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Research Article

Recharging the Transition to Low Carbon Economy: The Role of Battery Energy Storage Systems

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Abstract

The transition to a sustainable energy future requires significant changes to power generation, with a strong focus on decarbonisation. While renewable energy sources like wind and solar are expanding rapidly to replace fossil fuels, their variability poses challenges to grid stability and electricity costs. Traditional power grids struggle to accommodate these fluctuations, limiting renewable energy integration. Large-scale energy storage offers a crucial solution by storing excess renewable energy and releasing it during peak demand, enhancing grid reliability. Energy Storage Systems (ESS) play a vital role in enabling a greener energy landscape by ensuring a stable and efficient power supply while reducing fossil fuel dependence. Among these, Battery Energy Storage Systems (BESS) stand out due to their scalability, affordability, and growing adoption in the energy sector. Advances in battery technology are driving cost reductions, making BESS an increasingly viable solution for large-scale renewable energy integration. This paper examines the role of BESS in addressing grid challenges and supporting the expansion of renewable energy, highlighting its importance in the transition to a sustainable power system.

Keywords

Renewable Energy Integration, Battery Energy Storage Systems (BESS), Grid Stability, Energy Transition, Decarbonization, Energy Storage Systems (ESS), Sustainable Power Supply, Fossil Fuel Reduction

1. Introduction

The world must make significant changes to energy systems to protect the environment. A crucial part of this transformation is decarbonising power generation. Progress has been made in expanding renewable energies like wind and solar power to replace fossil fuels. However, while it's crucial to accelerate the growth of renewable energy, this also presents new challenges. Unlike traditional power plants, wind and solar power rely on weather conditions, meaning they are not as consistent. This raises concerns about the reliability of power grids and potential increases in electricity prices as the proportion of renewable energy increases.

Traditional power grids struggle to accommodate the variable nature of renewable energy sources like solar and wind. This variability can disrupt grid stability and limit the amount

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of renewable energy that can be integrated. One key solution is large-scale energy storage. By storing excess renewable energy during periods of high generation and releasing it during peak demand, we can improve grid stability and enable greater penetration of variable renewable energy sources.

In the 21st century, with a growing emphasis on sustainability and renewable energy, Energy Storage Systems play a crucial role in driving the shift towards a greener future. These systems offer a versatile and reliable solution to store excess energy generated from renewable sources, ensuring a stable and efficient power supply while reducing dependency on fossil fuels. As we strive towards a more sustainable energy landscape, the significance of such systems cannot be overstated.

2. Overview of Energy Storage Systems

Figure 1. *The fundamentals of energy storage, Source: Science Direct.*

In the 21st century, it would be very hard to imagine our modern societies without a secure supply of electricity. Therefore, ensuring a reliable, sustainable, and cost-effective energy service is a critical issue facing the power system [1].

Traditional power systems are centralised, raising reliability concerns as demand grows. They also depend on inefficient, polluting, and limited fossil fuels. Additionally, conventional power facilities are usually located far from populated areas to minimise the impact on the public. As a result, transmitting and distributing the generated electricity to end-use sites (such as buildings) often leads to significant power losses. To address these challenges, Distributed Energy Resources (DERs) have garnered significant attention due to their sustainability and cost-effectiveness. Their integration into the grid has proliferated in recent years. DERs, which are smaller power sources located near the point of consumption, often co-located with end-use sites, commonly consist of renewable energy (RE) generation and energy storage [2].

However, the intermittent nature of renewable energy sources (RES) and the mismatch between power generation and peak load periods present significant integration challenges. RES, such as solar and wind power, are sporadic and unpredictable, posing difficulties for effective grid integration. For instance, while significant photovoltaic (PV) production occurs during midday due to solar irradiance, increased power demand is observed during the early evening hours. As a result, integrating RES into the power system can impact user service reliability negatively.

In addressing this issue, Energy Storage Systems (ESS) are now being integrated into the power system to stabilise bulk power generation and mitigate the intermittency of RES. They function as a buffer between consumers and suppliers by storing excess energy during periods of high generation and utilising it when demand exceeds supply. Without energy storage, conventional power grids must significantly adjust power generation to meet demand, leading to inefficiencies.

By integrating ESS, particularly Battery Energy Storage Systems (BESS), into the power system, conventional power generation can operate at a constant level, enhancing efficiency and cost-effectiveness. Additionally, BESS can mitigate power fluctuations from RES or conventional generators. Network operators can employ BESS to respond to network conditions, while residential consumers can benefit from reduced energy costs by shifting demand to periods with low energy prices or leveraging on-site production. This not only offers consumers additional benefits but also positions them at the centre of the future power system [3].

Moreover, energy storage systems play a crucial role in facilitating the shift towards a more sustainable and dependable energy landscape by optimising the utilisation of renewable energy sources and ensuring a stable energy supply.

Energy storage serves as a vital element in delivering flexibility and facilitating the integration of renewable energy within the energy infrastructure. It can balance both centralised and distributed electricity generation, thus enhancing energy security.

Furthermore, energy storage complements demand response, and flexible generation, and supports grid development. Additionally, it contributes to the decarbonisation of other economic sectors, while enabling the integration of higher proportions of variable renewable energy (RES) in areas such as transport, buildings, and industry.

A storage technology's power, capacity, and response time define its applications and role in the electricity system. Along with efficiency and cost, these factors shape its market revenue potential.

3. Energy Storage Technologies

Energy can be stored through various technologies, including mechanical, thermal, chemical, electrochemical, and electrical. As a result, different energy storage systems exist, each with unique characteristics and applications. Common examples include:

1. Electrochemical batteries (e.g., lithium-ion, lead-acid)
2. Pumped hydroelectric storage
3. Compressed air energy storage
4. Flywheel energy storage
5. Thermal energy storage (e.g., molten salt, ice storage)

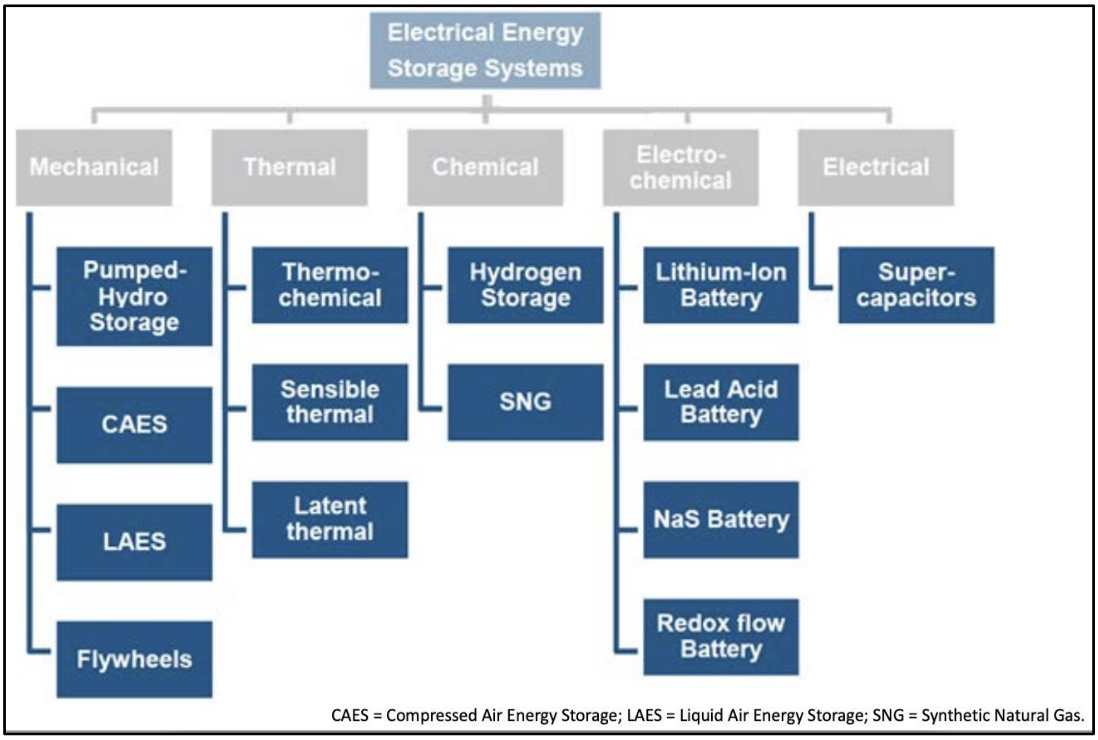

Figure 2. *Electrical Energy Storage Systems, Source: EU Commission.*

The choice of energy storage system depends on factors such as energy density, power capacity, response time, and cost-effectiveness for the specific application [4]. Lithium-ion batteries are believed to be the most economically viable energy storage solution, but there are several other technologies for battery storage currently being developed, including but not limited to the following:

Compressed Air Energy Storage (CAES): This technology is particularly effective in load shifting, which involves storing energy during periods of excess and releasing it during high-demand periods. These systems, typically housed in large chambers, use surplus power to compress and store air. When energy is needed, the compressed air is released and passes through an air turbine to generate electricity [5].

Mechanical gravity energy storage: Gravity batteries offer long-lasting energy storage solutions that can potentially last up to 50 years, making them a promising technology to address energy storage challenges [6]. Gravity batteries, also known as mechanical gravity energy storage solutions, store gravitational energy by lifting large rock masses or objects using hydraulic mechanisms. This technology is transforming the approach to long-duration energy storage. One example of this type of system is when energy is used to lift concrete blocks up a tower. When the energy is needed, the concrete blocks are lowered back down, generating electricity using the pull of gravity [7].

Flow batteries: These rechargeable fuel cells use chemical energy from two liquid components separated by a membrane.

Electrical charge is stored in liquid electrolyte tanks, which circulate through electrodes to extract electrons. The spent electrolyte returns to the tank, and when recharged by a solar panel or turbine, it is pumped back through the electrodes. Increasing storage capacity simply requires larger electrolyte tanks. Vanadium is a popular choice due to its reliability over thousands of cycles. These batteries can store 800 MWh of energy, enough to power thousands of homes. The market for flow batteries—led by vanadium cells and zinc-bromine, another variety—could grow to nearly $1 billion annually over the next 5 years [8].

One of the primary advantages of energy storage systems is their ability to facilitate the integration of renewable energy sources, such as solar and wind power [9]. By storing excess energy generated during peak production periods, energy storage systems can provide a consistent and reliable supply of electricity, even when renewable sources are not available.

Energy storage systems can help maintain grid stability by providing backup power during outages or periods of high demand [10]. This ensures a more reliable and resilient energy supply, reducing the risk of disruptions and minimising the impact of power outages on businesses and households.

Energy storage systems can store energy during off-peak hours when electricity rates are lower and then discharge that energy during periods of high demand. This capability helps reduce peak demand on the grid, resulting in cost savings for utilities and consumers alike [11].

By storing energy from renewable sources, energy storage systems can increase energy independence and reduce reliance on fossil fuels. This not only contributes to a cleaner environment but also enhances energy security by reducing dependence on imported fuels [12].

Energy storage systems are versatile and can be scaled to meet various energy needs, ranging from residential applications to large-scale utility projects. They can be deployed in different configurations, such as standalone systems or integrated with existing energy infrastructure, providing flexibility and adaptability [13].

Energy Storage Systems (ESS) are essential for meeting diverse energy needs. They include batteries, pumped hydro, and flywheels, storing energy through mechanical, electrochemical, or thermal methods. Despite their differences, all ESS serve the same purpose—providing a reliable power supply on demand.

4. Battery Energy Storage Systems

Battery Energy Storage Systems (BESS) are key to integrating renewable energy sources like solar and wind into the grid. They manage fluctuations by providing congestion relief, frequency regulation, and wholesale arbitrage. BESS charges from solar panels or the grid and releases stored energy when needed, ensuring a stable and reliable power supply essential for a sustainable energy network.

Figure 3. *Battery storage of renewable sources.*

The International Energy Agency (IEA) states that the global battery energy storage systems (BESS) capacity needs to increase drastically from 85 GW in 2023 to 1200 GW by 2030. This expansion is crucial to facilitate the seamless integration of renewable energy into the grid and achieve net-zero emissions by 2050. [14].

The UK government has projected that by facilitating the incorporation of a greater number of low-carbon technologies in the power, heat, and transport sectors, advanced energy storage solutions, such as battery storage systems, have the potential to yield substantial savings for the UK energy system. These savings could reach up to £40 billion (equivalent to $48 billion) by the year 2050. By enhancing the overall efficiency and flexibility of the energy system, these technologies would ultimately contribute to a reduction in consumer energy bills. This highlights the significant role that energy storage technologies can play in the transition towards a more sustainable and cost-effective energy future in the UK. [15].

BESS hardware includes battery modules, racks, and a power conversion system. Key software components are the EMS, BMS, and SCADA. The EMS integrates external systems. The BMS monitors and regulates battery modules. The SCADA controls, monitors, and protocols BESS processes. The BESS is protected from weather and fire.

Battery Energy Storage Systems (BESS) represent a significant advancement in power grid management due to their rapid response times. Unlike traditional power plants, which can take minutes or even hours to reach full power output, BESS can activate and deliver full power in as little as 0.02 seconds. This near-instantaneous response capability makes BESS invaluable for grid stability and reliability, particularly in scenarios where rapid power adjustments are required to maintain balance.

Beyond their speed, BESS provide additional benefits to grid operators. They can serve as contingency reserves, standing ready to inject power into the grid in the event of unexpected outages or demand surges. This can prevent blackouts and ensure a continuous supply of electricity to consumers. Furthermore, BESS can potentially defer the need for costly network upgrades. By providing localised power support and voltage regulation, BESS can alleviate stress on existing infrastructure and delay the need for capital-intensive expansion projects [16]. Flywheels have very fast reaction times, but they are currently too expensive to be used at scale and are therefore not a viable alternative to BESSs.

As shown in Figure 4, the only scalable technology with a quick enough activation time to meet the requirements for all types of frequency response services procured by grid operators in the UK and the EU are batteries. [17].

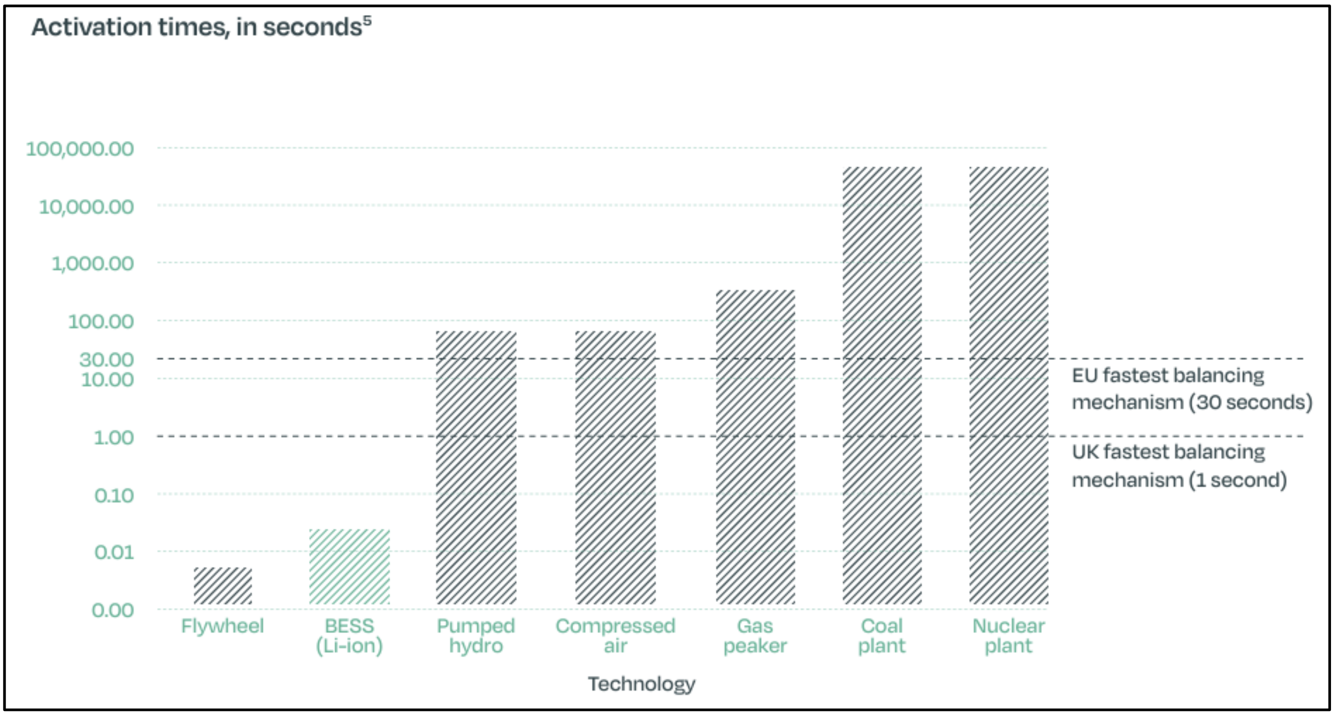

Figure 4. *Activation times, Source: ScienceDirect.*

Lithium-ion batteries have emerged as the leading technology for large-scale energy storage, despite the availability of various battery types. This dominance is attributed to several key benefits that make lithium-ion batteries particularly effective in addressing short-term and intra-day fluctuations in energy supply and demand. These advantages encompass high energy density, enabling the storage of significant amounts of energy within a compact space, and a relatively long lifespan, ensuring sustained performance over numerous charge-discharge cycles. Moreover, lithium-ion batteries exhibit rapid response times, allowing for swift adjustments to energy output in response to real-time grid conditions. Additionally, their modular design facilitates scalability, enabling the adaptation of energy storage systems to diverse capacity requirements. While other battery technologies may offer specific advantages, the overall combination of attributes positions lithium-ion batteries as the optimal solution for integrating renewable energy sources and maintaining grid stability in the face of intermittent generation patterns.

Batteries are electrochemical cells that can convert electricity to and from chemical energy. Different battery types, categorised by their chemical composition, have varying characteristics, including size, energy density, lifecycle, and cost [18]. Lead-acid, Nickel-Cadmium, and Lithium-Ion are the three most common types of rechargeable batteries. These secondary batteries are necessary for integration with renewable energy systems due to their ability to be recharged and used multiple times.

The most developed technology is focused on using lithium-ion batteries with key benefits listed below:

1. They can start charging and discharging at full capacity within milliseconds.
2. They can both increase and decrease the load in the grid.
3. They can store electricity for several hours or days.
4. They can charge and discharge multiple times per day.
5. They can perform up to approximately 10,000 charging cycles during their lifetime.
6. They have a high power density (power capacity divided by weight).
7. They have a high round-trip efficiency (energy discharged divided by energy charged) [19].

The energy potentially stored in a battery is usually determined as energy capacity and demonstrates the energy discharge in kilowatt-hours (kWh) from the fully charged battery state to a specific minimum voltage state. Lithium-ion batteries are a popular choice for battery energy storage systems (BESS) due to their advanced characteristics. [20]. Despite their high costs, lithium-ion batteries are rapidly declining in price and are expected to fall further in the coming years due to the widespread use of this technology. This, coupled with their advantages, which include high power and energy densities, long lifecycles, and the ability to be deeply discharged without degradation, makes them an attractive option.

BESS are ideal for integration with renewable energy technologies, especially in the form of BtM hybrid PV-BESS, due to the instantaneous response and high efficiency claimed by some BESS manufacturers. [21].

Battery Energy Storage Systems (BESS) are optimal solutions to address grid instability and reliability concerns arising from the increased use of Renewable Energy Sources (RES). BESS technologies provide several benefits, including peak load shaving, increased self-consumption, and greater energy flexibility for users. This reduces grid interaction by modifying the user's net demand profile. [22].

This suggests a shift away from residential-level, low self-consumption renewable energy (RE) systems, particularly PV systems. These systems are characterised by overnight unavailability and substantial excess generation fed back into Low Voltage Distribution Networks, which stresses the power system. Battery Energy Storage Systems (BESS) have been recognised as a proven technology for load management, utilising stored electricity during periods of increased energy consumption to balance supply and demand. [23].

5. The Role of BESS in Enhancing Grid Stability

Figure 5. *The Tesla Megapack battery storage-based Saticoy battery storage system, with a capacity of 100MW/400MWh, was launched last year.*

According to a report by IRENA, renewables are expected to account for 80–90% of power generation globally by 2050 [24]. As mentioned before, a major issue faced by solar and wind power is their intermittent nature. Sunlight and wind availability change throughout the day, so storing extra energy generated during high production times is crucial for low or no-generation periods. This is where Battery Energy Storage Systems step in, capturing, storing, and distributing energy efficiently.

The increasing use of renewable energy sources like photovoltaics (PVs) is causing power instability due to their intermittent nature. Battery energy storage systems (BESS) are a promising solution to manage these fluctuations by storing excess energy and releasing it when needed. Hybrid PV-BESS systems are gaining popularity due to their potential to provide reliable and efficient power for both residential and commercial applications.

The instability of renewable energy sources creates three types of power grid imbalances that vary in duration. These challenges must be addressed to ensure a successful energy transition. These can be categorised by their timescale:

Short-term imbalances: Grid frequency stability depends on balancing electricity generation and consumption. Fast frequency response capacity is essential to manage imbalances and prevent major disruptions. Traditional power plants, with turbines synchronised to grid frequency, offer crucial rotational inertia—slowing frequency changes and buying time for grid operators to activate reserve capacity. However, many renewable energy sources, like wind and solar plants, lack this inherent inertia, posing challenges to grid stability. This means that new sources of fast-frequency response are required in grids with large proportions of intermittent renewables [25]. Imbalances lasting 15 to 30 minutes are classified as short-term, although the cause may persist. These imbalances must be initially addressed by fast frequency response capacity; other mechanisms can be employed subsequently.

Intra-day imbalances: The daily pattern of electricity consumption does not tend to match electricity generation from renewable sources. This mismatch leads to intra-day imbalances that occur on most days and can last for several hours: when weather conditions are favourable for renewable energy generation, conventional power plants have to decrease their output to accommodate the influx of renewable energy into the grid. Conversely, when electricity consumption surpasses renewable energy generation, conventional power plants must ramp up their output to bridge the gap. These imbalances result in volatility in electricity spot market prices, which is exacerbated as the share of renewables in the grid grows.

Seasonal imbalances: Long-term energy storage solutions with minimal losses are necessary due to the mismatch between seasonal consumption patterns and the distribution of renewable power generation throughout the year. Battery Energy Storage Systems (BESSs) are not a viable solution for this particular imbalance, unlike the other two types of imbalances; alternative technologies are needed. To grasp the full potential of BESSs as a mitigant for the imbalances caused by renewables, it is helpful to understand how BESS functions and to know its main components [26].

Battery Energy Storage Systems (BESSs) have a rapid response time, measured in milliseconds, and a high round-trip efficiency of approximately 90%. This makes them ideally suited to mitigate both short-term and intra-day imbalances in power generation, outperforming other technologies in this regard. Due to significant cost reductions, BESSs are poised to play a pivotal role in stabilising the future electrical grid.

The global utility-scale energy storage market is projected to experience substantial growth, reaching a cumulative capacity of 250 GW by 2030. This represents an almost eightfold increase in the next 8 years compared to the current installed storage capacity.

Grid-connected Battery Energy Storage Systems (BESS) offer various services for grid use. Storing clean or excess energy when renewable energy production is high and using it later for Energy Self-Consumption is a key function. This becomes beneficial during high electricity prices, encouraging higher PV self-consumption in homes. This leads to incorporating renewable energy on-site in a controlled manner. BESS can support the power system by regulating frequency or time-shifting energy through Time-Scheduled Charging to help with load levelling and reduce stress on the system. Shifting energy in time could boost earnings for the owner and open avenues for Energy Trading by capitalising on price differences between base and peak loads.

Smart meters are being implemented globally by market operators to encourage consumer participation in the power system and enhance grid reliability. These meters can deliver cost and energy savings to consumers; however, to fully realise their benefits, it is essential to go beyond the meters and transform energy consumption patterns within buildings. This is crucial given that buildings, especially residential ones, account for a substantial portion of total energy consumption. Development of new technologies is currently underway to improve consumer engagement in the power system. This is primarily achieved by sending price signals to smart meters, which provide consumers with the information they need to participate in demand-side management programs. [27].

The additional benefit of causing zero disruption to consumers is what differentiates residential BESS from smart devices. Notably, BESS enable end-user participation in Demand Response programs without impacting any device operation [28]. The BESS allows for net-load increases or decreases to be performed in the background. This eliminates the need to shut down processes or adjust settings that may cause discomfort, such as heating/cooling setpoints or consumption habits.

Residential BESS can create additional revenue streams for their owners by providing services to the power system. Additionally, BESS can assist in meeting DSM objectives by harnessing Demand Response advantages, thus benefitting both the utility and the consumer.

Grid stability is crucial for ensuring a dependable power supply to meet consumer needs. Battery Energy Storage Systems (BESS) offer vital services to the grid like regulating frequency, supporting voltage, and shaving off peak loads. By incorporating energy storage systems into the grid, utilities can effectively handle supply and demand fluctuations, lowering blackout risks, and boosting system reliability.

Today's power systems encounter the challenge of supporting and expanding the use of Renewable Energy (RE) technologies, especially Photovoltaic (PV) systems, which face issues due to their intermittent nature. This issue is particularly significant in urban settings as PV installations in the Low Voltage (LV) Distribution Network of power systems and residential buildings have significantly grown. This growth is mainly attributed to substantial cost reductions for PV systems and government backing.

By the end of 2022, the total global installed capacity of renewable energy sources (RES) for both behind-the-meter (BtM) and front-the-meter (FtM) installations had reached 3372 GW, demonstrating a 9.6% increase from the previous year. [29] The anticipated tenfold increase in global BESS deployments to over 400 GWh per year by 2030 highlights the growing recognition of BESS technology as a vital component of future power systems, [30], while also the global Energy Storage market is anticipated to experience a 23 % Compound Annual Growth Rate (CAGR) until 2030 [31].

The residential BESS industry in Europe has now surpassed 1 million installations, with a total energy storage capacity of 9.3 GWh. This is based on the 1.1 million BESS systems installed. In 2022, almost 0.5 million BESS were installed in Europe, alongside over 1.8 million residential PVs. As most of these investments are hybrid installations, around 25% of new PVs in 2022 will have BESS. [32]. The crucial and expansive role that BESS can play in all power system segments is reconfirmed by the aforementioned observations. BESS can optimise energy usage and provide protection from price volatility in residential and commercial applications. In grid-scale cases, BESS can provide balancing services to operators, new business opportunities to investors, and manage energy prices to benefit the energy market.

To increase the use of photovoltaics (PVs) in buildings, it is critical to make buildings with on-site PV production more compatible with the power grid. Energy storage can help achieve this by turning buildings into more predictable power sources, which minimises the unpredictable injection of excess PV production and helps ensure the security and stability of the power system. With the continuously declining costs of PVs and Battery Energy Storage Systems (BESS), the solution of integrating BESS with PVs is expected to become cost-effective in the near future [33], thus enabling Energy Storage to assist in the further exploitation of Renewable Energy Sources (RES). The latter is one of the key targets of the EU's 2050 long-term strategy and the recent REPowerEU plan incorporates a manifesto for the rise of RES share in final energy consumption from 40 % to 45 %, towards the interim targets [34].

The incorporation of renewable energy sources into the grid presents technical challenges because of their variability and unpredictability. Battery Energy Storage Systems (BESS) can assist in stabilising these fluctuations, allowing for a greater integration of renewables in the energy mix. Through storing surplus energy during times of excess production and discharging it when necessary, battery storage systems are essential in grid stability and optimising the use of clean energy sources.

Their adaptability ensures a smoother transition towards sustainable energy systems, reducing reliance on fossil fuels. BESS technology continues to evolve, offering scalable solutions for diverse energy demands.

6. The Economics of BESS

Figure 6. *IoT infrastructure of a Battery Energy Storage System (BESS), Source: AdvanTech.*

Energy arbitrage is one of the primary economic benefits of battery storage systems. This process involves storing energy when costs are low, such as during periods of high solar generation, and releasing it during peak pricing periods. Energy arbitrage can lead to substantial cost savings, particularly in areas with significant differences between peak and off-peak electricity prices.

To monetise these advantages, BESSs have the potential to generate revenue in three primary ways:

1. Ancillary services: balancing services for when there are sudden mismatches in electricity generation and consumption in the grid, caused by plant outages, sudden changes in weather, etc.
2. Wholesale trading: charging (buying electricity) during periods of low prices and discharging (selling electricity) during periods of high prices on spot markets at electricity exchanges;
3. Capacity markets: generation capacity procured by grid operators for pre-defined periods in the future.

BESS owners can bid in tenders run by grid operators to provide ancillary services, such as frequency response. Frequency response is less costly than wholesale trading because it requires less battery discharge, and therefore causes less battery degradation. [35].

The fluctuating nature of wind and solar energy leads to increased trading volumes as the share of renewables in the grid grows. This also affects the volatility of intra-day electricity prices in some countries with high proportions of renewables.

Battery systems can take advantage of this price volatility by charging when electricity prices are low and discharging when prices are high. When renewable energy generation is high, or electricity demand is low, renewables can meet most or all of the electricity demand. During those times when renewables meet the entire demand in the spot market, they become the marginal technology that sets the price. [36].

The marginal cost of renewables is close to zero as they do not require fuel inputs, which means prices can drop close to zero or even below zero when there is excess generation [37].

During periods of high demand on the spot market or when renewable energy generation is low, traditional power plants set the prices as the primary generators. When the electricity required in the spot market surpasses what renewables offer, more traditional power plants come into play based on their costs, beginning with the cheapest and moving up to the more expensive ones until the market demand is satisfied [38].

Grid operators, besides offering extra services, also secure reserve generation capacity for a more extended period. Unlike frequency response markets that tackle short-term imbalances, these capacity markets handle imbalances between supply and demand over a day or more. While various generation technologies can join capacity markets, they usually offer lower compensation compared to frequency response or wholesale markets. As a result, BESS hasn't garnered significant revenue from capacity markets in many countries. Nonetheless, this trend might shift as some electricity markets place a greater emphasis on capacity markets. Engaging in a capacity market agreement could reduce a BESS's risk exposure by providing long-term, predictable revenues [39].

Assessing the risk-return profiles of BESSs and renewables can be aided by comparing their key characteristics. Figure 7 below compares stand-alone utility-scale 1-hour battery energy storage systems (BESS) with utility-scale onshore wind and solar plants without tracking capabilities in Germany and the UK.

	BESS	Wind/Solar
Equity IRR	8–10%[x]	4–8%[x]
Debt ratio	0–30%[x]	60–90%[x]
Main revenue streams	Wholesale markets, ancillary services, capacity markets	Power purchase agreements, subsidies, wholesale markets
Operational life	7,500 cycles (~21 years assuming one cycle per day)[x]	25–30 years[x]
Build-out of renewables	More volatile power markets → Higher revenue potential	More hours with low or negative prices → Lower capture price (price cannibalization)
Other key risks	Changes to market design, nascent technology	Meteorological conditions, grid curtailment

Figure 7. *Comparing key characteristics of BESSs and renewables, Source: TION Renewables AG.*

Battery Energy Storage Systems (BESS) projects currently have higher internal rates of return than onshore wind and solar projects, partly due to a lower proportion of contracted revenue. While some revenue-stabilizing products exist, most BESS revenues are non-contracted and depend on factors like power price volatility. In contrast, renewable energy projects often utilise PPAs to sell a large portion of their generated energy at a fixed price. The lower proportion of contracted revenues in BESS projects contributes to lower debt ratios, but as the technology matures and lenders become more comfortable, these ratios are expected to increase [40].

The lifespan of a BESS is heavily reliant on the cycling strategy, unlike wind or solar plants. The number of charge-discharge cycles per day is determined by the availability and profitability of revenue streams. Typically, the aim is to achieve an average of one to two daily cycles. A typical BESS can perform around 7,500 full cycles during their operational life [41]; the battery cells then have to be replaced after reaching the maximum degradation level. The operational lifespan of a BESS without replacing its battery cells can be estimated by dividing the maximum cycle count by the expected number of cycles. To match the operational life of a solar power plant, a BESS needs at least one battery cell replacement.

The cost of battery storage systems, especially lithium-ion batteries, has dropped significantly over the past decade, decreasing by around 89% since 2010. This decrease is due to technological advancements, economies of scale in production, and increased market competition. However, the total installation cost of a battery storage system still includes the power electronics, integration, and installation, which can fluctuate depending on the project's size and location.

Calculating the ROI of battery storage systems requires a comprehensive understanding of initial costs, operational and maintenance costs, and revenue streams or savings over the system's lifespan [42]. The Energy Storage Association estimates the average lifespan of lithium-ion battery storage systems to be approximately 10 to 15 years. Return on investment (ROI) is a long-term consideration, with break-even points fluctuating depending on usage patterns, local energy prices, and available incentives. For example, the ROI for a residential solar-plus-storage system will differ from that of a large-scale utility battery storage project.

BESS investments generally present an appealing risk-return profile, particularly when combined with renewable energy investments. This is further enhanced by long-term positive factors, such as easier access to financing, alongside other favourable conditions for investors.

The economics of battery storage are significantly influenced by government subsidies and incentives. In the United States, the investment tax credit (ITC) [43], which offers a tax credit for solar energy systems, has been extended to include battery storage when installed in conjunction with solar panels. The financial viability of battery storage projects can be significantly impacted by different schemes, such as grants or feed-in tariffs, that vary by country. These incentives improve ROI and lower upfront costs.

Battery storage is becoming increasingly viable due to decreasing costs, with lithium-ion battery costs projected to fall by 30-40% by 2030. However, challenges such as upfront costs, environmental concerns, and battery longevity need to be addressed.

In conclusion, while the economics of battery storage are intricate and constantly changing, the decreasing costs and potential for substantial savings and a favourable return on investment are making it an increasingly attractive option. However, informed investment decisions require careful consideration of various factors, including market trends, government incentives, and environmental impacts. As the world transitions toward a more sustainable energy future, battery storage will undoubtedly play a crucial role [44].

7. BESS Market Analysis

The BESS market is experiencing a significant shift towards safety, innovation, and sustainable energy storage solutions. This transformation is fuelled by the rapid growth of renewable energy projects, such as solar and wind farms. BESS integration addresses the intermittent nature of renewable energy generation, allowing for energy storage during periods of excess supply and release during peak demand. This not only stabilises the grid but also optimises revenue generation from renewable energy projects.

Furthermore, government grants are available to incentivise the inclusion of BESS in renewable energy projects. This not only provides a financial incentive for power providers but also addresses the grid instability caused by the fluctuating power supply from traditional renewable energy sources. Battery systems can stabilise the power supply and minimise voltage distortion, improving the overall grid performance [45].

The decentralisation of energy production is a growing trend, resulting in more households and businesses turning to solar panels and other distributed energy resources [46]. BESS allows consumers to store excess energy generated locally, reducing their reliance on the centralised grid and providing a pathway towards greater energy independence. This shift towards a more distributed energy model has the potential to increase resilience and sustainability in the face of disruptions.

As the demand for energy storage solutions continues to rise, advancements in battery technology are driving down costs and improving efficiency. Innovations in materials, design, and manufacturing processes are leading to lighter, more compact, and longer-lasting batteries, making BESS more accessible and cost-effective for a wide range of applications. This progress not only benefits the renewable energy sector but also opens up opportunities for new business models and applications.

A 2023 report by Bloomberg New Energy Finance (BNEF) highlights the rapid growth of the BESS market, driven by falling battery costs and increasing renewable energy penetration. This cost reduction makes BESS a more attractive proposition for grid operators and utility companies. Scientific research confirms lithium-ion's current stronghold in BESS due to its well-established technology and proven track record. However, advancements are being made within the lithium-ion domain itself. New cathode and anode materials are being explored to improve performance and safety characteristics. Additionally, alternative chemistries like flow batteries are gaining traction for specific applications where their longer lifespans and inherent safety advantages might outweigh the energy density of lithium-ion [47].

The North American BESS integrator market is concentrated: Tesla leads with a 25% market share, followed by Fluence (22%) and Sungrow (13%). Sungrow's success is due to cost competitiveness and advanced products. The Inflation Reduction Act and state policies will drive growth, increasing competition in the US BESS integrator market [48].

Figure 8. *A solar and storage project in Germany, the Spitalhöfe solar park.*

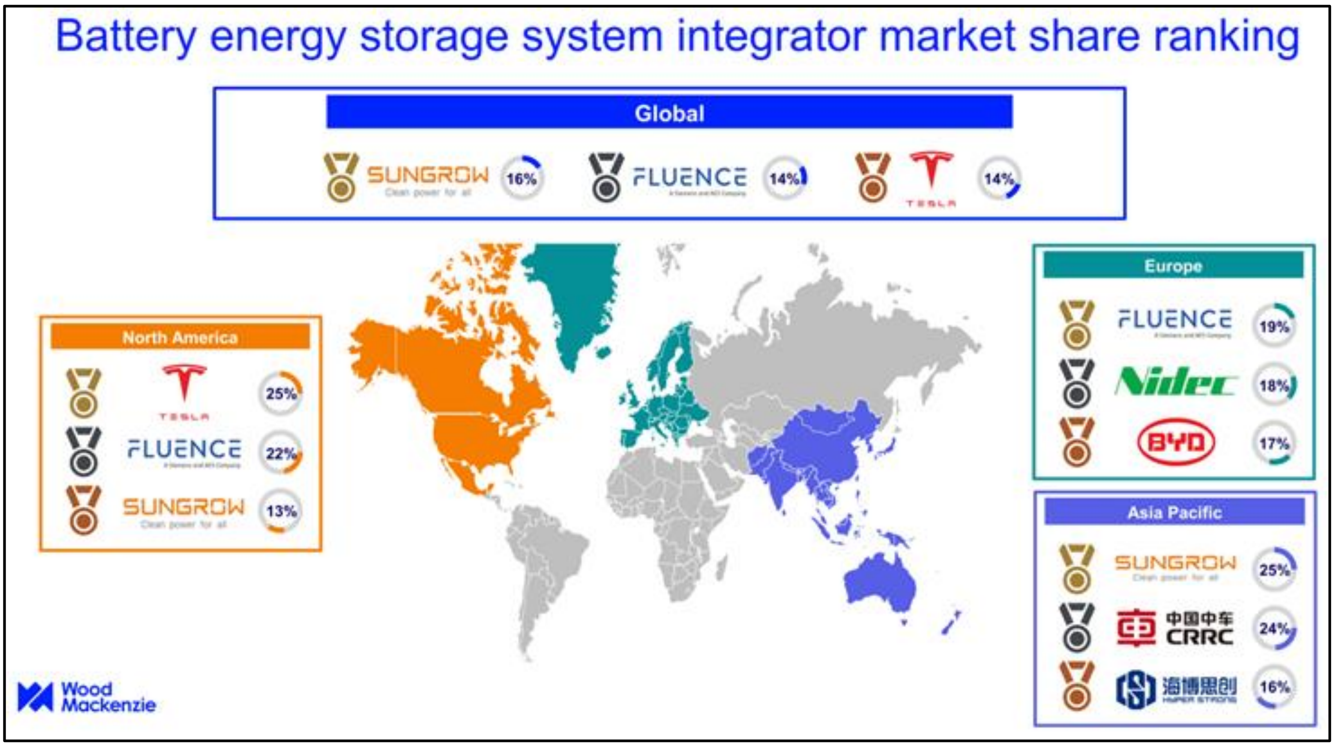

Figure 9. *BESS integrator market share ranking, Source: Wood Mackenzie.*

The global energy storage market experienced an unprecedented expansion in 2023, nearly tripling in size with the addition of 45 GW (97 GWh) – the largest year-on-year increase ever recorded. This upward trajectory is projected to persist in 2024, with the global energy storage capacity expected to surpass 100 GWh for the first time. This growth is primarily fuelled by the Chinese market, which is poised to retain its position as the world's largest energy storage market.

According to the European Market Outlook for Battery Storage 2024-2028 report [49], in 2023, Europe experienced a 94% year-on-year increase in new Battery Energy Storage Systems (BESS) capacity, installing 17.2 GWh. This marked the third consecutive year of doubling the annual market. Driven primarily by the residential sector's response to high electricity prices and the desire for self-sufficiency, 12 GWh of the total added capacity was installed in this segment, representing 70% of the total. The commercial and industrial (C&I) battery segment contributed 1.6 GWh (9%), while grid-scale batteries connected 3.6 GWh (21%).

By the end of 2023, Europe's total operational BESS fleet reached 35.8 GWh. The residential segment held the largest share of accumulated capacity (63%), followed by large-scale battery systems (27%) and C&I (10%).

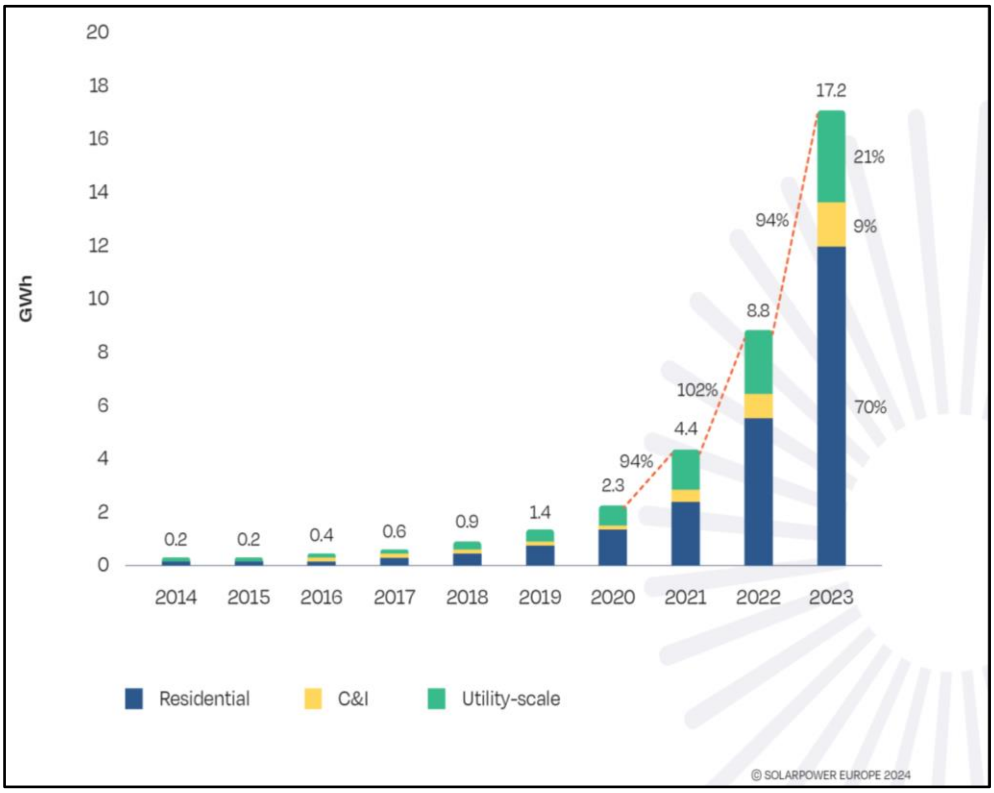

Figure 10. *Europe's total operating BESS fleet in 2023, Source: SolarPower Europe.*

Germany led the market in 2023, with 5.9 GWh of battery storage capacity deployed, a 152% increase over the previous year. Italy followed with 3.7 GWh (up 86%), and the United Kingdom with 2.7 GWh (up 91%). Austria and the Czech Republic also showed strong growth, with Austria adding more than 1 GWh (up 95%), and the Czech Republic tripling its market to over 900 MWh, driven by strong residential demand.

If we look at the top European countries in terms of installed and planned BESS capacity, we will have a different ranking as follows:

The UK - 25.68GWh: has been a pioneer in BESS adoption, with several large-scale projects already operational or in advanced stages of development. The country's favourable regulatory environment and renewable energy targets have driven significant investments in energy storage [50].

Italy - 12.23GWh: has emerged as a promising market for BESS, with several large-scale projects under development or recently commissioned. The country's focus on energy security and decarbonisation has driven investments in storage technologies [51].

Germany - 8.81 GWh: has a strong foothold in the European BESS market, driven by its ambitious renewable energy goals and the need to balance intermittent solar and wind power generation. The country has several gigawatt-scale BESS projects in the pipeline [52].

Spain - 8.09 GWh: ample solar and wind resources have fuelled the growth of BESS projects, particularly in regions with high renewable energy penetration. The country aims to leverage energy storage to support its clean energy transition [53].

France - 5.14GWh: slightly behind its European counterparts, France is rapidly catching up in the BESS race. The country's commitment to reducing carbon emissions and increasing renewable energy capacity has spurred interest in energy storage solutions [54].

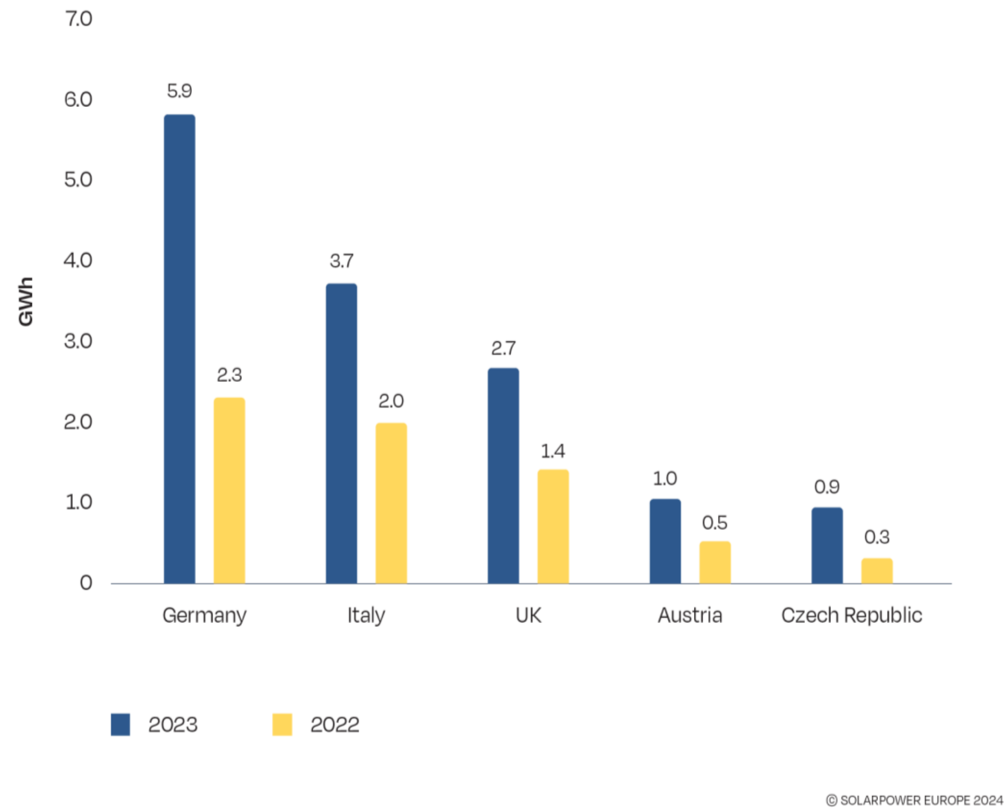

Figure 11. *Europe's top 5 countries in 2023 Source: SolarPower Europe.*

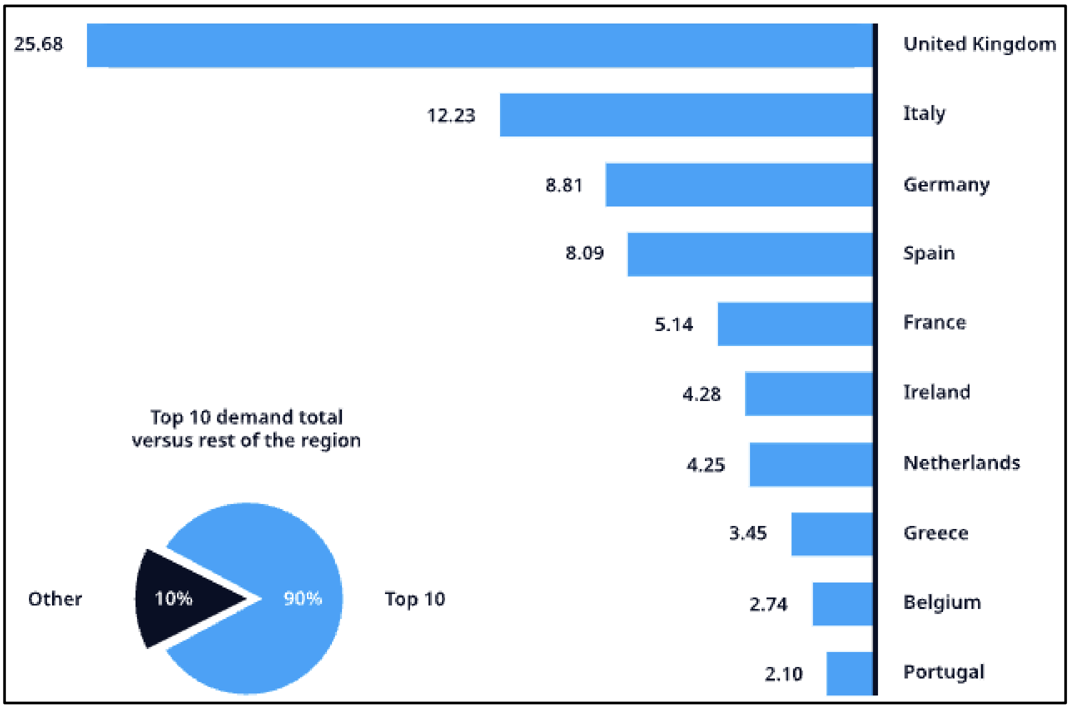

Figure 12. *New capacity forecasts for the top 10 European grid-scale energy storage markets 2022-2031 (GWh), Source: Wood Mackenzie.*

Belgium has recently witnessed the launch of one of Europe's largest BESS projects, reflecting the country's efforts to integrate more renewable energy sources into its grid [55]. It's important to note that the BESS landscape is constantly evolving, with new projects and policies shaping the market dynamics. Several other European countries, such as the Netherlands, Poland, and Sweden, are also making strides in energy storage deployment.

As per the latest edition of The Market Monitor by EASE and LCP-Delta:

1. The storage sector is experiencing unprecedented demand, with approximately 10GW of new installations expected in 2023. This includes 7GW of Behind-the-Meter (BtM) and 3GW of Front-of-the-Meter (FoM) storage power capacity.
2. The power capacity of the installed base is projected by EMMES to increase sixfold.
3. The impressive deployment results are driven by both supportive schemes and improved market conditions. Interestingly, the average storage duration for projects is also increasing. 2-hour projects are now more common, and 4-hour durations are expected soon across Europe.
4. The UK, Germany, and Italy are currently the primary markets for both BtM and FoM storage capacity and it is anticipated that they will maintain their dominance in the coming years. [56].

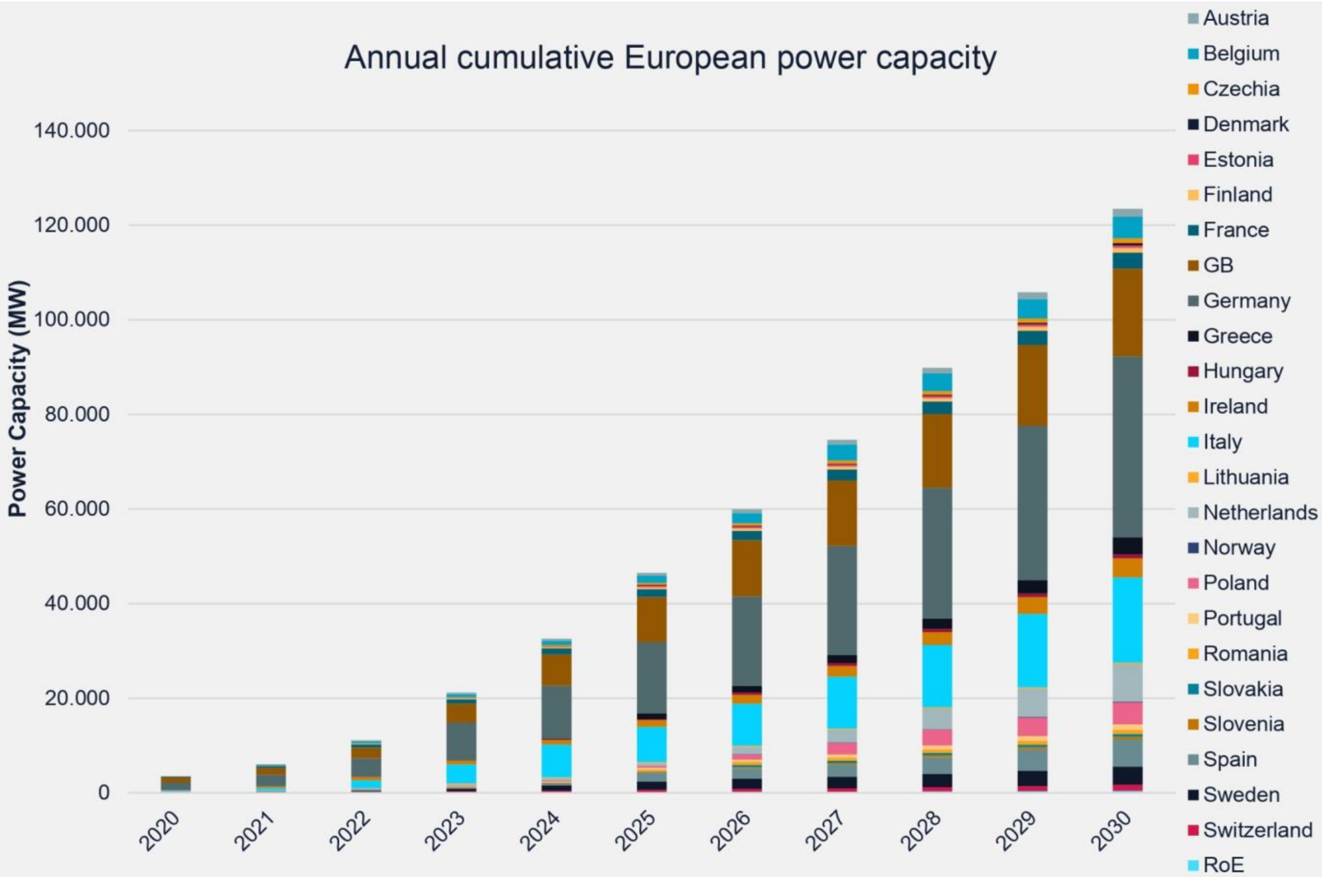

Figure 13. *Annual cumulative European power capacity, Source: EASE & LCP-Delta.*

In 2024, safety standards and regulations for BESS operations received increased attention. This focus extends beyond fire prevention to include advanced monitoring systems that enable early detection of potential problems and ensure reliable and secure grid integration.

The rapid expansion of Battery Energy Storage Systems (BESS) has been a significant development. In conjunction with renewable energy generation, battery storage has emerged as a cost-effective and efficient solution to the energy trilemma of security, affordability, and sustainability, which was exacerbated by the threat to European energy security posed by the war in Ukraine.

8. Global Lithium Ion Battery for Energy Storage Systems Market

Figure 14. Hybrid Renewable Battery Storage Systems.

The development of lithium-ion batteries began in the 1970s, with significant advancements occurring in the 1980s. This rapid progress culminated in the release of the first commercial lithium-ion battery in 1991, marking a remarkably short timeframe between laboratory research and industrial production [57]. Lithium-ion battery technology has significantly catalysed the evolution of energy storage systems, positioning it as a pivotal component in the global shift towards renewable energy solutions. Characterised by high energy density, longer life cycles, and efficiency in charging and discharging processes, lithium-ion batteries have emerged as the preferred choice for energy storage, underpinning a wide array of applications from residential and commercial to utility-scale projects.

As per the latest report published in March 2024, [58] the global lithium-ion battery market for energy storage systems is projected to experience significant growth in the coming years. It is expected to reach approximately USD 61,337 Million by 2033, increasing from USD 5,575.3 Million in 2023. This growth represents a compound annual growth rate (CAGR) of 27.1% during the forecast period of 2023 to 2033.

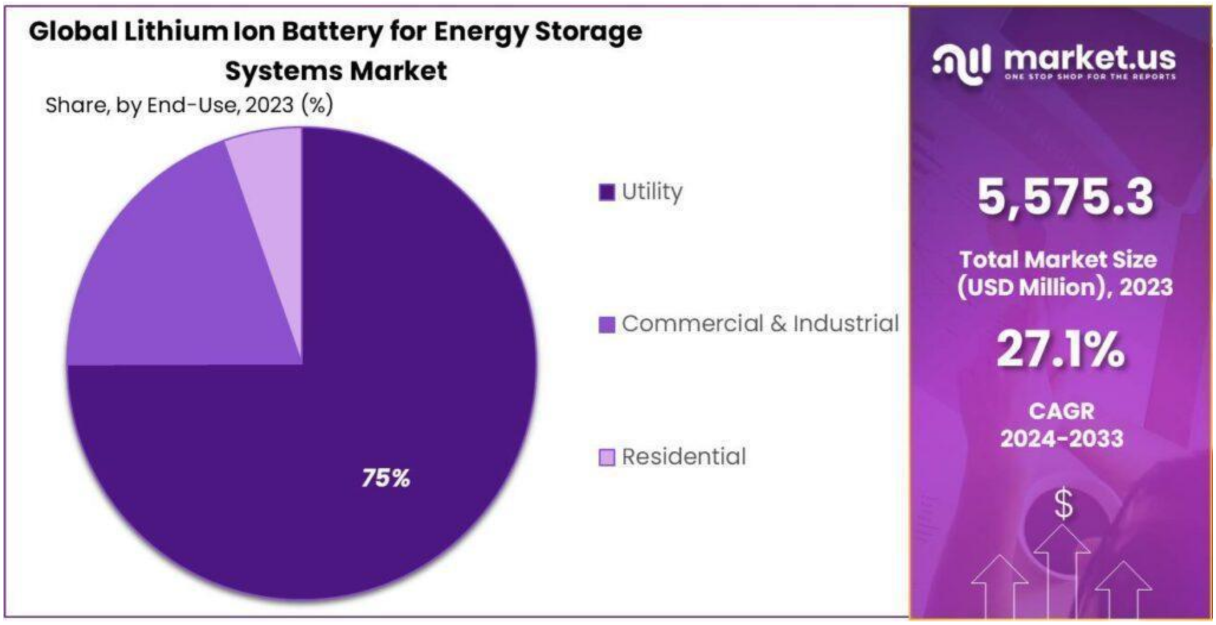

Figure 15. Global Lithium Battery for Energy Storage Systems Market Share, Source: market.us.

The above-cited report concludes that the market's growth is fundamentally driven by the escalating demand for clean and sustainable energy sources, alongside the global push for electrification and energy security. As governments and corporations intensify their commitment to decarbonisation and green energy initiatives, the deployment of lithium-ion battery-based storage systems is witnessing exponential growth, further bolstered by technological advancements, cost reductions, and supportive regulatory frameworks.

The current geopolitical landscape significantly influences the Lithium-Ion Battery for Energy Storage Systems (ESS) market, reflecting complex interactions between international trade policies, regional conflicts, and strategic alliances. Currently, several key geopolitical dynamics are shaping market trajectories, investment flows, and supply chain configurations in this sector.

Primarily, the intensification of trade tensions between major economies, notably the United States and China, impacts the Lithium-Ion Battery market. These tensions manifest in tariffs, trade barriers, and restrictions on technology transfers, affecting the cost structures and supply chain reliability for lithium-ion batteries [59]. China's dominant position in the lithium-ion battery supply chain, coupled with its significant reserves of critical raw materials [60] such as lithium, cobalt, and nickel, places it at the centre of geopolitical manoeuvres [61] affecting the market.

Moreover, the above-cited report says that recent geopolitical events, such as regional conflicts and sanctions, have underscored the vulnerability of global supply chains. For instance, the situation in the Democratic Republic of Congo (DRC), a major source of cobalt, illustrates how political instability can disrupt the availability of critical minerals for battery production. Similarly, Russia's role as a key supplier of nickel raises concerns about supply security amidst international sanctions and geopolitical tensions.

Asia Pacific held the largest market share, with 43.9% of the lithium-ion battery market for energy storage systems market in 2023. Asia Pacific dominates the Lithium-Ion Battery for Energy Storage Systems market due to several factors. Rapid urbanisation, industrialisation, and the adoption of electric vehicles in countries such as China, Japan, and South Korea drive substantial demand. Moreover, supportive government policies, incentives for renewable energy integration, and investments in infrastructure further bolster the market [62].

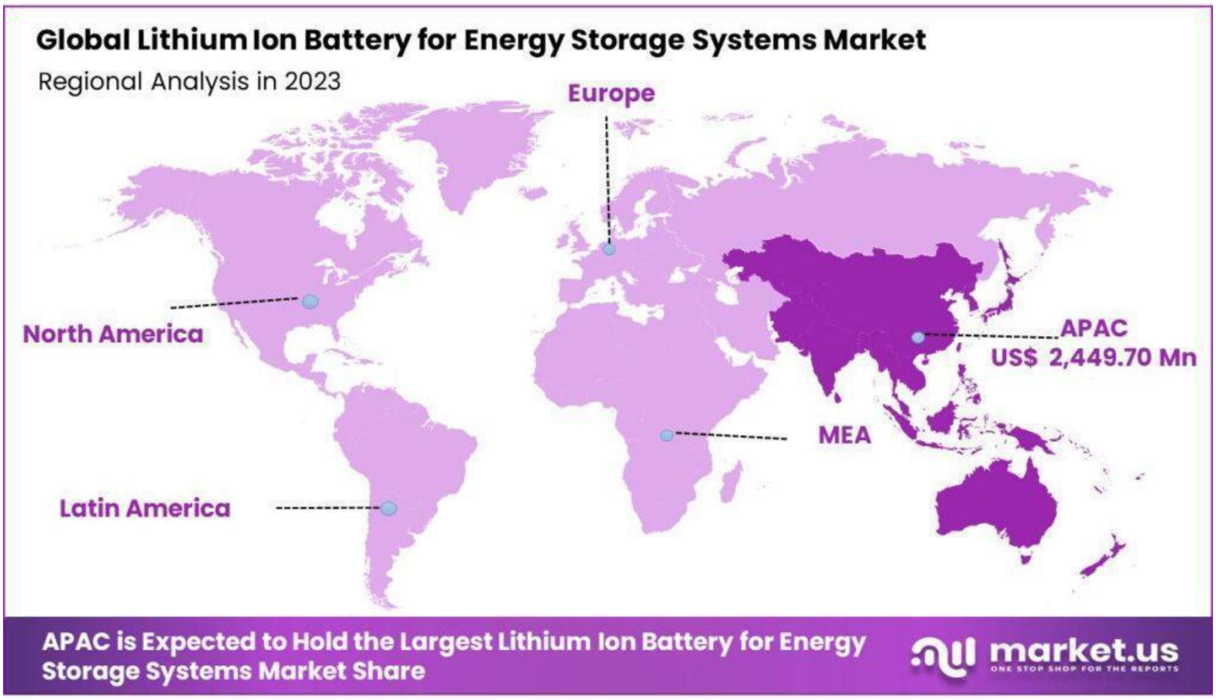

Figure 16. *Global Lithium Battery for Energy Storage Systems Market Regional Share, Source: market.us.*

Additionally, Asia Pacific hosts major manufacturers and suppliers of lithium-ion batteries, benefiting from established supply chains and economies of scale. These dynamics, coupled with growing environmental concerns and the push for clean energy solutions, consolidate Asia Pacific's position as the leading market contributor, capturing 43.9% in 2023.

8.1. Key Indicators

1. The global lithium-ion battery market for energy storage systems market was valued at USD 5,575.3 million in 2023.

2. The global lithium-ion battery market for energy storage systems market is projected to reach USD 61,337 million by 2033 with an estimated CAGR of 27.1%.
3. Among battery Types, Lithium Iron Phosphate (LFP) accounted for the largest market share at 51.4%.
4. Among capacity, the 100 to 500 MWh accounted for the majority of the market share with 51.5%.
5. Based on connection Battery Type, on-grid accounted for the largest market share in 2023 with 73.3%.
6. By end-use, the Utility is anticipated to dominate the market in the coming years. In 2023, it accounted for the majority of the share of 75.0%.
7. Asia Pacific is expected to hold the largest global lithium-ion battery market for energy storage systems market share with 43.9% of the market share.

8.2. Battery Type Analysis

The lithium-ion battery market for energy storage systems can be categorised into several battery types: Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA), Lithium Iron Phosphate (LFP), Lithium Titanate Oxide (LTO), Lithium Manganese Iron Phosphate (LMFP), and Lithium Manganese Nickel Oxide (LMNO).

Among these, Lithium Iron Phosphate (LFP) held the majority of the revenue share of 51.4% in 2023. LFP batteries offer superior safety, with a lower risk of thermal runaway compared to other chemistries, making them highly desirable for energy storage applications.

Furthermore, their long cycle life and stability under various thermal conditions enhance durability and reduce lifecycle costs. LFP's lower cost, attributed to the absence of cobalt, a costly and geopolitically sensitive material, also contributes to its preferential market position. These factors collectively ensure LFP's majority stake in the market, addressing the safety, economic, and operational priorities of energy storage systems.

8.3. Capacity Analysis

Based on capacity, the market is segmented into below 100 MWh, 100 to 500 MWh, and above 500 MWh. Among these, the 100 to 500 MWh accounted for the majority of the market share with 51.5% due to its optimal balance between scalability, cost-efficiency, and application versatility.

This capacity range effectively meets the requirements of a broad spectrum of applications, from grid support and renewable energy integration to commercial and industrial energy storage solutions. Its prominence reflects the segment's capacity to provide sufficient energy storage for peak shaving, load levelling, and emergency backup, while also being economically viable for a wide range of customers, thereby driving its significant market share.

8.4. Connection Type Analysis

Based on connection types, the market is further divided into on-grid and off-grid. Among these connection types, on-grid accounted for the largest market share in 2023 with 73.3% owing to the increasing adoption of renewable energy sources, such as solar and wind, which are integrated into the main electricity grid to ensure a stable and reliable power supply.

On-grid systems, by enabling energy storage and supply during peak demand periods, enhance grid stability and energy efficiency. Moreover, supportive government policies, incentives for renewable energy integration, and the growing need for grid modernization and resilience against power outages further propelled the dominance of on-grid connections in the energy storage market.

8.5. End-Use Analysis

The market is divided into utility, commercial & industrial, and residential based on end-users. In 2023, the utility sector held the largest market share at 75%, driven by the increasing demand for large-scale energy storage solutions that support the integration of renewable energy sources into the grid.

Utilities are making increasing investments in lithium-ion batteries to improve grid stability, manage peak load demands, and provide emergency backup power, reflecting a global shift toward sustainable energy practices. This significant market share highlights the critical role of energy storage in achieving energy transition goals, with utilities leading the adoption of advanced storage technologies to meet evolving energy demands effectively.

8.6. Challenges

Battery safety concerns primarily revolve around the risk of thermal runaway, a condition where an increase in temperature can lead to a self-sustaining reaction within the battery, potentially causing fires or explosions. Moreover, the environmental impact of lithium-ion batteries presents another significant challenge.

The production of these batteries requires the extraction of lithium, cobalt, and nickel, processes that are energy-intensive and can lead to significant environmental degradation. For example, lithium mining in regions such as Latin America's Lithium Triangle has raised concerns about water usage and pollution, impacting local ecosystems and communities.

The end-of-life disposal and recycling of lithium-ion batteries pose considerable environmental challenges. Currently, only a small percentage of lithium-ion batteries are recycled, leading to waste and the loss of valuable materials. The lack of efficient recycling processes and infrastructure exacerbates these issues, contributing to resource depletion and environmental pollution.

The increasing demand for lithium-ion batteries exacerbates these concerns. As the market for ESS and EVs grows, so does the demand for critical raw materials, price fluctuations, and potentially leading to more intensive mining activities and associated environmental impacts. For example, the increasing demand for copper, driven by the transition to renewable energy and decarbonisation efforts, has led to predictions of record-high copper prices [63]. This situation is compounded by geopolitical risks and supply chain vulnerabilities, as the majority of these critical materials are concentrated in a few countries, raising concerns about sustainable and ethical sourcing.

8.7. Expansion in Developing Markets

The growth of the global lithium-ion battery for energy storage systems market will be significantly impacted by the expansion in developing markets. This is due to factors such as the rising demand for renewable energy, government support for energy storage solutions, and increased adoption of electric vehicles (EVs) in these regions [64].

Developing economies are witnessing a substantial surge in energy consumption due to rapid industrialisation, urbanisation, and economic growth. As these economies strive for sustainable development, there is a growing emphasis on integrating renewable energy sources into their power grids.

Lithium-ion batteries are an increasingly essential technology for renewable energy storage due to their high energy density, efficiency, and long lifespan. This storage capability is vital in managing the fluctuating nature of renewable energy sources like solar and wind power, ensuring a consistent and dependable energy supply.

India has launched a National Energy Storage Mission to promote the use of energy storage technologies, such as lithium-ion batteries, to improve the country's energy security and grid stability. Developing countries are adopting similar policies and incentives to encourage energy storage solutions.

Similarly, China’s 13th Five-Year Plan prioritises energy storage as part of its broader energy strategy, facilitating substantial investments in lithium-ion battery production and deployment. These initiatives not only boost the local energy storage market but also open avenues for international manufacturers and investors to participate in these burgeoning markets.

9. Rise of Energy Storage as a Service (ESaaS)

The emergence of Energy Storage as a Service (ESaaS) has significantly influenced the trajectory of the global lithium-ion battery for energy storage systems market, marking a pivotal shift in how energy storage solutions are deployed and managed across various sectors. This innovative service model facilitates the adoption of energy storage technologies by mitigating upfront capital expenditure, thereby accelerating the integration of lithium-ion batteries into the broader energy ecosystem.

The ESaaS model leverages operational and financial flexibility to cater to a wide range of clients, from utility providers to commercial entities, encouraging the proliferation of lithium-ion batteries as a preferred choice for energy storage solutions. One of the core factors driving the growth of the lithium-ion battery for energy storage systems market within the ESaaS framework is the increasing demand for renewable energy integration [65]. As the global economy seeks to transition towards cleaner energy sources, the intermittent nature of renewable energy sources such as solar and wind necessitates robust energy storage solutions.

Lithium-ion batteries, known for their high energy density, efficiency, and longer life cycles, emerge as the ideal technology to bridge the gap between energy generation and consumption. The ESaaS model, by offering energy storage as a manageable service, lowers barriers to entry for utilising advanced lithium-ion battery technology, thereby enhancing grid stability and supporting the expansion of renewable energy infrastructure.

Key players are broadening their range of products to serve a wider range of applications beyond electric vehicles and stationary energy storage. These applications include batteries for consumer electronics, grid stabilisation, renewable energy integration, and backup power systems, ensuring stable revenue and market resilience. The evolution of major key players in the lithium-ion battery for energy storage systems market is distinguished by a focus on innovation, sustainability, and strategic partnerships. These are essential to capitalise on growth opportunities and address emerging challenges in the dynamic energy storage landscape.

The following are some of the major players in the industry:

1. BYD Co. Ltd.
2. Panasonic Corporation
3. Toshiba Corporation
4. Samsung SDI Co., Ltd.
5. Tesla Inc.
6. LG Energy Solution Ltd
7. Hitachi Energy Ltd.
8. GS Yuasa International Ltd.
9. Saft
10. Narada Power Source Co., Ltd.
11. Contemporary Amperex Technology Co., Limited.
12. BAK Power
13. Morrow

10. Conclusion

Battery energy storage systems are pivotal in transforming the energy grid into a more modern, efficient, and sustainable system. By smoothing out the variability and intermittency of renewable energy, batteries make it easier to integrate higher percentages of renewables into the grid. This reduces reliance on fossil fuels and helps in achieving clean energy targets. Their continued development and deployment will play a critical role in meeting global energy and climate goals.

The paradigm shift towards cleaner, sustainable energy solutions not only benefits the environment but also opens up avenues for economic growth and technological advancement. The versatility and reliability of BESS offer a glimpse into a future where energy is harnessed and utilised more efficiently than ever before, laying the foundation for a greener, more resilient world. In this pursuit of a low-carbon economy, Battery Energy Storage Systems are not just a tool for transitioning but a fundamental pillar defining the future energy landscape.

Battery Energy Storage Systems are at the forefront of the energy transition, offering a reliable, flexible, and sustainable solution to the challenges posed by the integration of renewable energy sources into the grid. Battery energy storage systems (BESS) support the transition from a centralised power grid to a decentralised one. This enhances grid resilience by distributing energy resources closer to where it's consumed, reducing the impact of localised outages.

By facilitating grid stability, enabling higher renewable penetration, empowering energy independence, and driving innovation, BESSs are paving the way for a cleaner and more efficient energy future. As we continue to strive towards a low-carbon economy, the role of battery storage systems will only become more prominent, shaping the way we generate, store, and consume energy in the years to come.

The growing demand for BESS drives innovation in battery technology, leading to advancements in energy density, lifespan, and safety. These improvements benefit not only the energy sector but also other industries such as automotive and consumer electronics.

Modern BESS are scalable and can be tailored to a wide range of applications, from small residential systems to large grid-scale installations. This flexibility allows for customized solutions that meet specific energy needs.

The expansion in developing markets is poised to create significant opportunities for the growth of the global lithium-ion battery for energy storage systems market. This can be attributed to several key factors, including the escalating demand for renewable energy sources, government initiatives to promote energy storage solutions, and the increasing adoption of electric vehicles (EVs). The evolution of major key players in the lithium-ion battery for energy storage systems market is characterised by a focus on innovation, sustainability, and strategic partnerships to capitalise on growth opportunities and address emerging challenges in the dynamic energy storage landscape.

Governments and regulatory bodies worldwide are increasingly recognising the benefits of Battery Energy Storage Systems (BESS) and offering incentives and subsidies to encourage their adoption. These policies are aimed at supporting the growth of the energy storage market and accelerating the transition to a sustainable energy future. It is paramount to strengthen the support and encourage collaboration between industry, academia, and government to accelerate technological advancements and ongoing research to push the boundaries of current battery technologies.

Overall, investments in Battery Energy Storage Systems (BESS) offer an attractive risk-return profile. This is particularly evident when considering their role as a complement to renewable energy sources within an investment portfolio.

Abbreviations

APAC	Asia-Pacific
BESS	Battery Energy Storage Systems
BMS	Battery Management System
BtM	Behind-the-Meter
CAGR	Compound Annual Growth Rate
CAES	Compressed Air Energy Storage
C&I	Commercial & Industrial
DERs	Distributed Energy Resources
DN	Distribution Network
DSM	Demand Management System
EASE	European Association for Storage Energy
EMS	Energy Management System
ESaaS	Energy Storage as a Service
ESS	Energy Storage Systems
EV	Electric Vehicle
FtM	Front-the-Meter
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ITC	Investment Tax Credit
LV	Low Voltage
PPA	Power Purchase Agreement
PV	Photovoltaic
RE	Renewable Energy
RES	Renewable Energy Sources
ROI	Return on Investment
SCADA	Supervisory Control and Data Acquisition System

Author Contributions

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Lorenc Xhaferraj: Formal Analysis, Methodology, Project administration, Resources, Supervision, Validation

Giulia Maria Bragagni: Data curation, Investigation, Resources, Software, Visualization

Maya Checchi: Data curation, Investigation, Resources, Visualization

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Conflicts of Interest

The authors declare no conflicts of interest.

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