20Ion%3A%20Li%2Dion%20can,diffusion%20rates%20on%20the%20anode (accessed on 12 September 2023).
42. Stan, A.-I.; Swierczynski, M.; Stroe, D.-I.; Teodorescu, R.; Andreasen, S.J. Lithium Ion Battery Chemistries from Renewable Energy Storage to Automotive and Back-Up Power Applications—An Overview. In Proceedings of the 2014 International Conference on Optimization of Electrical and Electronic Equipment (OPTIM), Bran, Romania, 22–24 May 2014; pp. 713–720. [CrossRef]

43. Willem, R. Lithium Battery Prices Plunge. Available online: https://www.statista.com/chart/23807/lithium-ion-battery-prices/ (accessed on 12 September 2023).
44. Kannan, D.R.R.; Weatherspoon, M.H. The effect of pulse charging on commercial lithium nickel cobalt oxide (NMC) cathode lithium-ion batteries. *J. Power Sources* **2020**, *479*, 229085. [CrossRef]
45. Thackeray, M.M.; Johnson, C.S.; Vaughey, J.T.; Li, H.N.; Hackney, S.A. Advances in manganese-oxide 'composite' electrodes for lithium-ion batteries. *J. Mater. Chem.* **2005**, *15*, 2257. [CrossRef]
46. Baccouche, I.; Jemmali, S.; Manai, B.; Nikolian, A.; Omar, N.; Essoukri Ben Amara, N. Li-ion battery modeling and characterization: An experimental overview on NMC battery. *Int. J. Energy Res.* **2022**, *46*, 3843–3859. [CrossRef]
47. Wang, M.; Liu, K.; Dutta, S.; Alessi, D.S.; Rinklebe, J.; Ok, Y.S.; Tsang, D.C. Recycling of lithium iron phosphate batteries: Status, technologies, challenges, and prospects. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112515. [CrossRef]
48. Ekawati, K.D.R.; Sholikah, A.P.; Yudha, C.S.; Widiyandari, H.; Purwanto, A. Comparative Study of NCA Cathode Material Synthesis Methods towards Their Structure Characteristics. In Proceedings of the 2018 5th International Conference on Electric Vehicular Technology (ICEVT), Surakarta, Indonesia, 30–31 October 2018; pp. 57–61. [CrossRef]
49. Parthasarathy, C.; Laaksonen, H.; Halagi, P. Characterisation and Modelling Lithium Titanate Oxide Battery Cell by Equivalent Circuit Modelling Technique. In Proceedings of the 2021 IEEE PES Innovative Smart Grid Technologies—Asia (ISGT Asia), Brisbane, Australia, 5–8 December 2021; pp. 1–5. [CrossRef]
50. Global Cell Prices Fall Below $100/kWh for First Time in Two Years. Available online: https://source.benchmarkminerals.com/article/global-cell-prices-fall-below-100-kwh-for-first-time-in-two-years (accessed on 31 October 2023).
51. Bruno, V. Visualized: How Much Do EV Batteries Cost? Available online: https://www.visualcapitalist.com/visualized-how-much-do-ev-batteries-cost/#:~:text=Lithium%20nickel%20cobalt%20aluminum%20oxide,point%20at%20%24112.7%20per%20kWh (accessed on 31 October 2023).
52. Schnell, J.; Günther, T.; Knoche, T.; Vieider, C.; Köhler, L.; Just, A.; Keller, M.; Passerini, S.; Reinhart, G. All-solid-state lithium-ion and lithium metal batteries—Paving the way to large-scale production. *J. Power Sources* **2018**, *382*, 160–175. [CrossRef]
53. Anuj. Solid State Battery vs Lithium Ion: Which One Is Better 2023? 2023. Available online: https://evbatteryhub.com/solid-state-battery-vs-lithium-ion-energy-density/ (accessed on 14 September 2023).
54. Bates, M.; Preger, Y.; Torres-Castro, L.; Harrison, K.L.; Harris, S.J.; Hewson, J. Are solid-state batteries safer than lithium-ion batteries? *Joule* **2022**, *6*, 742–755. [CrossRef]
55. Alex, E. Understanding the Energy Storage World Leaders, Anticipating the Next Big Markets. 2017. Available online: https://www.energy-storage.news/understanding-the-energy-storage-world-leaders-anticipating-the-next-big-markets/ (accessed on 12 September 2023).
56. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]
57. Baker, J.N.; Collinson, A. Electrical energy storage at the turn of the Millennium. *Power Eng. J.* **1999**, *13*, 107–112. [CrossRef]
58. Sa'ed, J.; Favuzza, S.; Massaro, F.; Telaretti, E. Optimization of BESS Capacity Under a Peak Load Shaving Strategy. In Proceedings of the 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), Palermo, Italy, 12–15 June 2018; pp. 1–4. [CrossRef]
59. Malhotra, A.; Battke, B.; Beuse, M.; Stephan, A.; Schmidt, T. Use cases for stationary battery technologies: A review of the literature and existing projects. *Renew. Sustain. Energy Rev.* **2016**, *56*, 705–721. [CrossRef]
60. Kim, Y.-J. Experimental Study of Battery Energy Storage Systems Participating in Grid Frequency Regulation. In Proceedings of the 2016 IEEE/PES Transmission and Distribution Conference and Exposition (T&D), Dallas, TX, USA, 3–5 May 2016; pp. 1–5. [CrossRef]
61. Jo, H.; Choi, J.; Agyeman, K.A.; Han, S. Development of Frequency Control Performance Evaluation Criteria of BESS for Ancillary Service: A Case Study of Frequency Regulation by KEPCO. In Proceedings of the 2017 IEEE Innovative Smart Grid Technologies—Asia (ISGT-Asia), Auckland, New Zealand, 4–7 December 2017; pp. 1–5. [CrossRef]
62. Krata, J.; Saha, T.K. Real-Time Coordinated Voltage Support With Battery Energy Storage in a Distribution Grid Equipped with Medium-Scale PV Generation. *IEEE Trans. Smart Grid.* **2019**, *10*, 3486–3497. [CrossRef]
63. Tongge, L.; Yonghong, H.; Junyi, M.; Yimin, X. The Research on Black Start Strategy of Distributed Photovoltaic-Battery Energy Storage Systems Based on Cluster Division. In Proceedings of the 2020 IEEE Sustainable Power and Energy Conference (iSPEC), Chengdu, China, 23–25 November 2020; pp. 337–342. [CrossRef]
64. Li, J.; You, H.; Qi, J.; Kong, M.; Zhang, S.; Zhang, H. Stratified Optimization Strategy Used for Restoration with Photovoltaic-Battery Energy Storage Systems as Black-Start Resources. *IEEE Access* **2019**, *7*, 127339–127352. [CrossRef]
65. Usama, M.U.; Kelle, D.; Baldwin, T. Utilizing Spinning Reserves as Energy Storage for Renewable Energy Integration. In Proceedings of the 2014 Clemson University Power Systems Conference, Clemson, SC, USA, 11–14 March 2014; pp. 1–5. [CrossRef]
66. Gowda, S.N.; Zhang, T.; Kim, C.J.; Gadh, R.; Nazaripouya, H. Transmission, Distribution deferral and Congestion relief services by Electric Vehicles. In Proceedings of the 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 18–21 February 2019; pp. 1–5. [CrossRef]

67. Eyer, J. *Electric Utility Transmission and Distribution Upgrade Deferral Benefits from Modular Electricity Storage: A Study for the DOE Energy Storage Systems Program*; Sandia National Laboratories (SNL): Albuquerque, NM, USA; Livermore, CA, USA, 2009. [CrossRef]
68. Eyer, J.; Corey, G. *Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide: A Study for the DOE Energy Storage Systems Program*; Sandia National Laboratories (SNL): Albuquerque, NM, USA; Livermore, CA, USA, 2010. [CrossRef]
69. Suberu, M.Y.; Mustafa, M.W.; Bashir, N. Energy storage systems for renewable energy power sector integration and mitigation of intermittency. *Renew. Sustain. Energy Rev.* **2014**, *35*, 499–514. [CrossRef]
70. Li, X.; Hui, D.; Lai, X. Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations. *IEEE Trans. Sustain. Energy* **2013**, *4*, 464–473. [CrossRef]
71. Oudalov, A.; Cherkaoui, R.; Beguin, A. Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application. In Proceedings of the 2007 IEEE Lausanne Power Tech, Lausanne, Switzerland, 1–5 July 2007; pp. 621–625. [CrossRef]
72. Willis, H.L. *Power Distribution Planning Reference Book*; CRC Press: Boca Raton, FL, USA, 2004. [CrossRef]
73. Gil, H.A.; Joos, G. On the Quantification of the Network Capacity Deferral Value of Distributed Generation. *IEEE Trans. Power Syst.* **2006**, *21*, 1592–1599. [CrossRef]
74. Mbungu, N.T.; Bansal, R.C.; Naidoo, R.M.; Siti, M.W. Analysis of a Grid-Connected Battery Energy Storage Based Energy Management System. In Proceedings of the 2020 First International Conference on Power, Control and Computing Technologies (ICPC2T), Raipur, India, 3–5 January 2020; pp. 1–5. [CrossRef]
75. Peng, C.-Y.; Kuo, C.-C.; Tsai, C.-T. Optimal Configuration with Capacity Analysis of PV-Plus-BESS for Behind-the-Meter Application. *Appl. Sci.* **2021**, *11*, 7851. [CrossRef]
76. Qatan, M.S.; Hepburn, D.M.; Zhou, C. Development of a Back-Up Battery Management System—A Case Study in Petroleum Development Oman. In Proceedings of the IEEE EUROCON 2009, St. Petersburg, Russia, 18–23 May 2009; pp. 475–479. [CrossRef]
77. Yukita, K.; Ichiyanagi, K.; Goto, Y.; Hirose, K. A Study of Electric Power Quality Using Storage System in Distributed Generation. In Proceedings of the 2007 9th International Conference on Electrical Power Quality and Utilisation, Barcelona, Spain, 9–11 October 2007; pp. 1–4. [CrossRef]
78. Rouco, L.; Sigrist, L. Active and Reactive Power Control of Battery Energy Storage Systems in Weak Grids. In Proceedings of the 2013 IREP Symposium Bulk Power System Dynamics and Control—IX Optimization, Security and Control of the Emerging Power Grid, Rethymno, Greece, 25–30 August 2013; pp. 1–7. [CrossRef]
79. Jo, J.; Cha, H. A Comparative Analysis of Stability for Battery Energy Storage System Operating with Diesel Generator in a Stand-Alone Microgrid. In Proceedings of the 2018 IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES), Hamilton, New Zealand, 31 January–2 February 2018; pp. 291–295. [CrossRef]
80. Thomas, D.; Deblecker, O.; Genikomsakis, K.; Ioakimidis, C.S. Smart House Operation Under PV and Load Demand Uncertainty Considering EV and Storage Utilization. In Proceedings of the IECON 2017—43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pp. 3644–3649. [CrossRef]
81. Wang, M.; Mu, Y.; Xu, X.; Jia, H.; Wang, T.; Jin, X.; Jiang, Q. Load Power Smoothing Control of Distribution Network Including Photovoltaic Generation with Energy Storage from Electric Vehicles. In Proceedings of the 2017 IEEE Power & Energy Society General Meeting, Chicago, IL, USA, 16–20 July 2017; pp. 1–5. [CrossRef]
82. Sun, Y.; Yue, H.; Zhang, J.; Booth, C. Minimization of Residential Energy Costs for PV-SWH and PV-T Systems. *IFAC-PapersOnLine* **2019**, *52*, 940–945. [CrossRef]
83. Thien, T.; Schweer, D.; vom Stein, D.; Moser, A.; Sauer, D.U. Real-world operating strategy and sensitivity analysis of frequency containment reserve provision with battery energy storage systems in the german market. *J. Energy Storage* **2017**, *13*, 143–163. [CrossRef]
84. Astero, P.; Evens, C. Optimum Operation of Battery Storage System in Frequency Containment Reserves Markets. *IEEE Trans. Smart Grid.* **2020**, *11*, 4906–4915. [CrossRef]
85. Baig, Q. Funding Instruments Driving the Residential Storage Market in Germany. Available online: https://ptr.inc/funding-instruments-driving-the-residential-storage-market-in-germany/ (accessed on 31 October 2023).
86. Charging up: UK Utility-Scale Battery Storage to Surge by 2030, Attracting Investments of up to $20 Billion. Available online: https://www.ogv.energy/news-item/charging-up-uk-utility-scale-battery-storage-to-surge-by-2030-attracting-investments-of-up-to-20-billion (accessed on 31 October 2023).
87. IRENA. Electricity Storage and Renewables: Costs and Markets to 2030. 2017. Available online: https://www.google.com/search?q=IRENA_Electricity_Storage_Costs_2017_Summary+2017&oq=IRENA_Electricity_Storage_Costs_2017_Summary+2017&aqs=chrome..69i57j0i546.1811j0j4&sourceid=chrome&ie=UTF-8 (accessed on 14 September 2023).
88. U.S. Department of Energy. Energy Storage Grand Challenge: Energy Storage Market Report. 2020. Available online: https://www.osti.gov/biblio/1908714 (accessed on 15 September 2023).