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Review

Large-Scale Renewable Energy Integration: Tackling Technical Obstacles and Exploring Energy Storage Innovations

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Abstract: The global transition to renewable energy sources (RESs) is accelerating to combat the rapid depletion of fossil fuels and mitigate their devastating environmental impact. However, the increasing integration of large-scale intermittent RESs, such as solar photovoltaics (PVs) and wind power systems, introduces significant technical challenges related to power supply stability, reliability, and quality. This paper provides a comprehensive review of these challenges, with a focus on the critical role of energy storage systems (ESSs) in overcoming them by evaluating their technical, economic, and environmental performance. Various types of energy storage systems, including mechanical, electrochemical, electrical, thermal, and chemical systems, are analyzed to identify their distinct strengths and limitations. This study further examines the current state and potential applications of ESSs, identifying strategies to enhance grid flexibility and the increased adoption of RESs. The findings reveal that while each ESS type has specific advantages, no single technology can tackle all grid challenges. Consequently, hybrid energy storage systems (HESSs), which combine multiple technologies, are emphasized for their ability to improve efficiency and adaptability, making them especially suitable for modern power grids.

Keywords: renewable energy integration; energy storage systems (ESSs); hybrid energy storage systems (HESSs); power grid stability; grid reliability and quality; energy transition; sustainable energy solutions

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1. Introduction

Global energy demand continues to rise rapidly due to industrialization, technological advancements, and economic growth. To meet this demand, conventional energy generation methods have historically relied heavily on fossil-based resources. However, this reliance poses significant challenges, including substantial contributions to greenhouse gas emissions and environmental pollution [1]. In response, the need for alternative energy sources has become increasingly critical. Renewable energy sources (RESs), often referred to as green and clean energy sources, are among the most promising alternatives.

A recent survey by the International Energy Agency (IEA) [2] reported a 2.2% increase in global energy demand in 2023, resulting in a corresponding 1.1% rise in carbon emissions. During the same year, the global installed capacity additions of RESs increased by over 440 GW in 2023. Consequently, the contribution of RESs to global electricity generation exceeded 30%, with solar energy and wind power systems alone accounting for 13.5% of this share [3]. Furthermore, as shown in Figure 1, there is a growing trend towards solar photovoltaics (PVs) and wind turbines, which is expected to continue [1].

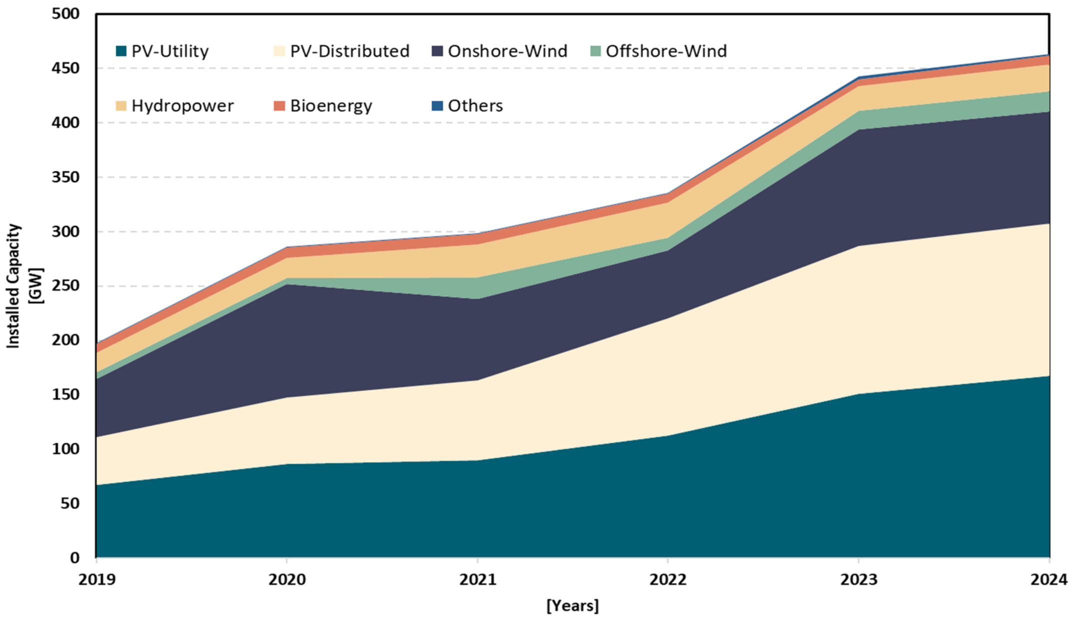

Figure 1. Annual growth in renewable energy installations (based on the data from IEA [1]).

In line with initiatives such as "Net Zero" and the Paris Agreement, renewable electricity generation is projected to grow significantly, further emphasizing the critical role of RESs in driving the transition to a decarbonized power sector [4]. This transition is pivotal in combating climate change by reducing greenhouse gas emissions and supporting global sustainability efforts. Looking ahead, the International Renewable Energy Agency (IRENA) projects that by 2050, 80% of global electricity generation will come from RESs, with PV and wind power systems (WPSs) accounting for 52% of this total [5]. These projections highlight the urgent need to scale up renewable energy deployment to address environmental challenges and facilitate a sustainable energy future.

RESs have long been integrated into existing power grids. RESs are categorized based on capacity as micro- (1 kW–5 kW), small- (5 kW–5 MW), medium- (5 MW–50 MW), and large-scale (over 50 MW), with smaller RESs connected through distribution systems while the larger ones are connected via transmission systems [6,7]. RES technologies as well as wind and solar energy have demonstrated the greatest potential, with rapid increases in installed capacity over the years, as shown in Figure 1. However, due to the intermittent and uncontrollable stochastic nature of these RESs, they produce electricity independently of the grid operators' control and load demand. Unlike conventional generators, RESs possess unique characteristics such as lower inertia and inherently variable output [8]. These unique features reduce the overall system flexibility and introduce new challenges for system reliability, power quality, and power supply stability [4,9,10].

To address these challenges and enhance system flexibility, energy storage systems (ESSs) have emerged as promising solutions. ESSs offer a wide range of applications and can unlink supply from demand, effectively managing the load–supply imbalance. They perform this by transitioning between charging and discharging modes and providing rapid ramp-up and ramp-down capabilities [11]. However, each type of ESS comes with unique characteristics, limitations, and application areas, which necessitate a detailed understanding and analysis of these aspects. Selecting the most suitable ESS for specific needs and determining its optimal size are critical factors in maximizing its usefulness [12]. Insufficient storage capacity may compromise power system reliability, including loss of load and generation curtailment, whereas excessive storage can lead to increased system costs and resource inefficiencies [13].

In recent years, there has been an increasing focus on improving the design, optimization, and management strategies of energy storage technologies to enhance their performance across various energy systems and scales [13–15]. Le et al. [13] focused on hydrogen/battery storage systems, employing a Multi-Objective Modified Firefly Algorithm to balance system efficiency and economic returns, such as Net Present Value (NPV) and Self-Sufficiency Ratio (SSR). Their findings showed that hybrid systems outperform battery-only and hydrogen-only systems, with significant benefits for high renewable energy penetration scenarios and long-term energy storage efficiency in tropical climates. Wang et al. [15] proposed an enhanced min–max dispatching approach to optimize battery utilization and enhance the integration of renewable energy into the power grid. Moreover, with the rapid integration of RESs into power systems, conducting a comprehensive review has become crucial to prepare power systems for future challenges [16–20]. For example, Lee et al. [19] examined the role of ESSs, particularly lithium-ion batteries, in managing power and mitigating the intermittent nature of renewable energy generation. Chreim et al. [20] analyzed ESSs in residential applications, highlighting their role in renewable energy integration, improvements in power quality, and the financial benefits of shared battery systems.

Based on the literature analysis, it is evident that several recent review studies have explored the role of ESSs in enhancing power system flexibility and minimizing the challenges arising from RES integration into the grid. However, this paper provides an in-depth, greater examination of ESSs and offers a broader perspective, exploring their potential to enhance grid flexibility, power quality, reliability, and stability for more resilient and sustainable power infrastructure.

The rest of this research article has been organized as follows: Section 2 examines the technical impacts of large-scale renewable energy integration into the existing grid, focusing on three key aspects: power stability, reliability, and quality. Section 3 provides a detailed overview of ESSs focusing on their technologies and characteristics. Section 4 builds on this by analyzing the technical requirements for different ESS applications and showcasing real-world examples of various ESS types at the grid-scale level. Section 5 delves into an in-depth analysis of the technical, economic, and environmental dimensions of ESSs, thoroughly summarizing their advantages and disadvantages. Section 6 concludes the findings of this study and outlines possible future trends.

Methodology of This Study

This review employs a thematically structured approach enriched with systematic elements to investigate the challenges of integrating large-scale RESs into power grids, specifically focusing on the potential role of ESSs. The methodology reflects a deliberate effort to synthesize diverse sources of knowledge transparently and rigorously while maintaining flexibility to explore emerging and interdisciplinary perspectives.

The approach is particularly suited to this review, as it comprehensively evaluates a complex, rapidly evolving topic while integrating technical, environmental, and operational dimensions. While not adhering to the strict protocols of a systematic literature review (SLR), such as PRISMA guidelines, this review incorporates systematic principles to ensure clarity, transparency, and replicability.

This review is guided by three primary objectives:

- To identify and critically analyze the technical challenges posed by the large-scale integration of RES into modern power grids.
- To evaluate the potential of the various ESS technologies in mitigating these challenges and enhancing grid stability, reliability, and power quality.

- To explore future directions in ESS research, focusing on innovative technologies, the potential of hybrid configurations, and scalable solutions for grid-level applications.

This review's scope includes literature addressing large-scale RES and ESS integration at the grid level, encompassing diverse energy storage technologies such as mechanical, electrochemical, thermal, electrical, and chemical energy storage systems.

The literature search was conducted across leading academic databases such as Scopus, IEEE Xplore, Web of Science, and Google Scholar. These platforms were selected to ensure access to a broad and authoritative range of sources, including peer-reviewed journal articles, conference proceedings, technical reports, and industry white papers. To capture the most relevant and recent advancements in the field, the search focused on the most recent publications. Keywords and Boolean operators were used strategically to refine the search process, with terms such as "renewable energy integration", "energy storage systems", "hybrid energy storage technologies", and "challenges of large-scale renewable energy integration" forming the basis of the query. The resulting literature pool was further refined by applying inclusion criteria that prioritized studies addressing grid-level applications of RESs and ESSs, with a focus on technical and operational aspects. The contents of articles focused solely on small-scale systems, non-English publications, and studies lacking substantive technical content were carefully assessed on their relevance. Additionally, reference lists of key articles were examined to identify further relevant works, ensuring the breadth and depth of this review.

ESSs form the backbone of this review, and their categorization and evaluation play a pivotal role in the thematic analysis. ESSs are categorized into five primary types based on the form of energy they store: mechanical, electrical, electrochemical, thermal, and chemical. These categories encompass a diverse range of technologies, each with unique characteristics and applications. Mechanical ESSs include gravitational potential energy storage, compressed air energy storage (CAES), and flywheel energy storage (FES). Electrical ESSs feature supercapacitor energy storage (SCES), superconducting magnetic energy storage (SMES), and electric vehicles (EVs). Electrochemical ESSs are divided into flow batteries, such as polysulfide bromine (PSB), zinc–bromine (ZnBr), and vanadium redox flow batteries (VRFB), as well as conventional batteries like lead–acid (Pb–acid), lithium-ion (Li-ion), nickel–cadmium (Ni-Cd), and sodium–sulphur (NaS). Thermal ESSs include latent phase change materials (PCMs) and sensible thermal storage (STES), while chemical ESSs are exemplified by hydrogen storage systems.

To evaluate the suitability of these technologies for grid-level applications, a detailed analysis was conducted on key parameters, including lifespan (life and cycling capability), power rating, specific energy, specific power, energy density, power density, efficiency (round-trip efficiency and self-discharge rate), discharge time, and response time. Additionally, their level of technological maturity, power, and energy costs, and associated advantages and disadvantages, were assessed. These parameters are critical for understanding the applicability of ESS technologies to address challenges such as intermittency, grid stability, power quality, and grid reliability in renewable energy integration.

The thematic analysis framework employed in this review facilitated the categorization of the literature into interconnected themes. The identified themes include the technical challenges of integrating RES into power grids, the comparative evaluation of ESS technologies, and the exploration of emerging trends and future directions in ESS development.

Effort was made to ensure methodological transparency and enhance reproducibility. The detailed documentation of the search parameters, inclusion criteria, and thematic analysis process provide a clear framework for others to replicate or adapt this approach. Although this review does not claim to exhaustively catalogue all of the available literature, its structured yet flexible methodology allows for the integration of diverse perspectives and insights, making it particularly suited to the dynamic and interdisciplinary nature of RES and ESS research.

By integrating a detailed evaluation of ESS technologies into the broader methodological framework, this review contributes a holistic perspective on renewable energy integration. The synthesis of diverse knowledge sources and the critical analysis of technological and operational factors ensure that this review provides valuable insights for advancing both research and practice in sustainable energy systems.

2. Technical Impact of Integrating LS-RESs on Existing Grid

Intermittent RESs, such as wind and solar power, play an increasingly vital role in modern energy systems. However, as shown in Table 1, their dynamic characteristics differ significantly from those of conventional generators, creating new challenges for renewable power generation owners and grid operators. The intermittent nature of wind and solar energy uniquely affects electricity generation, complicating grid operation and security. High penetration levels of intermittent RESs reshape power system dynamics, requiring innovative solutions to manage variable demand and generation effectively.

Table 1. Intermittent RES characteristics.

Characteristics	Description
Based on inverter	The transition to inverter-based generation lowers grid inertia, increasing vulnerability to rapid frequency changes [8]. Intermittent RES generators, with less rotational inertia than synchronous generators, cause faster frequency excursions, risking dynamic stability and necessitating dispatch or curtailment of RES generation [21]. Additionally, reducing conventional generators may result in an inability to meet ramping requirements [22].
Capacity factor	Wind and PV systems have low-capacity factors, averaging 30% and 15%, respectively, in resource-rich areas [23]. Despite this, they can achieve high short-term outputs. For instance, In September 2020, Croatian wind farms met 50% of the system's hourly electricity demand, while their daily average contribution was approximately 15% [24].
Partially unpredictable	Energy generation from PV and wind systems depends on partially unpredictable variables, such as wind speed and sunlight. Their power output can fluctuate over short periods due to factors like passing clouds and changes in wind speed and direction. However, distributing PV systems across a wide geographical area can help to reduce the impact of localized shading, as cloud cover typically affects only specific regions [25].
Uncontrollable variability	The output power of RESs is influenced by sunshine availability and wind speed fluctuations. While grid operators can forecast this output, managing variability remains challenging. To maintain stability, operators must continuously monitor the system and balance supply and demand through active or reactive power adjustments. Essential ancillary services like frequency regulation, spinning reserves, black-start capacity, and voltage support are required [26].
Location dependence	Solar and wind energy availability is highly location-dependent, unlike transportable fossil fuels. Thus, RES generation must occur where resources are available, often requiring additional transmission capacity for integration [27].

Grid operators must possess a comprehensive understanding of the impacts associated with the replacement of conventional generators by intermittent large-scale RESs. This knowledge is crucial for maintaining the reliability and stability of the system, ensuring high-quality power flows, and addressing the challenges associated with planning and operating the power system [28]. The impacts identified in the literature are categorized in Figure 2, with a detailed analysis presented in the subsequent sub-headings.

In the literature, various studies have been conducted to address the challenges arising from large-scale RES integration. Some of these findings are summarized in Table 2, highlighting the key outcomes.

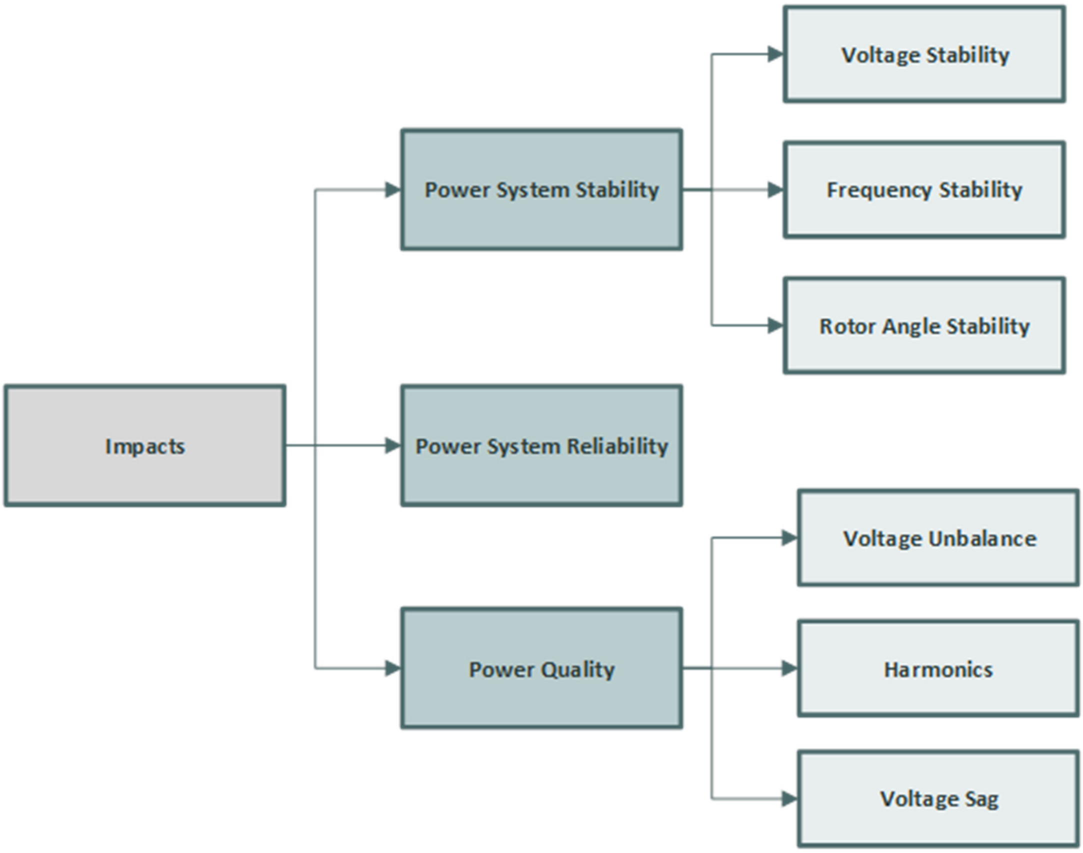

Figure 2. Key technical impacts on power systems with LS-RES integration.

Table 2. Key findings from some research on the impacts of large-scale renewable energy integration on the grid.

Analyzed Impact	Challenge	Type of RES	Max. Penetration (%)	Key Findings	Ref.
Voltage stability	Overvoltage	Wind	35	Integration of DFIG-based WPS can mitigate overvoltage issues [29].	[29,30]
		PV	19	In the presence of high-speed winds, the system voltage was observed to be 1.051 p.u., thus exceeding the threshold [30].	
	Low reactive power support and short-circuit contribution	PV	30	High PV penetration increases voltage instability due to its low reactive power and short-circuit contribution compared to conventional generators [31].	[30–33]
Frequency stability	System inertia reduction	Wind PV	50	RES penetration reduces the inertia of the system, which will lead to an increase in the rate of frequency and compromised frequency stability [24].	[24,34,35]
	Delayed active power recovery	Wind	60	Delayed active power recovery after voltage dips in grid code-compliant WPSs can exceed primary reserve capacity, causing the frequency nadir to fall below thresholds and risking system collapse.	[36]

Table 2. *Cont.*

Analyzed Impact	Challenge	Type of RES	Max. Penetration (%)	Key Findings	Ref.
Rotor angle stability	Reduced damping of rotor angle oscillations	Wind PV	80	Reduced rotor angle damping increases risks of instability during disturbances, as large-scale RES-penetrated systems lack inherent inertia [37].	[31,37]
	Fault proximity to solar-PV	PV	45	At high levels of solar-PV penetration, the severity of transient instability increases significantly when faults occur near locations where synchronous generators have been replaced with solar-PV systems [38].	[35,38]
Power reliability	Low inertia	Wind PV	50	The reduction in system inertia caused by the replacement of synchronous generators results in quicker frequency drops and poses significant challenges to grid reliability during disturbances [39,40].	[39,40]
	Short/long-term system adequacy	Wind PV	-	Increasing VRE generation demands faster ramping capability for short-term system adequacy, or improved seasonal balancing for long-term system adequacy, from conventional systems; inadequate capacity to meet these requirements can result in mismatches, leading to re-dispatch or curtailment.	[28]
Voltage unbalance		PV	-	High penetration of rooftop PV systems worsens voltage unbalance in LV networks due to uneven phase distribution and dynamic power fluctuations [41].	[41,42]
Harmonics		Wind PV	-	The total harmonic distortion rises as the penetration level increases [43].	[43–45]
Voltage sag		Wind PV	-	The optimal size and location of ESSs can be effective in mitigating voltage sag issues [46].	[46,47]

2.1. Impact of RES on Power System Stability

The stability of a power system is one of the most important criteria for ensuring the system's demand balance. It refers to the system's ability to recover operational stability after physical disturbances [48].

2.1.1. Voltage Stability

Voltage stability refers to the ability of the power system to maintain voltage levels at all its busbars within acceptable limits after a disturbance, under both normal and abnormal operating conditions. Voltage instability in power systems is a problem that emerges with a continuous increase or decrease in voltage on certain buses [49]. The main reason for this instability is the lack of reactive power support. However, other factors, such as incorrect positioning of the Flexible AC Transmission System's (FACTS) controllers, weak interaction among them, and the distance of power plants from load centres, can also contribute to instability. Voltage instability may result in load loss and transmission line failures. Some generators may also experience synchronization problems and cascading outages can ultimately lead to system collapse [50].

Several authors have researched the impacts of increasing the penetration level of RESs on voltage stability [29–32,51]. For instance, the study by [51] examined the effect of various penetration levels (from 5% to 35%) and location scenarios (single location and dual locations) on the system voltage stability. The results indicated that voltage stability tends to improve at lower penetration levels, while at higher levels, the improvement is less pronounced. Additionally, it has been observed that the integration of wind power sources at multiple locations produced better results for voltage stability.

Adetokun and Muriithi [29] investigated the effect of large-scale Doubly Fed Induction Generator (DFIG)-based WPS integration on voltage stability in a weak national grid, using active power–voltage (P-V) and reactive power–voltage (Q-V) analyses. The findings showed that large-scale WPS integration can enhance voltage stability of the system, maintaining voltage levels within 1.0 ± 0.05 p.u., and improve voltage stability. Conversely, Hossain et al. [32] indicated that DFIG-based WPSs might perform worse in terms of voltage stability, as they provide less reactive power and minimal short-circuit current during faults. Unlike synchronous generators, which deliver substantial fault currents crucial for stabilizing voltage and enabling grid protection systems to isolate faults, DFIGs are limited by the capacity of their power electronic converters, making them less effective in supporting the grid under such conditions. This discrepancy highlights the need for further research on the effects of high wind energy penetration levels.

Research by Refaat et al. [31] claimed that integrating large-scale PV into the grid can improve dynamic voltage stability. Additionally, it was concluded that integration can enhance static system stability, reduce the angle instability, and increase the reliability of the overall power system. In another study, Mokeke and Thamae [30] demonstrated that while PV systems do not experience voltage instability at penetration levels up to 19%, they can cause instability at higher penetration levels. Consequently, the integration of LS-RES still requires further in-depth research and investigation.

2.1.2. Frequency Stability

The frequency of the grid is associated with the rotational speed of conventional synchronous generators; the control of these generators is adjusted—either accelerated or decelerated—depending on the active power balance to maintain the equilibrium between load and generation [52]. The contribution of inertia is one of the most essential features of synchronous generators. The rotating mass of the generator either transmits kinetic energy to the grid or absorbs it, with this kinetic energy being proportional to the rate of change in frequency [48]. Systems equipped with large synchronous generators slow down system dynamic changes, facilitating the tracking of system parameters by inverter-based power supplies. This allows for precise synchronization with the grid voltage angle and enables the injection of current at the correct phase angle and frequency.

However, the increasing penetration of RES, such as wind and solar power, has introduced challenges to maintaining system inertia. Although wind turbines have inertia, they do not contribute to frequency response due to their interface with the grid through power electronics technologies. Similarly, solar PV systems connected via inverters also provide no inertia, thereby reducing the system's overall frequency response capability [44,53]. This reduction in inertia can lead to a faster rate of frequency change, compromising frequency stability and potentially destabilizing the grid dynamics [34].

As the share of RES continues to grow in power systems worldwide, their impact on system inertia and frequency stability has become a critical concern. To achieve ambitious renewable energy integration targets, such as Croatia's 2030 goal of over 6 GW of planned RES integration, strategic upgrades in transmission systems and adopting grid-forming strategies are essential [24]. Furthermore, the delayed recovery of active power following voltage dips poses additional challenges. Grid code-compliant WPSs often take longer to restore active power compared to conventional generators, which can exceed the primary reserve capacity and cause the frequency nadir to drop below grid code thresholds. In severe cases, this delay could cause system collapse [36]. Therefore, addressing these issues through enhanced system design and operational strategies is essential for ensuring grid stability in high-RES scenarios.

2.1.3. Rotor Angle Stability

Rotor angle stability is related to the ability of synchronous generators connected to the power grid to stay synchronized after being exposed to a disturbance. Generation sources interfaced with the grid via inverters are static systems; therefore, they do not have rotor angles [48]. For instance, replacing synchronous generators with DFIG-based WPSs has been shown to negatively affect rotor angle stability, although control strategies can mitigate these impacts [54]. Similarly, studies on PV integration, such as those by Munkhchuluun et al., reveal that rotor angle stability improves in less critical locations but deteriorates in more critical areas, with fault distance being a key factor [38].

High PV penetration, along with the location and dynamic characteristics of neighbouring systems, further complicates rotor angle stability. Depending on system configurations and control strategies, it can either enhance stability under specific conditions or intensify rotor angle oscillations and reduce damping in other generators [35]. Particularly under fault conditions, high penetration of RES leads to significant increases in rotor angle oscillations, with oscillatory modes exhibiting low frequencies such as 1.85 Hz, indicating poor damping and prolonged instability [37]. These findings underscore the need for further investigation into rotor angle stability to ensure the overall stability of power systems under varying scenarios and penetration levels. Hence, further investigation into rotor angle stability is necessary, particularly in analyzing different situations and penetration levels, to maintain overall system stability.

2.2. Impact of RES on Power System Reliability

Reliability is a critical factor in power systems, including two key aspects: security of power supply and system adequacy [55]. The integration of intermittent RES poses challenges to maintaining power supply reliability. For example, wind turbines produce less power at low wind speeds, and similarly, solar energy output decreases on cloudy days. Additionally, wind turbines may shut down in excessively high winds to avoid damage, resulting in the abrupt loss of a significant power source.

Systems with high levels of RES penetration require more rapid frequency control due to reduced inertia; failure to provide such control rapidly can bring about load shedding or generator damage. With the anticipated increase in intermittent RES, determining next-generation system adequacy becomes increasingly critical. This is particularly relevant as stochastic fluctuations in renewable generation, plant availability, and regional transmission constraints underscore the need for robust capacity planning and system flexibility to ensure reliable operation in future power systems [56].

Similarly, Johnson et al. emphasize that high-RES penetration significantly reduces system inertia, displacing synchronous generators and increasing the risk of frequency instability [40]. Their findings, based on the ERCOT grid, highlight that low inertia can worsen reliability challenges, particularly during periods of high renewable penetration. Furthermore, transmission congestion and renewable curtailment underscore the need for robust capacity planning. Advanced solutions, such as synthetic inertia and grid-scale energy storage, are critical to ensuring reliable operation and addressing these challenges in future systems. Supporting this, it has been found that placing grid-scale energy storage near renewable generation not only enhances grid inertia but also lowers system costs, reduces renewable energy curtailment, and strengthens grid reliability [39]. This approach directly addresses the challenges posed by large-scale renewable energy integration, ensuring a more resilient and flexible grid infrastructure in the face of increasing RES penetration.

2.3. Impact of RES on Power System Quality

Power quality problems, which arise from deviations in specified current, voltage, and frequency values, can cause damage or faults in equipment in the power system. Integration of LS-RESs can create power quality issues that lead to high cost and low efficiency, increasing power system losses and equipment failure. A recent study by Abas [57] identified voltage unbalance, harmonics, and voltage sags as key power quality concerns associated with integrating RESs.

2.3.1. Voltage Unbalance

Voltage unbalance occurs when the line voltage or phase is not evenly balanced. Balanced voltage is essential for maintaining power quality and system reliability. Voltage unbalance is commonly defined as the ratio of positive to negative voltage components. In ideal systems, the three-phase voltages are in balance [58].

Recent research conducted by Then et al. [41] offers a significant perspective, proposing a decentralized control strategy for coordinating electric vehicle (EV) charging to mitigate voltage rise, primarily caused by rooftop PV systems. The researchers employed a droop-based control method, adjusting the charging rates of EVs based on the state of charge (SOC) of the EV batteries. Their findings indicate that this approach substantially reduces voltage unbalance.

Pinthurat et al. [42] also highlight the increasing prevalence of rooftop PV systems and their contribution to unbalanced conditions in low-voltage networks. Their research suggests that further study is needed to explore the impact of energy storage systems on mitigating voltage unbalance.

2.3.2. Harmonics

Integration of RESs into the grid is made possible with power electronic converters. However, due to the converter's presence, harmonics can emerge, and these harmonics can damage the equipment and reduce the efficiency and lifetime of the equipment [59]. Harmonics, a critical power quality issue, arise primarily from nonlinear inverter operations in RESs, causing distortions in current and voltage waveforms. This power quality problem is characterized by measuring the total harmonic distortion (THD) of the voltage and the current. Standards have been set to synchronize voltage and current waveforms with the grid [60].

Studies have shown that PV systems contribute notably to harmonic generation, particularly under low irradiance and high penetration levels, as these conditions lead inverters to inject more harmonics. Low irradiance often causes inverters to operate in partial load modes, where their nonlinear behaviour results in increased harmonic injection. These harmonics spread throughout distribution networks, impacting voltage stability and compromising grid reliability [45]. Similarly, WPSs contribute to harmonic generation due to the switching operations of power converters and the variability of wind energy [43].

Therefore, appropriate filters have been implemented for the harmonic reduction in power systems, which can be categorized as active, passive, and hybrid [59]. It has been determined that passive filters are not entirely effective in reducing harmonics. The use of shunt-oriented filters as an alternative method has been effective in improving power quality. However, as the size of active filters grows with increasing RES penetration levels, it is suggested that using hybrid filters could be a more cost-effective solution. Hybrid filters combine shunt-oriented and passive filters to reduce low- and high-order harmonics, respectively. As the penetration level of RESs interfaced with power electronic converters increases in power systems, there is an expectation that research into mitigating harmonics and improving power quality will expand.

2.3.3. Voltage Sag

Voltage sag, one of the most significant power quality issues, arises in distribution and transmission systems, often contributing to more than 80% of power quality problems [61]. It is typically caused by grid faults, motor start-ups, and high renewable energy penetration, where the RMS voltage deviates from its nominal value between 10% and 90% for a short duration [62]. High renewable energy penetration contributes to this issue due to its intermittent nature, which causes rapid power fluctuations and reduces system inertia. Additionally, the reliance on inverter-based generation often limits the grid's ability to provide sufficient reactive power during disturbances, further exacerbating voltage sag events [46].

Recent advancements in inverter technology, such as grid-forming inverters (GFMs), have demonstrated the potential to address these challenges. GFMs are effective in stabilizing voltage, facilitating efficient power balancing, and mitigating frequency oscillations during disturbances through their damping capabilities [63,64]. However, their reliable operation often requires access to a dispatchable energy source. In this regard, ESSs provide the necessary energy reserves, enhancing grid flexibility and improving dynamic response capabilities. The integration of GFMs with ESS significantly improves voltage sag mitigation, offering faster and more stable control during transient conditions.

Historically, voltage sag events often required the disconnection of RES from the grid to prevent islanding. However, with increasing RES penetration, such disconnections have become impractical, necessitating innovative mitigation strategies. For instance, battery energy storage systems (BESSs) have been proposed to mitigate voltage sag in renewable-integrated networks. Ahmed et al. demonstrated that optimally placing and sizing BESSs enhances grid flexibility, reduces operational costs, and effectively addresses voltage-related issues caused by renewable intermittency [46]. Similarly, SMES systems, when optimally designed and controlled, can rapidly deliver both active and reactive power, successfully mitigating voltage sag and improving grid quality during transient conditions [47].

3. Energy Storage Systems

ESSs play a critical role in enabling higher penetration of RESs into power systems by enhancing system flexibility and addressing the challenges posed by intermittent and variable energy production. Unlike conventional power plants, RESs such as wind and solar are inherently variable and unpredictable, creating difficulties in maintaining grid reliability, stability, and power quality. ESSs provide dispatchable power by storing excess energy during periods of high-RES generation and releasing it during low generation or high demand.

By integrating ESSs, power systems can balance supply and demand more effectively, manage grid congestion, and mitigate forecast errors. ESSs also enhance system ramping capabilities, reducing dependence on costly and inefficient fast-start thermal units. Furthermore, during periods of high renewable energy generation, when demand is low or grid limitations restrict energy transmission, ESSs mitigate curtailment output by storing surplus energy. This stored energy can then be dispatched during peak demand or grid stress, maximizing the utilization of renewable resources and reducing reliance on conventional generation [65].

As future energy systems increasingly incorporate dynamic loads and intermittent renewables [65], the importance of ESSs is expected to grow significantly. A recent study forecasts that global cumulative energy storage installations will climb to 411 GW/1194 GWh by 2030, which represents a fifteenfold increase from 27 GW/56 GWh in 2021 [66]. ESSs offer a diverse range of applications, from demand-side management to grid operation support, positioning them as a fundamental component in the transition toward a sustainable and resilient power grid.

Energy storage systems can be broadly categorized into five main types: mechanical, electrical, electrochemical, thermal, and chemical ESSs [67]. Figure 3 illustrates the classification of various ESS technologies, highlighting their diversity.

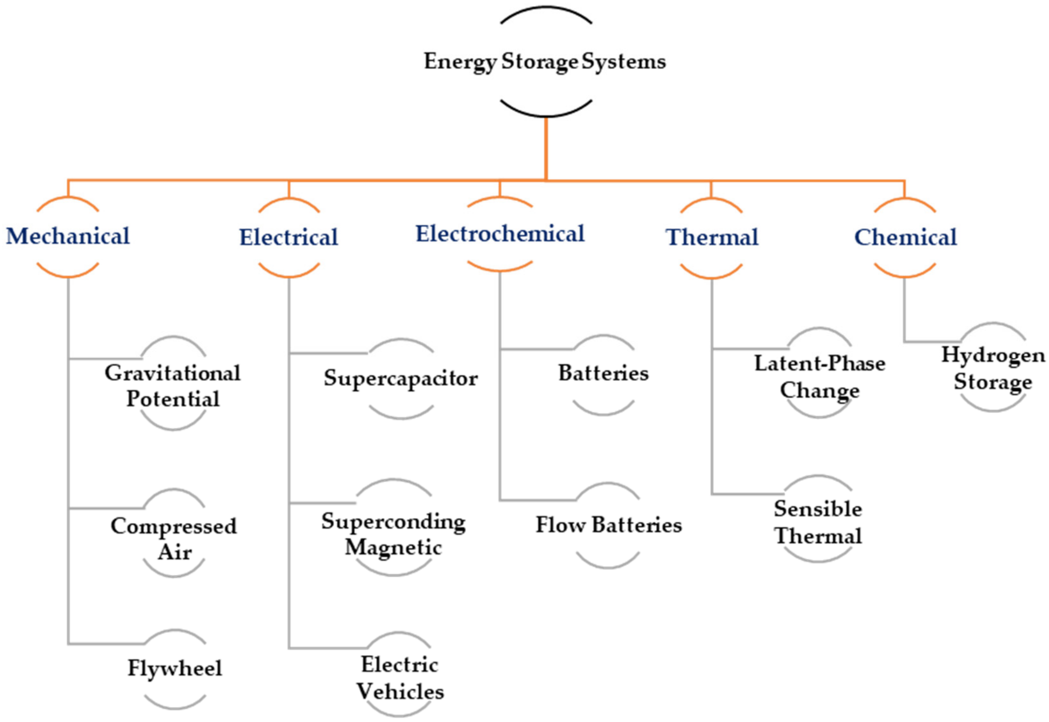

Figure 3. Classification of energy storage devices, illustrating various types and their subcategories based on technology.

The following subsections provide a detailed review of these ESS categories, focusing on their current state of deployment and the applications for which they are predominantly used. This analysis offers insights into the capabilities and challenges associated with each technology, as well as their roles in supporting the integration of RESs into modern power systems.

3.1. Overview of Mechanical Energy Storage Technologies

3.1.1. Gravitational Potential Energy Storage

Pumped hydro storage (PHS): PHS is the most mature ESS technology, with large capacities and over 90% of global installed storage capacity [68]. It operates by pumping water to a high-elevation reservoir during low electricity demand and releasing it to a lower reservoir to generate power during peak demand, using turbines connected to electrical machines [69]. Compared to battery systems, the current storage volume of the battery is 8 GWh, while that of the PHS is 9000 GWh [70]. They have lifetimes exceeding 40 years and power ratings from 1 MW to 3003 MW, and are used for time-shifting, frequency control, and supply reserves. Key limitations include site selection constraints, long construction times, and high installation costs [71]. Additionally, PHS technologies lack flexibility in pumping mode as operations are often restricted to fixed periods, highlighting the need for innovations to enhance the flexibility of PHSs [72].

Solid gravity energy storage (SGES): SGES is a novel system designed to address the PHS's limitations, offering similar energy storage potential without geographical constraints [73]. There are different types of SGES, including piston-based and tower-based systems. The piston-based SGES uses a water-filled container, a heavy piston, a reverse pump turbine, and a return pipe. In charge mode, water pumps lift the piston, storing energy as gravitational potential. In discharge mode, the piston descends, forcing water through a turbine to generate electricity. The tower-based SGES relies on weights, motor generators, ropes, transmission equipment, and towers. Motors lift weights to store potential energy and weights are released to generate power when needed. With 80–85% cycle efficiency and a lifespan exceeding 35 years, this system can be scalable [74].

3.1.2. Compressed Air Energy Storage (CAES)

Developed as an alternative to PHS, CAES offers high reliability, economic feasibility, and low environmental impact [75]. A typical CAES system includes a motor-driven compressor, a multi-stage compressor, a storage cavity (e.g., underground caverns, depleted gas fields, rock caverns, or artificial pressure tanks), turbines, and a generator [76]. Energy is stored by compressing air with storage capacity depending on the pressure and temperature of the stored air, as well as the container's volume [77]. CAES can deliver over 100 MW of power per unit. During charging cycles, the air is compressed and stored in a storage cavity using energy from the grid or RESs. During discharging cycles, the compressed air is released and heated in combustion chambers by mixing it with natural gas. This high-temperature, high-pressure gas drives turbines to generate electricity. A recuperation unit can recycle waste heat, improving efficiency to 48–54%, which is higher than that of conventional gas turbines [78]. CAES systems are suitable for both small- and large-scale applications and help stabilize and smooth intermittent renewable energy output [79]. However, their adoption is constrained by the need for specific geological formations and the reliance on fossil fuels, which limit their cost-effectiveness and applicability in regions lacking suitable storage locations. These dependencies often hinder the widespread deployment of CAES systems, despite their potential to enhance grid stability and support renewable energy integration.

3.1.3. Flywheel Energy Storage

A flywheel contains a dual-function electric motor to store and generate energy. A flywheel stores energy in a rotating mass and the kinetic energy produced is stored as rotational energy. The amount of kinetic energy depends on the inertia and speed of the rotating mass. This stored energy is transferred to or from the flywheel by the machine acting as a motor generator. This situation is controlled depending on the load angle. The flywheel is placed in vacuum containment to minimize frictional energy losses in the system. In addition, magnetic bearings can be used to ensure operational stability and reduce mechanical losses. As a result, the efficiency of FES can reach up to 95%, as it does not include a thermodynamic process. This high efficiency is enhanced by minimizing energy losses during rotation.

There are two types of FES configurations: low-speed FES and high-speed FES. Low-speed FES is generally used for short-term applications, while high-speed FES is more suitable for relatively longer-duration applications. The performance characteristics of FESs, including high energy and power density, high cycle efficiency, and superior power quality, depend heavily on advanced rotor materials, operational speeds, and power electronics. The use of advanced composite materials in the rotor enhances energy storage capacity and stability at higher speeds. Additionally, precise control mechanisms and power electronics play a critical role in maintaining system performance and efficiency. FES systems also offer easy maintenance, a wide operating temperature range, and quick response times. However, the main drawbacks of this technology are high idling losses during standby and significant self-discharge rates [80–82].

3.2. Overview of Electrical Energy Storage Technologies

3.2.1. Superconducting Magnetic Energy Storage (SMES)

The working principle of SMES is to store electrical energy in the magnetic form while charging; this magnetic field is generated by passing the direct current through the superconducting coil, and a cooling mechanism is used that keeps this coil in a specific temperature range to reduce the application's losses. At the discharge, the SMES system releases this stored energy through power converters [83]. This technology is quite mature, with its advantages including high power density, high efficiency, low degradation, support for power quality, and stability [84]. However, the drawbacks include the high cost of superconductors, high self-discharge rate, and high sensitivity that comes from the necessity to provide the required low-temperature level.

3.2.2. Supercapacitor Energy Storage (SCES)

Supercapacitors, called electrochemical double-layer capacitors (EDLCs) or ultracapacitors, consist of two carbon electrodes, an electrolyte, and a porous membrane separator. EDLCs contain characteristics of both electrochemical cells and capacitors [85]. Energy is stored in the form of static charge on the surfaces between the electrolyte and two conductive electrodes. In high-performance supercapacitors, nanomaterials are used to increase the electrode surface, which increases the capacitance. Supercapacitors can deliver high power with discharge times lasting up to a few minutes. They have a service life of up to 10 years under room temperature conditions, high cycle efficiency, and fast charge–discharge capabilities [86]. Because of their high self-discharge rate, supercapacitors are generally used for short-term storage [87].

3.2.3. Electric Vehicles

Electric vehicles (EVs) are redefining the future of transportation, emerging not only as an eco-friendly alternative to conventional vehicles with internal combustion engines but also as pivotal components in transforming nations' energy systems. The expanding EV market offers a unique opportunity for reshaping energy systems, particularly through the integration of EVs as dynamic energy storage units within the grid [88]. This capability is especially valuable in the context of renewable energy integration, where EVs can store excess renewable energy and transfer it back to the grid using vehicle-to-grid (V2G) technology [89]. This key innovation enables the use of the full potential of EVs in energy systems.

V2G technology represents a critical instrument in benefiting the energy storage potential of EVs. It allows EVs to not only draw energy from the grid for charging but also to feed energy back into the grid when needed. This bidirectional energy flow enables EVs to actively contribute to ancillary services, such as providing spinning reserves [90], frequency control, voltage regulation [91], peak shaving, and valley filling [92], thus supporting system reliability, stability, and quality [93,94]. Moreover, the integration of smart charging strategies can further optimize the interaction between EVs and renewable energy systems, aligning charging schedules with periods of high renewable energy generation to improve efficiency and reduce grid stress [95]. In addition to grid-level contributions, EVs equipped with vehicle-to-home (V2H) technology can directly support residential energy needs. By storing renewable energy during periods of high production and supplying it to homes during peak demand, V2H systems help enhance energy independence and reduce reliance on conventional energy sources [96].

3.3. Overview of Electrochemical Energy Storage Technologies

3.3.1. Lead–Acid Batteries

Lead–acid batteries consist of a cathode made of PbO_2 and an anode made of sponge metal Pb in a sulphuric acid solution. While in the discharge cycle, H_2O is formed and the acid in the electrolyte is diluted; the anode and cathode electrode are also converted to lead sulphate ($PbSO_4$) [97]. Due to the weakening of the acid and the decrease in the difference between the plates, the battery cannot provide sufficient voltage and discharge occurs [98]. While in the charging cycle, the electrodes return to their initial state. The two most common lead–acid battery topologies are flooded and valve-regulated. Lead acid batteries have features such as low daily self-discharge (<0.6%), fast response time, moderate round-trip efficiencies of about 70–80%, and low cost. The battery performs relatively poorly at high temperatures, and its main disadvantages are periodic water maintenance and not being environmentally friendly [99]. In addition, the specific energy and power of the battery are relatively low: 30–50 (Wh/kg) and 180–200 (W/kg), respectively.

3.3.2. Lithium-Ion Batteries

Lithium-ion batteries have a high efficiency of 90–97% and high specific energy and power density of 75–200 Wh/kg and 245–500 W/kg, respectively, making them suitable for transportation and stationary applications [67,100]. Furthermore, they possess fast responses, a low daily self-discharge rate of 0.1–0.3%, and a long cyclic life of 6–20 years. While the anode in lithium-ion batteries is formed of graphite carbon, the cathode can be made of various lithium metal oxides, such as lithium manganese oxide, lithium-iron phosphate, and lithium cobalt oxide. An electrolyte is a lithium salt in an organic solvent. Electrodes are placed in this electrolyte, where a medium is created for Li+ ion transfer. When the battery is charged, the cathode is turned into lithium ions and moves through the lithium salt electrolyte toward the anode, where they combine with external electrons. However, the main difficulty in using a large scale is the high cost of this technology due to the need for special packaging and internal overcharge protection circuits [101].

3.3.3. Nickel–Cadmium (Ni–Cd) Batteries

Ni-Cd batteries consist of nickel hydroxide as the positive electrode and metallic cadmium as the negative electrode and use an aqueous alkaline solution as an electrolyte. High reliability and low maintenance costs are among their advantages. However, their disadvantages include the environmental hazards posed by cadmium and nickel, which are classified as toxic metals. Cadmium is especially harmful due to its severe toxicity and environmental impact, while nickel's effects are generally less severe [102]. Furthermore, the battery's maximum capacity can decline due to the memory effect, where repeated charging at low depths of discharge (DoD) causes it to perceive reduced capacity as full, lowering efficiency. Consequently, Ni-Cd batteries have not been commercially successful in utility-scale EES applications [103].

3.3.4. Sodium–Sulphur (NaS) Batteries

The active materials in the electrodes of a NaS battery are molten sulphur as the positive electrode and molten sodium as the negative electrode, separated by a ceramic, sodium alumina, which acts as a solid electrolyte. These batteries function optimally at elevated temperatures, typically between 300 and 350 °C, to facilitate efficient reactions and maintain low internal resistance [104]. NaS batteries have a specific energy of 150–240 (Wh/kg), specific power of 150–230 (W/kg), near-zero self-discharge rate, round-trip efficiency of 75–90 (%), and a service life of 10–20 years. They are also constructed from inexpensive, non-toxic, and highly recyclable materials [85]. Their energy density significantly exceeds that of conventional lead–acid batteries, offering a much more efficient and cost-competitive option for power applications. Furthermore, these batteries can provide brief pulses of power far exceeding their rated capacity, making them ideal for applications such as peak shaving and grid load balancing. However, challenges like the necessity for high operating temperatures and the flammability risks associated with sulphur require careful consideration. Recent advancements, including the development of room-temperature NaS batteries, promise safer and more versatile solutions, expanding the potential of this technology for both stationary and transportation applications [105].

3.3.5. Flow Batteries

Electroactive materials are used as two redox couple solutions in flow batteries. Unlike conventional batteries, their energy capacity is not limited by the size of the cell, as the electrolyte solutions are stored externally. These electrolytes are pumped from external tanks to the cell stack separated by ion-selective membranes, where reduction–oxidation reactions occur. During charging, these reactions occur, and electrical energy is converted into electrolyte chemical energy. On the contrary, during discharge, this chemical energy is converted into electrical energy [106].

Flow batteries are categorized based on their chemical components, such as polysulphide bromine (PSB), zinc–bromine (ZnBr), and vanadium redox flow batteries (VRFBs) [107]. VRFBs are especially notable for their long lifespan, low maintenance, high efficiency of around 85%, ability to last over 15,000 cycles, and minimal self-discharge, making them ideal for utility-scale applications such as peak shaving and load-levelling [106]. Similarly, PSB and ZnBr offer unique advantages, such as rapid response times and high design flexibility. Challenges like metal corrosion in ZnBR and the significant pumping demands of PSB limit their broader commercialization [108].

The modular design of flow batteries allows for flexible scaling of both energy capacity and power output, making them suitable for a wide range of applications. While challenges such as low energy density and specific energy remain, their scalability, adaptability, and large energy storage capabilities make them highly valuable for grid applications. Additionally, ongoing advancements in electrolyte and membrane technologies continue to enhance their efficiency and practicality [109].

3.4. Overview of Thermal Energy Storage Technologies

3.4.1. Sensible Thermal Energy Storage (STES)

STES is the most commonly utilized TES type, which stores energy by increasing the temperature of a medium without changing its phase. The storage capacity primarily depends on factors like the material's specific heat, its mass, and the temperature range during operation [110].

3.4.2. Latent-Phase Change Storage (PCM)

PCM systems store energy using phase transitions, such as solid–liquid or liquid–gas changes. Among these, the solid–liquid phase transition is the most commonly used due to its minimal volume variation and significant heat storage capacity [111]. PCMs are frequently studied to enhance energy density and system efficiency [112].

3.4.3. Thermochemical Energy Storage (TCES)

TCES systems utilize reversible chemical reactions to store and release energy. These systems are known for their high energy density and broad operational temperature range. Energy is stored during endothermic reactions and released during exothermic reactions [113]. Although TCES offers the advantage of long-term storage without heat loss, its complexity and high implementation costs remain significant challenges. Current research focuses on improving materials, optimizing system designs, and enhancing reaction mechanisms to address these issues [114,115].

3.5. Overview of Chemical Energy Storage Technologies

Hydrogen Energy Storage

Hydrogen, as a clean and carbon-free energy carrier, is primarily produced through water electrolysis or photocatalytic water splitting. A hydrogen energy system typically consists of three main components: a hydrogen generation unit (electrolyser), a storage system, and a hydrogen energy conversion unit, such as a fuel cell. During the charging phase, hydrogen is generated via electrolysis and stored, while in the discharging phase, it is converted back into electricity through fuel cells [116].

Despite its promising potential, fuel cells face several challenges. Many still rely on hydrocarbons as a source, leading to emissions of harmful gases like carbon dioxide, nitrogen oxides, and sulphur oxides. Moreover, the high initial capital cost of fuel cell systems remains a significant obstacle to their widespread adoption [71].

On the other hand, hydrogen storage systems are increasingly being integrated with RESs, enabling the production and storage of hydrogen for later energy conversion. This integration not only enhances grid stability but also helps manage supply–demand imbalances [117,118]. In this context, Yi et al. [119] introduced a high-resolution collaborative planning model for the year 2050 that incorporates the complete hydrogen energy chain, which includes the processes of production, compression, storage, transportation, and application. Their findings, based on a case study of northeast China, demonstrated that such a system could reduce renewable energy curtailment by 97% at zero carbon emissions. The study also highlights the critical role of hydrogen pipelines and seasonal storage, such as salt caverns, in optimizing inter-regional energy allocation and addressing supply–demand imbalances, particularly under high renewable energy penetration scenarios. These findings underscore hydrogen's essential role as a cornerstone of sustainable and highly efficient energy systems for the future.

4. Overview of ESS Applications

ESSs are highly versatile technologies that can address a wide range of applications across all levels of the power grid, providing solutions to meet specific operational needs. At the transmission level, ESSs enhance system efficiency by supporting voltage and frequency regulation, alleviating congestion, and facilitating energy time-shifting. These capabilities help to optimize power flows and maintain grid stability during fluctuations in supply and demand.

Additionally, centralized ESS solutions can address both hourly and seasonal variations in energy availability ensuring a balanced and dependable power supply. According to a study by IRENA [120], EESs are employed in a variety of grid applications, as illustrated in Figure 4. Further insights into specific application requirements are detailed in Table 3, showcasing the breadth of use cases for these systems in modern power grids.

Table 3 outlines the key technical requirements for various ESS applications, highlighting parameters such as power output, response time, cycle requirements, and discharging time. These criteria serve as a foundation for selecting suitable ESS technologies for specific operational needs within the power grid.

Building on these requirements, Table 4 presents examples of current ESS technologies and their respective applications, demonstrating how the ESS applications in Table 3 translate into practical use cases.

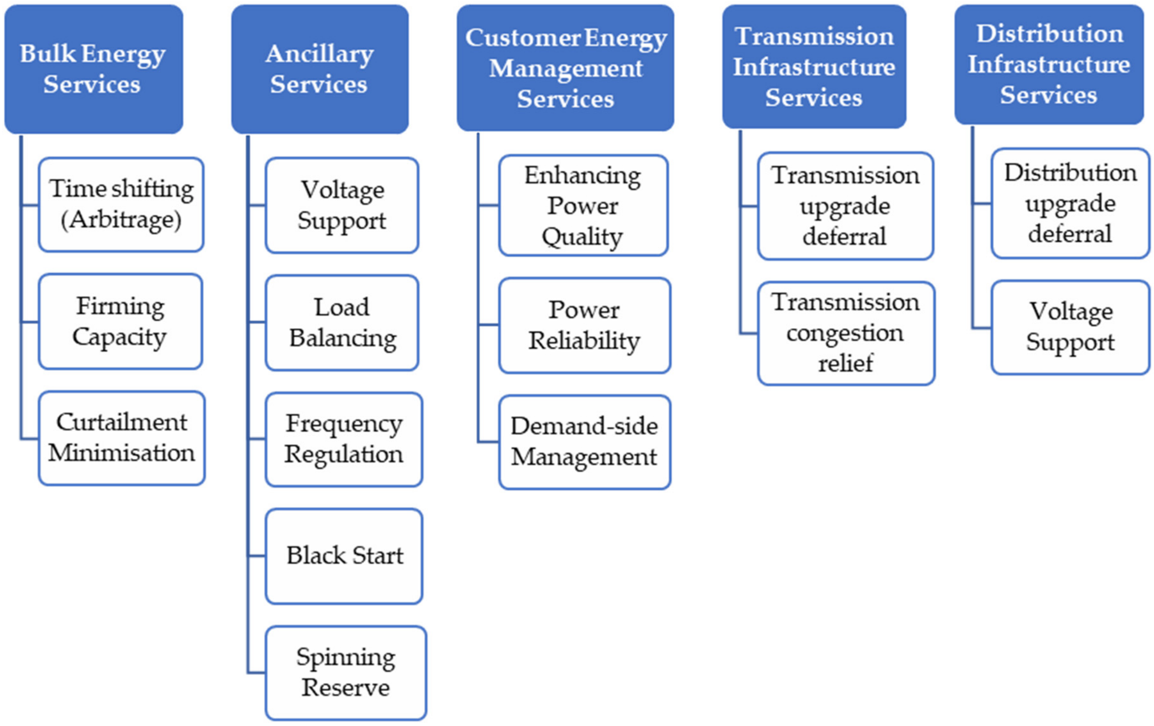

Figure 4. Overview of ESS applications (adapted from IRENA [120]).

Table 3. Key requirements for ESS applications (based on data and analysis from [16,118,121,122]).

Application	Description	Power Output	Response Time	Cycle Requirements	Discharging Time
Power Curtailment	Control power output to prevent grid congestion	Not required	-	-	-
Time Shifting (Arbitrage)	Energy is stored during low-cost off-peak hours and utilized during peak demand periods to lower consumption and costs	1–500 MW	Minutes	>4000/yr	3–12 h
Firming Capacity	Sustain a constant energy output	1–500 MW	Minutes	300–500/yr	1–12 h
Peak Shaving	Using stored energy during peak demand lowers costs and reduces the need for high-power generators	Up to several hundreds of MW	Minutes	50–250/yr	~<6 h
Voltage Support	Enhance the management of voltage dynamic responses	1–10 MW distributed 10–400 MW centralized	Milliseconds	5000 to 10,000/yr	Up to ~minutes
Frequency Regulation	Stabilizing the grid by balancing power generation and consumption, adjusting active power to limit frequency deviations	1–50 MW	seconds-minutes	250–10,000/yr	15 min–2 h
Load Levelling	Balances demand fluctuations	Up to several hundreds of MW	Minutes	* N/A	12 h
Black Start	Capability to restore power grids after blackouts	5–50 MW	Few seconds	10–20/yr	15–60 min
Spinning Reserve	Provides quick compensation for sudden changes in load or generation, offering immediate response and maintaining output for hours	10–100 MW	≤4 h	* N/A	≤5 h
Power Quality	Voltage and frequency remain within set limits, with a smooth sine-like voltage waveform and alignment between load and generation	≤10	≤200 ms	50/yr	≤2 h

Table 3. *Cont.*

Application	Description	Power Output	Response Time	Cycle Requirements	Discharging Time
Transmission Upgrade Deferral	Enhancing transmission lines or substations to increase capacity and reduce congestion	10–100 MW	Minutes	10–50/yr	1–6 h
Transmission Congestion Relief	Eliminating constraints in the transmission network to ensure smooth electricity flow and meet demand	1–100 MW	* N/A	50–100/yr	1–4 h
Distribution Upgrade Deferral	Improving local distribution networks to meet demand and ensure reliable power delivery	500 kW–10 MW	Minutes	50–100/yr	1–4 h

* N/A: No relevant data found for this field.

Table 4. Global examples of ESS technologies.

Type of ESS	Location/ Year of Operation	Storage Power/Energy Rating	Application	Ref.
PHS	US/1985	3003 MW	Time shift	[17]
	Spain	2000 MW	Time shift Firming capacity	[17]
CAES	Huntorf, Germany/1978	290 MW	Arbitrage Spinning reserve Black starts	[123]
	McIntosh, US/1991	110 MW	Load following Spinning reserve	[123]
FES	Massachusetts, US/2011	20 MW/5 MWh	Frequency regulation Power quality	[118]
	US/2007	100 kW/5 kWh	Peak shaving Power quality	[118]
Li-ion	Queensland, Australia	20 MW/80 MWh	Time shift Firming capacity	[16]
	US/2017	30 MW/120 MWh	Enhancing reliability Firming capacity	[124]
NaS	Futamata, Japan/2010	34 MW/244.8 MWh	Load levelling Wind smoothing	[104]
	Abu Dhabi, UAE/2019	108 MW/648 MWh	Peak shaving	[125]
Pb–acid	US/2012	36 MW/24 MWh	Peak shaving Power stabilization	[126]
VRFB	Dalian, China/2016	200 MW/800 MWh	Peak shaving	[127]
	Ireland	2 MW/12 MWh	Wind smoothing Frequency regulation	[128]
	Miyagi Prefecture, Japan/2013	40 MW	Frequency regulation Power stabilization	[126]
SMES	Nosoo power station/Japan	10 MW	Power stabilization	[118]
	UK/2013	10 kW/60 kJ	Power stabilization	[129]
SCES	North Carolina, USA	1.2 MW (with BESS)	Load shifting, solar smoothing	[130]
Hydrogen storage	Germany/2013	6 MW	Time shift	[131]
	Canada/2019	2 MW	Frequency regulation	[131]

Table 4. *Cont.*

Type of ESS	Location/ Year of Operation	Storage Power/Energy Rating	Application	Ref.
Thermal	Spain/2007	20 MW	Time shift Capacity firming	[17]
	US/2013	280 MW	Time shift Capacity firming	[17]

5. Performance Evaluation of Energy Storage Systems

To evaluate the technical performance of selected ESS key technical parameters such as power rating, specific energy, specific power, energy and power density, round-trip efficiency, response time, discharge duration, lifespan, technology maturity, and daily self-discharge have been identified. Tables 5–7 provide comprehensive data derived from an up-to-date review of the energy storage literature, forming a robust basis for analyzing and comparing the performance, cost, and feasibility of different ESS technologies.

Table 5. Technical characteristics of ESS technologies.

Technology	Lifespan		Power Rating	Specific Energy	Specific Power	Energy Density	Power Density
	Life (Years)	Cycling Capability	(W)	(Wh/kg)	(W/kg)	(kWh/m^3)	(kW/m^3)
PHS	40–60 [71]	(1–3) × 10^4 [118]	10–5000 [71]	0.5–1.5 [71]	0.01–0.12 [132]	0.5–1.5 [71]	0.5–1.5 [71]
SGES	30–60 [133]	12.103–30.103 [133]	1–1600 [133]	- [133]	- [133]	- [133]	- [133]
CAES	20–30 [67]	(8–12) × 10^3 [118]	5–300 [67]	30–60	- [118]	0.4–20 [118]	0.5–2 [118]
FES	15–20 [118]	20,000 [118]	0.1–20 [67]	~5 low speed ~100 high speed [118]	400–1500	20–80	1000–2000
Li-ion	6–20 [67]	up to 20,000 [118]	0.1–100 [67]	75–200 [67]	150–315 [67]	200–500 [67]	50–800 [67]
NaS	10–20 [67]	2500–4500 [118]	0.05–34 [67]	150–240 [67]	150–230 [67]	150–250 [67]	150–250 [67]
Pb–acid	5–15 [67]	500–1000 [118]	0–40 [67]	30–50 [67]	180–200 [67]	25–100 [67]	10–400 [67]
Ni-cd	13–20 [67]	2000–2500 [118]	0–40 [67]	50–75 [67]	100–160 [67]	60–150 [67]	150–300 [67]
VRFB	5–15 [67]	12,000+ [118]	0.3–3 [67]	10–20 [67]	80–150 [67]	20–70 [67]	1–34 [67]
PSB	10–15 [67]	- [118]	8–12 [67]	20–29 [67]	1.31 [67]	20–30 [67]	2–3.5 [67]
ZnBr	8–10 [67]	2000+ [118]	0.1–6 [67]	30–50 [67]	90–110 [67]	30–60 [67]	<25 [67]
SMES	20 [67]	2 × 10^4+ [118]	0.1–10 [67]	10–75 [67]	500–2000 [67]	0.2–2.5 [67]	1000–4000 [67]
SCES	8–17 [67]	5 × 10^4 [118]	0.02–10 [67]	2.5–15 [67]	2000–5000 [67]	1–35 [67]	1000–5000 [67]
Hydrogen storage	5–15 [118]	2 × 10^4 [118]	0.1–1000 [118]	100–150 [118]	- [118]	500–3000 [118]	500+
PCM	20–40 [67]	- [118]	0.001–1 [67]	150–250 [67]	10–30 [67]	150–250 [67]	- [67]
STES	10–20 [67]	- [118]	0.001–10 [67]	80–120 [67]	10–30 [67]	80–120 [67]	- [67]

Table 6. Cost-related parameters.

Technology	Cost Power (USD/KW)	Cost Energy (USD/KWh)
PHS [132]	850–2126 [133]	22–58 [133]
SGES	2252–3285 [133]	791–908 [133]
CAES	645–750 [133]	1–33 [133]
FES	250–350 [67]	1000–14,000 [67]
Li-ion	1200–4000 [67]	300–1300 [67]
NaS	1000–3000 [67]	300–500 [67]
Pb–acid	300–600 [67]	200–400 [67]
Ni-cd	500–1500 [67]	800–1500 [67]
VRFB	600–1500 [67]	150–1000 [67]
PSB	800–2900 [67]	150–1000 [67]
ZnBr	800–2900 [67]	150–1000 [67]
SMES	200–489 [67]	1085–10,854 [67]
SCES	100–450 [67]	300–2000 [67]
Hydrogen storage	1500–3000 [118]	2–15 EUR/kW h [118]
PCM	200–300 cryogenic [67]	13.65–68.26 [67]
STES	3650 hydrothermal [67]	0.14–13.65 [67]

Table 7. Performance metrics and maturity levels of ESS technologies.

Technology	ESS Efficiency Round-Trip Efficiency (%)	Self-Discharge Rate (%/day)	Discharge Time	Response (ms to h)	Technological Maturity
PHS	65–85 [118]	Almost zero [132]	6–24 h [122]	Minutes [118]	Mature [118]
SGES	65–90% [133]	Almost zero [74]	Sec −8 h [133]	Sec [133]	Demo/early commercializing [133]
CAES	70–80 [132]	Almost zero [118]	≤20 h [122]	Minutes [118]	Mature [67]
FES	75–90 [118]	55–100 [131]	≤1 h ms—15 min [67]	≤10 ms [67]	Mature/ commercializing [118]
Li-ion	90–97 [118]	0.1–0.3 [67]	Min–h ≤1 h [67]	20 ms–s [67]	Proven/commercializing [67]
NaS	75–90 [118] 89–92 [132]	0.05–2 [67]	≤6 h 1–24 h [67]	1–2 min [67]	Proven/commercialized [67]
Pb–acid	63–90 [118]	0.1–0.3 [71]	≤4 h [67]	ms [67]	Mature/commercialized [67]
Ni-cd	65–80 [118]	0.2–0.6 [67]	Sec-h [67]	20 ms–s [67]	Commercialized [67]
VRFB	65–85 [118]	0.2 [67]	≤8 h [67]	Sec [67]	Proven/commercializing [67]
PSB	72–83 [67]	Small [67]	- [67]	- [67]	Developing [67]
ZnBr	65–75 [118]	Small [67]	- [67]	- [67]	Demo/early commercializing [67]
SMES	80–95 [85]	10–15 [67]	1 min [67]	≤10 ms [67]	Commercializing [67]
SCES	90–98 [67] 65–90 [85]	5–40 [67]	1 min [67]	≤10 ms [67]	Demonstration [67]
Hydrogen Storage	20–66 [118]	Almost zero [118]	Secs–24 h+ [118]	Secs, <1/4 cycle [118]	Developing [118]
PCM	75–90 [67]	0.5–1 [67]	h–days [67]	≤10 min [67]	Demo/early commercialized [67]
STES	50–90 [67]	0.05–1 [67]	≤10 min [67]	Days–months [67]	Mature/commercialized [67]

As outlined in Table 5, supercapacitor energy storage (SCES) exhibit the highest specific power among all ESSs. Additionally, lithium-ion (Li-ion) and sodium–sulphur (NaS) batteries demonstrate both high specific power and energy, making them ideal for lightweight applications requiring these attributes. ESSs with high specific energy and power, such as Li-ion, lead–acid (Pb–acid), vanadium redox flow batteries (VRFBs), polysulfide bromide (PSB), and zinc–bromine (ZnBr), also exhibit low daily self-discharge rates, making them suitable for long-term energy storage. In contrast, electrical ESS technologies, including SCES and SMES, tend to have the highest daily self-discharge rates, making them suitable for short-term energy storage and more appropriate for power quality and regulation applications. Additionally, electrical ESSs offer exceptionally fast response times and high-power capabilities, making them ideal for applications requiring rapid energy delivery.

The volumetric dimensions of ESS play a significant role in the selection of appropriate storage devices. Hydrogen storage stands out for its exceptionally high energy density, driven by various storage methods and its utility for electricity generation. On the other hand, mechanical ESS, such as pumped hydro storage (PHS) and compressed air energy storage (CAES), have the lowest energy and power densities, requiring substantial physical space for medium- to large-scale applications. Despite these spatial demands, PHS and CAES possess the highest power ratings, making them well suited for long-term and bulk energy applications, alongside Li-ion and NaS batteries. SGES has also emerged as a promising candidate for bulk energy applications. SGES is noted for its adaptability to diverse geographical conditions, offering potential solutions where other mechanical energy technologies may face limitations. However, it is still in the development stage, with its technological maturity being relatively new. Current efforts focus on engineering prototypes to evaluate their practical applicability and effectiveness. Regarding service life, mechanical ESS technologies provide the longest operational durations, with PHS capable of functioning for up to 60 years. These extended lifespans make mechanical systems ideal for bulk energy storage over decades. In contrast, electrochemical ESS technologies generally have shorter lifespans, making them more suitable for ancillary services that prioritize response time and operational flexibility. Pb–acid and Li-ion batteries are particularly effective for energy optimization due to their balance of performance and operational flexibility.

As outlined in Table 6, electrochemical batteries, including Pb–acid and Li-ion, are widely used with LS-RES in the market, despite their cost and other limitations. Li-ion batteries, while highly advanced, are still undergoing intensive research to improve their cost-efficiency and scalability for commercialization. In terms of costs, Pb–acid and TESs have the lowest capital costs per kWh while SMES, STES, and FES technologies exhibit higher capital costs, limiting their broader application. Li-ion and NaS batteries, while more expensive per kWh, offer superior energy densities and efficiencies, justifying their use in specific high-value applications.

Electrical energy storage systems and FES excel in short-term, high-power applications, offering low power costs but higher energy costs. These systems are well suited for power quality and regulation tasks. Meanwhile, electrochemical batteries remain critical for large-scale renewable energy integration, although their cost and operational limitations must be managed effectively.

Another critical parameter in ESS selection is the self-discharge rate, as shown in Table 7. Electrical energy storage technologies, such as SCES, exhibit the highest self-discharge rates, while NaS batteries also have relatively high rates among electrochemical ESSs. In contrast, Pb–acid, VRFB, and ZnBr batteries demonstrate much lower self-discharge rates, enhancing their suitability for long-term storage.

The maturity levels of ESS technologies vary significantly. Fully mature technologies include PHS, Pb–acid, PHS, and Ni-Cd batteries, which have been in widespread use for decades.

In addition to discussing the key technical and economic aspects of various ESSs, Table 8 presents a general overview of their advantages and disadvantages. It is important to note that although some energy storage technologies may appear to have more drawbacks than others, they can still be the most suitable option for specific applications.

Intermittent RESs are poised to play a pivotal role in global energy transition; however, a single ESS offers only limited flexibility and addresses a narrow subset of operational challenges. As highlighted in [133,134], no single ESS can simultaneously provide high power density, high energy density, fast response, and both long- and short-duration storage capabilities. To overcome these limitations, hybrid ESS (HESSs) have emerged as a promising solution and a significant focus of ongoing research. By electronically integrating at least two complementary ESS technologies, HESSs utilize their combined strengths to minimize individual disadvantages [97]. For example, combining batteries, TES, and EVs optimizes cost and enhances grid performance, as TES effectively meets cooling demands while bidirectional charging in EVs provides additional storage capacity with minimal infrastructure modifications—potentially reducing annual energy costs by up to 55.8% in multi-scale urban environments [135].

In a typical HESS configuration, one ESS is optimized for high energy storage and low self-discharge, making it suitable for sustained energy delivery. The other ESS is designed for rapid response and high energy applications, ensuring grid stability during fluctuations. For example, a hybrid system combining CAES and FES has demonstrated the ability to improve power quality by effectively mitigating power fluctuations for a 25.5 MW WPS [99]. Similarly, research presented in [103] demonstrated that an HESS integrating SMES with a battery outperforms a single-battery system in frequency regulation, showcasing the superior functionality of HESS in balancing renewable energy variability.

Table 8. Main advantages and disadvantages of ESS technologies (based on [16,17,74,82,97,118]).

Technology	Storage Duration	Advantages	Disadvantages
PHS	Mid–long	Long life period Provides flexibility in power regulation	Geographical restriction High installation costs Long construction time
SGES	Mid–long	Rapid response capability High scalability features Adaptability to diverse geographical conditions	Efficiency (sealing friction) High installation costs
CAES	Mid–long	Low daily self-discharge rate Provide flexibility in power regulation High lifetime	The lack of advanced adiabatic CAES concept to reduce the use of natural gas and solve the problem of the scarcity of suitable caves
FES	Seconds, short	High cycle life Very fast charge Fast response High power quality	High idling loss High self-discharge rates
Li-ion	Short–mid	High energy density Light weight Long life period Low daily self-discharge rate Ongoing production cost reduction	Higher production cost Limited lifecycle Needs overcharging protection
NaS	Long	High power and energy density Near-zero self-discharge Non-toxic materials	Limited lifecycle Requires external heat system Flammability risks
Pb–acid	Short–mid	Low capital cost Fast response Low daily self-discharge rate	Low cycle life Requires periodic maintenance Low specific energy
Ni-Cd	Short–long	Low maintenance cost High round-trip efficiency	Relatively expensive Harmful environmental effects Poor performance while high charging rates
VRFB	Long	High design flexibility Low daily self-discharge rate Long life period High cycle life	Low specific energy; low energy density Lower round-trip efficiency
PSB	Short–long	High design flexibility	Not proven to be useful for utility-scale
ZnBr	Short–long	High cycle life Energy density Deep discharge capacity	Contamination risk Not proven to be useful for utility-scale
SMES	Short	High efficiency High power rates Fast response time	High investment cost High self-discharge rate
SCES	Short	High cycle life Very fast charge and discharge period High power rates	High capital cost Low energy density High daily self-discharge
Hydrogen storage	Short–long	High specific energy Fast charge period	Low volumetric density
PCM	Short–long	High cycle life	Low daily self-discharge

6. Conclusions and Future Research Directions

This study has analyzed the challenges posed by the large-scale integration of renewable energy sources (RESs) into the existing power grid, focusing on three critical aspects:

power supply stability, reliability, and quality. The findings reveal that even at today's levels of RES penetration, there are cases of grid flexibility issues, power quality degradation, and adverse stability and reliability impact. As the global energy transition accelerates and the capacity of RESs continues to expand, these challenges are expected to intensify, reinforcing the need for effective and adaptable solutions. Energy storage systems (ESSs), capable of storing energy in various forms, act as a bridge between intermittent renewable energy generation and demand. These systems differ in terms of their technological maturity, lifespan (life and cycling capability), power rating, specific energy, specific power, energy density, power density, efficiency (round-trip efficiency and self-discharge rate), discharge time, response time, power and energy costs, and associated advantages and disadvantages. Thus, their evaluation requires careful consideration of the grid's specific requirements and the intended application.

This research has reached the following conclusions:

- Mechanical ESSs, including PHS and CAES, are reported to have large-scale and long-duration storage potential, offering unmatched power ratings, extended operational lifespans, and significant contributions to power system flexibility and stability. Moreover, SGES, though still in the developmental stage, appears to be a promising technology for long-duration storage. On the other hand, FES is particularly valuable for short- and medium-duration storage, playing a crucial role in improving power quality.
- Electrochemical ESSs excel in short–medium-term applications, offering high energy and power densities, superior ramping capacity, operational flexibility, and low self-discharge rates. Li-ion technology, being one of the most commonly adopted options, is particularly suited for applications that demand power quality and reliability due to its rapid response times and long discharge duration capabilities. Furthermore, alternative technologies such as Pb–acid, NaS, Ni–Cd, VRFB, and ZnBr batteries contribute to enhancing reserve and flexibility in power systems, with their ability to provide fast response, moderate discharge durations, significant discharge capacities, and low self-discharge characteristics.
- Electrical ESSs, including SCES and SMES, are ideal for applications requiring rapid response and high-power delivery. However, their limited energy storage capacity makes them better suited for short-duration applications rather than addressing sustained energy deficits over longer periods. Electric vehicles (EVs) serve as eco-friendly alternatives to conventional cars and emerge as innovative ESSs through vehicle-to-grid (V2G) technology, enhancing grid flexibility and stability.
- TES is effective for peak demand management and CO_2 emission reduction but faces cost and integration challenges.
- Hydrogen storage, with its exceptional energy density and versatility, enables long-term storage and cross-sector applications in transportation and electricity generation. However, infrastructure and cost barriers remain significant hurdles to widespread implementation.

While each type of ESS exhibits distinct advantages, no single technology can address all the diverse challenges posed by the integration of RESs. Hybrid energy storage systems (HESSs), which combine the strengths of multiple storage technologies, emerge as a promising solution to this limitation. By integrating technologies that cater to both short-term and long-term energy storage needs, HESSs provide enhanced flexibility, adaptability, and overall efficiency, making them particularly well suited for modern power grids transitioning to high levels of RES penetration.

To further advance ESS technologies and ensure seamless integration, a multi-pronged strategy is required. This includes developing advanced techno-economic models that account for lifecycle cost, energy efficiency, power density, environmental impact, and scalability. Equally important are comprehensive financial analyses—covering metrics such as lifecycle cost analysis, levelized cost of storage, and payback periods—as well as robust risk assessments and flexible operational strategies.

Finally, the success of large-scale ESS deployment requires more than technological advancements. Supportive policy frameworks, market incentives, and clear regulatory measures are essential to foster investment and reduce financial risks. Governments and regulatory bodies can accelerate ESS adoption by offering subsidies, tax benefits, and guidelines that ensure grid compatibility. As the global energy landscape continues to evolve, sustained innovation, strategic planning, and cross-disciplinary research will be key to realizing the full potential of ESSs. This holistic approach—merging technology, policy, and market mechanisms—sets the stage for a cleaner, more resilient, and sustainable energy future for generations to come.

While this study provides a comprehensive assessment of the challenges and potential solutions associated with large-scale renewable energy integration, it is not without limitations. Regional differences in grid infrastructure and policy frameworks were not addressed in depth, which may impact the applicability of some conclusions. Furthermore, while HESSs were identified as a promising solution to address the limitations of individual ESS technologies, their practical implementation, optimization, and long-term performance under diverse grid conditions remain areas for further research.

Future research should focus on the integration of HESSs in diverse regional contexts, tailoring solutions to region-specific grid challenges and policy environments. Additionally, studies could investigate the optimization of HESS configurations, their socio-economic implications, and their scalability to maximize efficiency and performance under varying grid conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery energy storage
CAES	Compressed air energy storage
ESS	Energy storage system
EV	Electric vehicle
FES	Flywheel energy storage
HESS	Hybrid energy storage systems
Li-ion	Lithium-ion
MW	Megawatt
MWh	Megawatt hour
Na–S	Sodium–sulphur
Ni–Cd	Nickel–cadmium
Pb–acid	Lead–acid

PCM	Latent-phase change material
PHS	Pumped hydro storage
PSB	Polysulphide bromine flow batteries
PV	Photovoltaic
RESs	Renewable energy sources
SCES	Supercapacitor energy storage
SGES	Solid-gravitational energy storage
SMES	Superconductive magnetic energy storage
STES	Sensible thermal energy storage
TES	Thermal energy storage
V2G	Vehicle-to-grid
VRFB	Vanadium redox flow battery
Wh/kg	Watthour per kilogram
W/kg	Watt per kilogram
WPS	Wind power system

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