# Advanced energy storage technologies for renewable power systems: a comprehensive review

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**ABSTRACT**

The accelerating deployment of renewable energy, particularly solar and wind power, has intensified the need for advanced energy storage systems (ESS) to address intermittency and enhance grid reliability. However, existing reviews often provide fragmented technology comparisons without a unified techno-economic framework for systematic evaluation. This paper presents a comprehensive review of studies published between 2011 and 2025, examining electrochemical, mechanical, thermal, and hydrogen-based energy storage technologies using four standardized metrics: round-trip efficiency (RTE), levelized cost of storage (LCOS), cycle life, and technology readiness level (TRL). Lithium-ion batteries (LIBs) demonstrate the highest maturity and efficiency (RTE: 90–95% and LCOS: 120–200 USD/MWh), whereas sodium-ion batteries offer promising cost reductions of 30–40% through abundant materials and scalable manufacturing. Pumped hydro and compressed air energy storage (CAES) remain suitable for large-scale applications owing to their long service life and scalability, while thermal energy storage (TES) provides cost-effective long-duration storage for concentrated solar power (CSP). Hydrogen-based storage, despite lower RTE (25–45%), offers unique advantages for seasonal energy balancing. Unlike previous reviews, this study integrates techno-economic performance with technology maturity through a TRL-oriented comparative framework, enabling systematic technology assessment based on deployment readiness, economic viability, scalability, and application suitability, thereby supporting informed decision-making and future hybrid energy storage development.



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## 1. INTRODUCTION

The growing penetration of renewable energy sources, particularly solar and wind, has accelerated the need for new approaches to energy management and storage [1]. Because renewable generation is inherently variable, power systems face increased operational uncertainty and challenges in maintaining grid stability and reliability [2]. Energy storage systems (ESS) therefore play an essential role in balancing supply and demand, smoothing fluctuations, and improving overall system resilience [3]. Within this context, advanced energy storage technologies (AEST) provide a broad portfolio of options, including electrochemical batteries, mechanical storage, thermal energy storage (TES), and hydrogen-based storage, each with distinct performance characteristics and deployment constraints [4]. Despite the expanding literature, comparative evidence that clearly links technical performance to integration suitability across these technology classes remains fragmented. Motivated by this need, this review synthesizes the current status, advantages, limitations, and future research directions of major storage pathways to support informed selection and system design for renewable power applications [3], [4].

The past decade has seen a rapid increase in the deployment of renewable energy sources, particularly solar and wind, driven by the need to mitigate climate change and reduce greenhouse gas emissions [5], [6]. Despite these benefits, their growth also introduces major operational challenges because renewable generation is inherently intermittent and strongly influenced by weather variability [7]. This variability can strain power system operation and control, increasing generation uncertainty, affecting power quality, and complicating real-time balancing and dispatch [6], [8]. Improving grid reliability and stability therefore requires robust energy storage solutions that can absorb surplus generation and supply energy during periods of low renewable output [3]. As the transition toward a more sustainable energy landscape progresses, the role of ESS becomes increasingly important for coordinating renewable and conventional generation and for strengthening system flexibility [9]. Beyond balancing supply and demand, storage systems also enhance the resilience and adaptability of power networks under evolving technical and environmental constraints [10].

Integrating variable renewable energy sources such as solar and wind into power grids requires effective strategies to manage generation fluctuations and maintain secure operation [10]. ESS are central to this objective because they reduce the operational impact of intermittency and help preserve grid stability and reliability [11]. By abs orbing surplus electricity during periods of high renewable output and releasing it during demand peaks or renewable shortfalls, ESS enable more consistent balancing between supply and demand [12]. This operational flexibility improves energy management and reduces risks associated with voltage deviations, frequency instability, and supply interruptions [6], [13]. In parallel, continued development across multiple storage families, including mechanical, thermal, and hydrogen-based approaches, expands the range of solutions available for different grid services and time scales [14], [15]. Ongoing research therefore increasingly focuses on optimizing storage performance, cost, and integration strategies to support reliable renewable deployment and the broader transition to sustainable power systems [16].

AEST further strengthen system flexibility by providing complementary capabilities across response speed, storage duration, and deployment constraints [17], [18]. Among these options, TES offers particularly relevant pathways for renewable integration, especially where heat-to-power conversion or thermal coupling is feasible [19]. TES includes sensible heat, latent heat, and thermochemical storage, each characterized by different operating temperatures, storage densities, and discharge durations. Molten salt systems are widely used for sensible heat storage and are strongly associated with concentrated solar power (CSP) applications, enabling energy delivery beyond daylight hours [20]. Latent heat systems based on phase change materials (PCMs) can improve storage density and temperature regulation, while thermochemical storage provides promising potential for long-duration operation through reversible reactions [21]. Collectively, these TES approaches, alongside other AEST pathways, justify a more systematic and comparative evaluation of performance, cost, and application suitability to inform grid-scale integration decisions, consistent with recent studies and ongoing research directions [22], [23].

The continued expansion of renewable energy sources, particularly solar and wind, increases the urgency of addressing the primary technical barrier to high penetration, namely the intermittency of generation [24]. This has elevated ESS as enabling technologies for maintaining grid stability, improving reliability, and supporting flexible operation under variable supply conditions [25]. To advance both research and deployment, a rigorous comparative review of AEST is needed. Beyond consolidating recent findings, such a review should clarify the technical and operational distinctions among storage options and translate these differences into guidance on appropriate use cases and system-level integration. In addition, growing attention to environmental impacts, efficiency, and economic viability further strengthens the need for structured comparisons across technologies. Prior work indicates that, despite the maturity or promise of certain solutions, important gaps remain in understanding their performance and suitability across diverse applications and operating contexts [26]. Addressing these gaps can support stakeholders in making better-informed decisions about integrating renewable power systems within existing energy infrastructures [6]. Therefore, a comprehensive comparative analysis is timely and necessary.

Within renewable power systems, energy storage technology selection is a central issue because different services require different combinations of response speed, discharge duration, cost, and site constraints [27]. This review therefore evaluates major storage pathways, including electrochemical batteries, mechanical storage, TES, and hydrogen-based storage, and discusses how each contributes to the broader energy system. Hydrogen storage is a particularly relevant case for long-duration and seasonal balancing because it can decouple energy storage capacity from short-term electrochemical limitations, although it continues to face challenges related to round-trip efficiency (RTE), infrastructure requirements, and safety considerations [28], [29]. These trade-offs reinforce the importance of assessing storage technologies holistically, linking technical performance to economic feasibility, and integration constraints. Overall, the comparative synthesis developed in this review provides a basis for identifying appropriate technology roles and for improving storage-supported strategies to enhance grid stability and reliability under increasing renewable penetration.

This comprehensive review provides a structured synthesis of AEST in response to the growing reliance on variable renewable generation and the resulting requirements for flexibility, stability, and reliability in modern power systems. Rather than offering a descriptive comparison alone, the paper evaluates major storage families, including electrochemical batteries, mechanical storage, TES, and hydrogen-based storage, and links their technical characteristics to practical roles in renewable power applications. Key performance metrics and integration considerations are summarized to support consistent cross-technology comparison and to clarify where each option is most suitable. The paper is organized to guide the reader from electrochemical to mechanical, thermal, and hydrogen storage pathways, enabling a coherent understanding of their capabilities, limitations, and system-level interactions. Comparative tables consolidate performance parameters and application suitability, reinforcing the basis for informed technology selection and highlighting areas where further research is required [22], [23].

## 2. READINESS ASSESSMENT AND COMPARATIVE EVALUATION FRAMEWORK

### 2.1. Technology readiness level assessment

Technology maturity was evaluated using the technology readiness level (TRL) framework originally developed by NASA and subsequently adopted by the International Energy Agency (IEA), the European Commission, and other energy technology assessment frameworks. In this review, technologies classified at TRL 1–3 represent laboratory-scale concepts, TRL 4–6 correspond to prototype validation and pilot-scale demonstrations, TRL 7–8 indicate demonstration in operational environments, and TRL 9 denotes commercially deployed technologies with established industrial implementation.

TRL assignments were determined primarily from evidence reported in peer-reviewed literature and supplemented, where appropriate, by authoritative industry reports and IEA publications. Commercial deployment status, demonstration projects, manufacturing capability, and documented field operation were collectively considered when assigning representative maturity levels. Because technology development continues rapidly, the reported TRL values should be interpreted as representative maturity levels during the review period rather than fixed classifications.

The progression of TRL across storage technologies also provides insight into future commercialization pathways. Mature technologies such as pumped hydro storage (PHS) and lithium-ion batteries (LIBs) have reached commercial deployment (TRL 9), whereas sodium-ion batteries, solid-state batteries, advanced thermochemical storage, and several hydrogen storage technologies remain in intermediate demonstration stages (typically TRL 5–8), reflecting ongoing improvements in manufacturing scalability, reliability, and economic competitiveness.

### 2.2. Comparative framework and evaluation criteria

To ensure a consistent comparison across diverse energy storage technologies, this review adopts a unified evaluation framework based on four primary indicators: RTE, levelized cost of storage (LCOS), cycle life, and TRL. RTE is used to quantify the ratio of energy delivered to energy stored under complete charge-discharge operation. LCOS represents the lifetime cost of storing one unit of electricity while accounting for capital investment, operation and maintenance costs, replacement requirements, and system lifetime. Cycle life refers to the number of complete charge-discharge cycles before storage capacity declines to approximately 80% of the initial rated capacity, whereas TRL reflects the maturity of each technology from laboratory validation to commercial deployment.

Because the reviewed studies employed different experimental conditions, system boundaries, and reporting methods, the reported values were harmonized by extracting representative ranges rather than relying on single values whenever possible. For quantitative comparisons, values were interpreted within comparable operating conditions reported in the original references, while technology-specific assumptions were preserved when direct normalization was not feasible. Consequently, the presented ranges should be interpreted as representative performance intervals rather than absolute performance limits.

Economic values reported in different publications were normalized, where possible, to a common currency basis expressed in 2024 US dollars using published inflation indices and exchange-rate adjustments. When original studies provided only regional cost estimates or different reporting years, these values were converted to comparable units while retaining the underlying assumptions stated by the respective authors.

This normalization improves consistency across technologies while acknowledging unavoidable variations caused by regional market conditions and project-specific characteristics.

The reviewed technologies are organized into electrochemical, mechanical, thermal, and hydrogen-based categories because these groups represent fundamentally different energy storage mechanisms and operational characteristics. Electrochemical storage converts electrical energy into chemical energy through reversible electrochemical reactions; mechanical storage relies on kinetic or gravitational potential energy; thermal storage stores energy as sensible, latent, or thermochemical heat; whereas hydrogen systems convert electricity into chemical fuel through electrolysis and subsequently reconvert hydrogen into electricity or other energy services. This classification enables consistent comparison among technologies with similar physical principles while facilitating evaluation of their respective roles in renewable power systems.

The comparative synthesis presented throughout this review considers the trade-offs among technical performance, economic feasibility, scalability, and technology maturity. Rather than identifying a universally superior technology, each storage option is evaluated according to its suitability for specific renewable energy applications, considering metrics such as efficiency, storage duration, deployment constraints, lifecycle cost, and commercial readiness. This multi-criteria perspective reflects the practical reality that technology selection depends strongly on the intended grid service and operating conditions.

## 3. ELECTROCHEMICAL ENERGY STORAGE TECHNOLOGIES

Electrochemical energy storage has become a cornerstone of renewable power systems because it can respond rapidly to variability and support grid operation under intermittent solar and wind generation [6]. LIBs currently dominate the market due to their high energy density and strong RTE, but limitations related to cost, lifetime degradation, and material constraints can restrict wider deployment in large-scale and long-duration applications [24], [30]. In parallel, solid-state and sodium-ion batteries are emerging as promising alternatives, with ongoing progress in safety, cost, and supply-chain resilience that could improve their suitability for grid integration [27], [31]. Redox flow batteries (RFBs) provide a different value proposition, offering scalable energy capacity and long-duration storage characteristics that are well matched to sustained balancing and renewable firming services [32]. Overall, electrochemical storage technologies continue to evolve through active research aimed at improving performance, durability, and sustainability while expanding the range of applications across renewable energy systems [33].

### 3.1. Principles and characteristics of electrochemical storage

Electrochemical energy storage relies on reversible redox reactions to convert electrical energy into chemical potential and release it on demand, enabling controllable charging and discharging for a wide range of applications [34], [35]. Among available technologies, LIBs have become the most widely adopted due to their high energy density, strong efficiency, and ability to deliver high power, which makes them suitable for both mobility and stationary renewable integration [31]. Despite their maturity, LIB deployment at scale remains constrained by critical material dependence and end-of-life management challenges, including recycling and circularity requirements [36]. The pursuit of alternatives, such as sodium-ion and RFBs, showcases the industry’s response to these challenges, focusing on cost-effectiveness and scalability for grid applications [14]. Overall, the diverse array of electrochemical batteries, characterized by their varied applications from electric vehicles to renewable integration highlights the pivotal role they play in enhancing energy management and grid stability amidst the growing reliance on intermittent renewable sources [36].

The range of electrochemical storage options, including lithium-ion, solid-state, sodium-ion, and RFBs, illustrates an evolving landscape of solutions designed to meet different performance and deployment needs in renewable energy systems [37], [38]. Figure 1 provides an overview of the major electrochemical energy storage technologies considered in this review.

### 3.2. Battery technologies: lithium-ion, solid-state, sodium-ion, and redox flow

Recent progress in battery technologies has been central to improving the flexibility and reliability of renewable energy systems by enabling fast, controllable energy balancing under variable solar and wind generation [38], [39]. Table 1 summarizes representative characteristics of major battery pathways discussed in this review. LIBs remain the dominant technology due to their high energy density, established supply chains, and technological maturity, although concerns related to critical material dependence and end-of-life sustainability continue to attract scrutiny [40], [41]. Solid-state batteries represent an important development direction because solid electrolytes can improve intrinsic safety and potentially increase energy density and lifetime, but many designs are still limited by manufacturing scalability, interfacial challenges, and cost barriers that constrain near-term grid deployment [42]. Sodium-ion batteries have emerged as a promising alternative for large-scale applications because sodium is abundant and potentially lower cost, which may improve supply-chain resilience and support broader stationary deployment as performance improves [43]. RFBs provide a distinct architecture that decouples power and energy capacity, making them attractive for long-duration storage and renewable firming services where scalability and cycling durability are prioritized [25]. Collectively, these battery technologies illustrate an evolving portfolio of solutions that can support grid stability and reliability, with technology choice depending on discharge duration, safety requirements, cost targets, and sustainability constraints [15], [44].

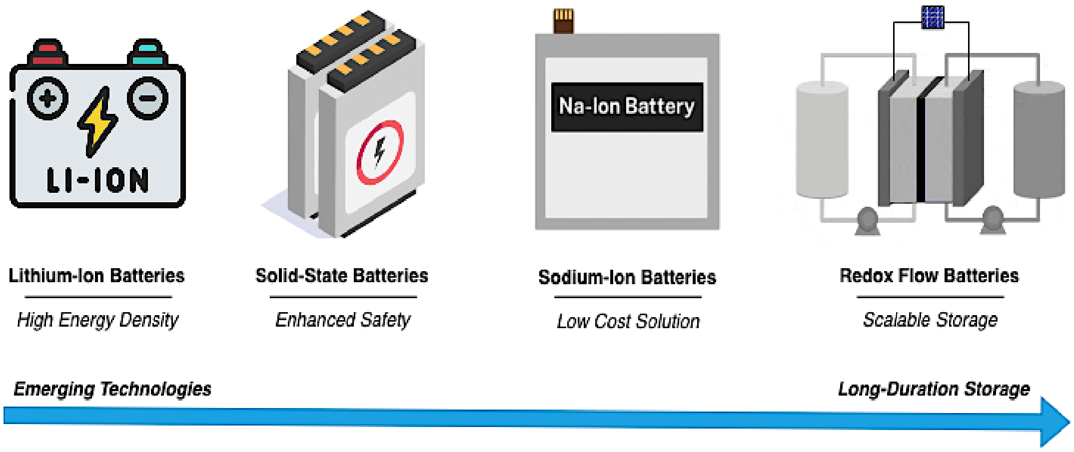


Figure 1. Overview of major electrochemical energy storage technologies used in renewable power systems

Table 1. Battery technologies comparison [45]

| Battery type | Energy density (Wh/kg) | Cycle life (cycles) | Cost ($/kWh) |
|---|---|---|---|
| Lithium-ion | 150 | 500 | 150 |
| Solid-state | 500 | 3000 | 200 |
| Sodium-ion | 160 | 2500 | 70 |
| Redox flow | 20 | 20000 | 300 |

### 3.3. Lithium-ion batteries: current dominance, performance metrics, and limitations

LIBs remain the most widely deployed electrochemical storage technology due to their strong performance and versatility across portable, mobility, and stationary applications, including renewable energy integration [46]. Their high energy density and high RTE support fast response and frequent cycling, which makes LIBs particularly effective for mitigating short-term variability from solar and wind generation [47]. Continued improvements in materials, cell design, and power electronics have further strengthened their practical suitability for grid and hybrid power management systems [48]. Despite this maturity, LIB deployment at scale faces persistent constraints, including safety risks under abuse conditions, performance degradation with cycling and calendar aging, and supply-chain pressures linked to critical materials [49]. As stakeholders seek solutions to improve grid reliability and performance, a critical evaluation of these limitations alongside their advantages leads to informed decision-making in energy storage technology deployment, essential for the evolving landscape of renewable power systems. The balance between leveraging their strengths and addressing their challenges remains crucial for advancing energy storage solutions. Table 2 listed the key performance characteristics of LIBs. It highlights their energy density, cycle efficiency, safety concerns, lifespan in charge cycles, and resource availability. The highest value is the lifespan at 2000 charge cycles, indicating durability, while energy density and cycle efficiency are also strong metrics [42]. Safety concerns are noted as significant, and resource availability issues reflect critical material scarcity [45].

Table 2. Key performance characteristics of LIBs

| Parameters | Values |
|---|---|
| Energy density (Wh/kg) | 250 |
| Cycle efficiency (%) | 90 |
| Safety concerns (ranked 1-5) | 4 |
| Lifespan (charge cycles) | 2000 |
| Resource availability (critical materials) | 3 |

### 3.4. Solid-state batteries: safety improvements and future potential

Solid-state batteries are an emerging pathway in electrochemical storage, attracting strong interest because they can address key safety limitations associated with liquid-electrolyte lithium-ion systems and may enable higher performance for both mobility and stationary applications [50]. In conventional LIBs, flammable liquid electrolytes can increase the risk of leakage and thermal runaway under fault or abuse conditions. Solid-state designs replace the liquid electrolyte with a solid electrolyte, which can reduce these hazards and improve intrinsic safety characteristics [51]. Beyond safety, solid-state architectures may support higher energy density and longer lifetime through improved electrochemical stability and by enabling the use of high-capacity electrode materials, although these benefits depend on material choice and interface engineering [52], [53]. Their potential to operate across a wider temperature range can further improve reliability for grid applications exposed to varying environmental conditions and cycling profiles [50]. However, despite clear promise, practical deployment remains constrained by challenges such as manufacturing scalability, interfacial resistance, dendrite suppression, and cost. Ongoing research and industrial development are therefore critical to translating laboratory progress into economically viable systems for renewable power integration [22], [54].

### 3.5. Sodium-ion batteries: cost advantages and large-scale grid suitability

As renewable energy deployment expands, cost-effective and scalable storage solutions are increasingly needed to support reliable grid operation under variable solar and wind generation [55]. Sodium-ion batteries have attracted growing attention because sodium is abundant and widely available, which can reduce material supply risk and lower projected manufacturing costs compared with lithium-ion systems in certain stationary applications [56], [57]. Recent studies highlight several attributes that support their relevance for grid-scale deployment, including potentially competitive cost structure, strong power capability, wider operating temperature tolerance, and improved sustainability considerations through material availability and recyclability [58]. These characteristics make sodium-ion batteries a promising option for applications such as renewable firming, peak shaving, and load shifting, particularly where energy density requirements are less stringent than in mobility use cases. At the same time, performance and durability remain chemistry- and design-dependent, and further development is required to strengthen lifetime, efficiency, and standardization for large-scale integration. Overall, the growing emphasis on diversified battery pathways reinforces sodium-ion technology as a credible component of future storage portfolios for renewable power systems, alongside lithium-ion and flow battery solutions [25], [59].

### 3.6. Redox flow batteries: architecture, scalability, and long-duration storage potential

RFBs are increasingly recognized as a strong candidate for grid-scale applications because their architecture enables independent scaling of power and energy capacity [60]. In RFB systems, power output is primarily determined by the electrochemical stack, while energy capacity is determined by the volume and concentration of the liquid electrolytes stored in external tanks. This separation is particularly advantageous for long-duration storage, where increasing discharge duration can be achieved by expanding electrolyte storage without proportionally increasing stack size [61]. Their potential viability is amplified by recent explorations into cost reduction and technological maturity, as RFBs offer advantages over traditional lithium-ion and lead-acid batteries, specifically in terms of longevity and safety [60]. Consequently, the unique capabilities of RFBs position them as essential components in the future landscape of energy storage technologies, providing robust solutions for grid stability and renewable resource management [62].

### 3.7. Advantages, limitations, and typical applications in renewable systems

As renewable penetration increases, selecting appropriate energy storage solutions requires a clear understanding of the strengths, limitations, and operating roles of different technologies [63]. ESS mitigate the intermittency of solar and wind generation by providing services such as ramp-rate control, frequency support, peak shaving, and energy shifting, thereby strengthening grid stability and operational flexibility [64]. Storage options, however, differ markedly in response speed, discharge duration, efficiency, siting constraints, and lifecycle cost. Electrochemical batteries typically provide fast response and high efficiency, which makes them well suited to short-duration applications and high-cycling grid services. In contrast, hydrogen-based systems can provide long-duration and seasonal balancing due to their scalable energy capacity and high gravimetric energy density, as highlighted in recent work [23], [65]. These advantages are accompanied by important limitations. Battery systems face degradation, thermal management requirements, and self-discharge behaviors that can reduce effectiveness and economic value over extended time horizons [66]. Hydrogen pathways, while attractive for large-scale storage, generally exhibit lower RTE and higher infrastructure complexity, which limits their suitability for frequent charge and discharge operation [67]. A critical evaluation of these trade-offs supports more strategic matching of storage technologies to specific renewable integration needs and grid service requirements.

## 4. MECHANICAL ENERGY STORAGE TECHNOLOGIES

Mechanical energy storage technologies play an important role in improving the reliability and efficiency of renewable power systems by providing inertia-like support, fast balancing capability, and, in some cases, large-scale energy shifting [24]. PHS is the most mature option and remains the dominant form of bulk mechanical storage, using gravitational potential energy by pumping water to an upper reservoir during surplus generation and releasing it through turbines during high demand [68]. Compressed air energy storage (CAES) offers another pathway for medium-to-long duration storage by using excess electricity to compress air for later expansion, with adiabatic CAES designs aiming to increase efficiency through improved thermal management and better suitability for underground storage configuration [69], [70]. Furthermore, flywheel energy storage systems (FESS) offer a high-power density solution characterized by rapid response times, making them ideal for frequency regulation in power grids [71], [72]. Figure 2 summarizes the principal mechanical storage technologies and their operational characteristics. As renewable penetration grows, the performance, siting constraints, and cost competitiveness of these mechanical options become increasingly important for planning storage portfolios alongside electrochemical, thermal, and hydrogen-based solutions [22], [23].

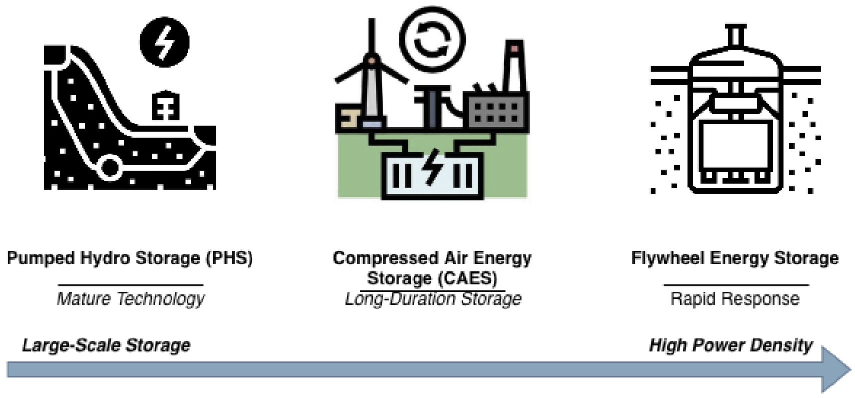


Figure 2. Mechanical energy storage technologies: PHS, CAES, and FESS

### 4.1. Working principles of mechanical storage systems

The effectiveness of mechanical storage systems lies in their ability to leverage kinetic and potential energy for energy management, which is particularly crucial for addressing the intermittency characteristic of renewable energy sources [73]. PHS and CAES typically store surplus electricity by pumping water to an elevated reservoir or compressing air into a storage volume, and they recover this energy through turbines or expanders during periods of higher demand or reduced renewable output [74], [75]. These systems are highly mature, with PHS being the most widely adopted form due to its efficiency and scalability [54]. In contrast, FESS store energy as kinetic energy in a rotating mass and are optimized for rapid charge and discharge, high cycling durability, and short-duration services such as frequency regulation and power quality support [9]. Understanding these operating principles, together with key performance metrics and cost drivers, is essential for matching mechanical storage technologies to specific grid needs and optimizing their deployment within renewable-rich energy systems.

### 4.2. Key technologies: pumped hydro, compressed air, and flywheel systems

As renewable penetration increases, mechanical storage technologies remain important for supporting grid stability and reliability across a range of operating time scales [63]. Among the prominent mechanical storage solutions, pumped hydro, compressed air, and flywheel systems stand out for their diverse applications and operational efficiencies [33]. PHS remains the most established, excelling in large-scale deployment due to its high energy density and efficiency, making it ideal for balancing supply and demand on a daily basis [63]. In contrast, CAES has gained attention for its potential in long-duration storage, showing competitive economic viability relative to PHS, especially as it evolves towards larger scales and higher efficiencies [76]. Meanwhile, FESS are distinguished by their rapid response capabilities, crucial for frequency regulation in modern power grids [22]. Table 3 summarizes representative performance metrics for these technologies and provides a basis for comparing their roles in mitigating renewable intermittency and improving power system resilience.

Table 3. Performance metrics of mechanical energy storage technologies

| Technology | Energy density (Wh/kg) | RTE (%) | Typical capacity (MW) | Lifetime (cycles) |
|---|---|---|---|---|
| PHS | 0.2-3 | 70-90 | 500-3000 | 20,000-30,000 |
| CAES | 30-60 | 60-70 | 10-300 | 10,000-20,000 |
| FESS | 5-100 | 80-90 | 0.1-100 | 1,000,000 |

### 4.3. Pumped hydro storage: technology maturity and large-scale deployment

As power systems transition toward higher shares of renewable generation, large-scale and reliable energy storage becomes increasingly important for maintaining secure operation and balancing variability [63]. PHS has emerged as a front-runner, benefiting from its technology maturity and large-scale deployment capabilities without necessitating novel inventions [75], [77]. PHS operates by utilizing excess electricity to pump water to elevated reservoirs, which can then be released to generate power when demand peaks, thereby providing essential grid stability and reliability [22]. This established technology has demonstrated efficacy in integrating variable renewable sources, such as wind and solar power, into the energy mix by addressing their inherent intermittency challenges [68]. Nevertheless, broader deployment is constrained by site-specific requirements, environmental and permitting considerations, and the availability of suitable topography and water resources. These factors should be explicitly considered when evaluating PHS as part of storage portfolios for sustainable energy transitions.

### 4.4. CAES and adiabatic CAES: efficiency improvements and underground storage systems

CAES is a mechanical storage option that can support renewable integration by shifting energy from periods of surplus generation to periods of higher demand, thereby reducing the operational impacts of intermittency [78]. CAES systems, particularly when combined with adiabatic processes, have demonstrated enhanced efficiency improvements that are critical for large-scale implementation [79]. These systems utilize underground caverns for storing compressed air, which not only optimizes their operational footprint but also facilitates prolonged energy storage capabilities essential for balancing supply and demand in energy systems [80]. Recent studies indicate that the LCOS for CAES is competitive with more established methods, such as PHS, further affirming its viability in the energy landscape [76]. Despite challenges like relatively low roundtrip efficiency and slow response times, the inherent advantages of CAES such as scalability, durability, and minimal environmental impact position it as a pragmatic solution for integrating renewable energy sources [81]. Continued development in thermal management, system integration, and underground storage engineering is therefore important for improving CAES performance and enabling broader deployment within holistic energy strategies.

### 4.5. Flywheel energy storage systems: high power density and fast response for frequency regulation

As the demand for reliable power management escalates with the growing integration of renewable energy sources, effective solutions for frequency regulation have become imperative [82]. Among the various options available, FESS stand out due to their high-power density, and rapid response capabilities, which are crucial for stabilizing fluctuations in voltage and frequency within the grid [83]. The mechanical nature of FESS, where kinetic energy is stored in a rotating mass, allows for swift energy discharge and recharge cycles, making it particularly suitable for balancing intermittent energy outputs typical of solar and wind generators [84]. Moreover, FESS technology boasts a long operational lifespan, enhanced efficiency, and minimal environmental impact compared to conventional systems, effectively addressing many limitations associated with other energy storage solutions [85]. Recent advancements in artificial intelligence and machine learning have further optimized FESS functionalities, supporting critical applications across various scenarios [71]. Overall, FESS represent a valuable component of mechanical storage portfolios where rapid response and high-cycle ancillary services are prioritized to support grid stability and reliability.

### 4.6. Performance comparison and integration with renewable generation

Integrating AEST into renewable power systems directly affects operational performance, reliability, and the ability to accommodate variability from wind and solar generation [17]. Identifying the strengths and limitations of various storage solutions is essential for optimizing their deployment alongside intermittent energy sources such as wind and solar. Electrochemical systems, particularly LIBs, offer high efficiency and rapid response times, thus proving effective for short-term storage needs; however, they struggle with self-discharge and capacity loss over time, as highlighted in the literature [23]. Conversely, hydrogen-based systems present substantial advantages for large-scale, long-duration storage, given their low energy loss and high energy density, despite operating at lower efficiencies in practice [86]. The ongoing pursuit of hybrid systems synthesizing these technologies may offer a path forward leveraging the rapid discharge capabilities of batteries with the long-term storage potential of hydrogen [87]. Ultimately, such integrations promise not only to enhance energy management but also to address the overarching challenges of reliability and sustainability within modern power systems. Table 4 shows key performance metrics for various energy storage technologies. It highlights LIBs with a cycle efficiency of 90% and a lifespan of about 2000 charge cycles. Hydrogen storage systems operate at around 60% efficiency but have a high energy density of 1500 Wh/kg. Additionally, PHS has an efficiency around 80% and significant capacity of approximately 180 GW [45].

Table 4. Key performance metrics for various energy storage technologies

| Storage system | Parameter | Value | Unit |
|---|---|---|---|
| LIB | Cycle efficiency | 90 | % |
| | Lifespan | 2,000 | Charge cycles |
| Hydrogen energy storage (HES) | Energy conversion efficiency | 60 | % |
| | Energy density | 1,500 | Wh/kg |
| PHS | Round-trip efficiency | 80 | % |
| | Global installed capacity | 180 | GW |

## 5. THERMAL ENERGY STORAGE TECHNOLOGIES

TES technologies are increasingly important for managing variability in renewable-integrated energy systems, particularly where thermal energy can be stored directly or coupled to electricity generation and demand [88]. By harnessing excess thermal energy during peak generation, these systems facilitate a reliable supply when demand surges or production wanes [89]. Various methods underpin TES, notably sensible heat storage, which includes systems such as molten salt that effectively capture high temperatures for later use in applications such as CSP [90]. Additionally, latent heat storage utilizes PCMs to absorb or release heat at specific temperatures, thus enhancing efficiency and performance across diverse applications [91]. Furthermore, TCES emerges as a promising avenue that promises long-duration capabilities, facilitating energy management in complex renewable power systems [92]. Figure 3 summarizes these TES categories and their working principles. Overall, TES supports decarbonization by improving energy utilization and flexibility and can contribute to system stability and resilience when integrated appropriately within renewable-rich energy infrastructures [93].

### 5.1. Fundamentals of thermal energy storage

The integration of TES technologies plays a pivotal role in enhancing the reliability of renewable energy systems, particularly in addressing the intermittency characteristic of sources like solar and wind [88]. TES is commonly classified into three categories: sensible heat storage, latent heat storage, and thermochemical storage, each defined by a distinct storage mechanism and operating profile [91]. Figure 3 presents a conceptual classification of TES technologies, including sensible heat, latent heat, and thermochemical storage methods. Sensible heat storage, for instance, often utilizes materials such as molten salts to store thermal energy by raising the temperature of a medium, allowing for efficient energy dispatch when generation is insufficient [94]. Latent heat storage systems, incorporating PCMs, capitalize on the energy absorbed or released during phase transitions, thus enabling higher energy density storage [95]. In contrast, TCES offers the advantage of long-duration storage potential by harnessing endothermic and exothermic reactions. These diverse TES solutions can be effectively implemented in systems such as CSP and district energy networks, highlighting their significance in achieving sustainable energy management and utilization [23], [28].

### 5.2. Thermal energy storage: sensible, latent, and thermochemical methods

Within advanced energy storage portfolios, TES comprises approaches that capture thermal energy and deliver it later as heat or through heat-to-power conversion, helping to manage variability associated with renewable generation and thermal demand profiles [91]. Central to TES are sensible heat storage systems, such as molten salt and water tanks, which store energy through temperature changes in a medium, and latent heat storage technologies that utilize PCMs to absorb and release energy during phase transitions [93]. Furthermore, TCES represents a more innovative approach, where chemical reactions are harnessed to store and release thermal energy over extended periods, thus enhancing the system’s capabilities for long-duration storage [92]. The integration of these thermal storage methods is particularly advantageous in applications such as CSP and district energy systems, offering significant reductions in peak energy demand while promoting energy efficiency [96]. Table 5 summarizes recent market developments and published growth projections for TES technologies over the 2023 to 2033 period, including the projected market sizes and the corresponding compound annual growth rate (CAGR) for this timeframe. These developments reinforce the role of TES as a key component in renewable-integrated energy infrastructures, particularly where flexible thermal dispatch can improve reliability and support a resilient transition toward sustainable power systems [94].

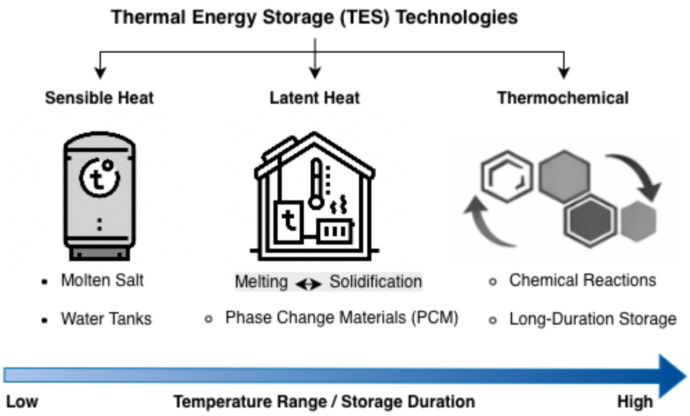


Figure 3. Classification of TES technologies: sensible heat storage, latent heat storage using PCMs, and TCES

Table 5. TES market trends 2023-2033 [45]

| Market size (USD billion) | Year |
|---|---|
| 6.50 | 2023 |
| 10.00 | 2030 |
| 17.36 | 2033 |
| CAGR (8.5%) | 2023-2033 |

### 5.3. Sensible heat storage (e.g., molten salt systems)

Sensible heat storage is an established TES pathway that is particularly relevant for renewable systems with strong solar contributions, where dispatchability depends on shifting thermal energy beyond periods of peak irradiance [97]. Molten salt systems have gained wide attention because they can store large amounts of thermal energy at elevated temperatures with practical scalability and proven integration in CSP plants [92]. These systems operate by storing thermal energy generated during peak sunlight hours, subsequently releasing it to produce steam for electricity generation when sunlight is insufficient. This capability supports grid stability, enabling a more seamless integration of renewable energy sources into existing power networks [91]. In addition, molten salt storage aligns with system-level findings that highlight the need for effective storage solutions capable of balancing renewable variability and reducing curtailment under increasing renewable penetration [22], [26]. Overall, sensible heat storage using molten salts remains a key TES option for enhancing renewable dispatchability and strengthening energy management strategies in low-carbon power systems.

### 5.4. Latent heat storage using phase change materials

As renewable energy deployment expands, efficient storage solutions are increasingly needed to manage intermittency and supply variability across both power and thermal applications [98]. One notable advancement in TES is the utilization of latent heat storage through PCMs, which allow for energy to be stored and released during phase transitions, typically from solid to liquid and vice versa [99]. This technology not only enhances energy density but also improves the thermal management of systems, optimizing performance in applications such as CSP and industrial waste heat recovery. Recent studies underscore the significance of medium-high temperature PCMs, focusing on enhancing thermal conductivity and designing effective heat exchangers to maximize energy recovery and storage efficiency [91]. In addition, the adaptability of PCMs to different operating temperatures and heat sources supports broader integration across solar thermal systems and industrial processes, helping to reduce mismatch between thermal supply and demand and strengthening the stability of renewable-integrated energy systems [20].

### 5.5. Thermochemical energy storage and long-duration storage potential

TCES is increasingly considered a promising pathway for long-duration storage in renewable-integrated energy systems because it can address intermittency over extended time horizons [92]. By harnessing reversible endothermic and exothermic reactions, TCES can effectively absorb, store, and release thermal energy. This technology not only enhances the stability and flexibility of energy systems but also offers significant potential for large-scale deployment, particularly in conjunction with CSP installations [100]. The merit of TCES lies in its ability to provide energy storage over extended periods, making it ideal for balancing supply and demand during seasonal variations [92]. Additionally, the integration of TCES within district energy systems can reduce peak energy demands and promote efficient resource utilization. As reported, advancements in various TES methods, including latent heat systems and phase-change materials, further highlight the ongoing evolution and economic viability of TCES solutions in modern energy contexts [54], [93]. Overall, TCES remains an important candidate for future energy frameworks that require reliable long-duration storage and flexibility.

### 5.6. Applications and role of thermal energy storage in long-duration and seasonal storage

The integration of TES into renewable power systems is a critical strategy for addressing the intermittency associated with renewable energy sources such as solar and wind [92]. TES offers versatile applications in both long-duration and seasonal energy storage, effectively capturing thermal energy for later use [101]. This capability is particularly relevant in residential and commercial settings, where TES systems can harness solar heat for heating, cooling, and even electricity generation, thereby reducing reliance on conventional power while alleviating peak demand on the grid [91]. Moreover, the emergence of materials like PCMs enhances the efficacy of latent heat storage systems, allowing for greater energy density and improved thermal management [93]. The development of sensible heat storage solutions, including molten salt and underground storage methods, further expands the potential of TES by facilitating large-scale applications such as CSP plants and district heating systems [93]. Overall, TES contributes to low-carbon energy transitions by improving energy utilization, enhancing resilience, and enabling more reliable operation of renewable-integrated power and thermal infrastructures.

## 6. HYDROGEN-BASED ENERGY STORAGE SYSTEMS

Hydrogen-based energy storage is increasingly discussed as a complementary option for renewable-rich power systems because it can address long-duration and seasonal balancing needs that are difficult to meet using batteries alone [86]. Hydrogen, produced through electrolysis using surplus renewable energy, serves as an effective chemical energy carrier, enabling large-scale and long-duration storage that batteries struggle to achieve [102]. Figure 4 illustrates the full power-to-hydrogen-to-power pathway, including hydrogen production, storage, and electricity generation through fuel cells or turbines. Although hydrogen offers advantages in storage duration and scalability, the overall RTE remains a major challenge because conversion stages introduce substantial losses, and many current pathways retain only a fraction of the original electrical input as delivered electricity [93]. Despite these drawbacks, the need for long-term energy storage is driving research and development in this domain. Moreover, hybrid systems that incorporate hydrogen alongside traditional storage technologies, such as batteries, can harness the strengths of each method, thereby enhancing overall efficiency and performance [23]. Consequently, hydrogen-based systems remain essential in advancing the integration and stability of renewable power systems, particularly in addressing seasonal energy demands [103].

### 6.1. Fundamentals of hydrogen as a chemical energy storage carrier

Hydrogen is increasingly positioned as a chemical energy storage carrier that can help address intermittency challenges in renewable-integrated power systems, particularly when storage is required over long durations or across seasons [104]. By harnessing surplus electricity through electrolysis, hydrogen production can effectively convert excess energy into a storable form, thus facilitating grid stability and enhancing energy management [102]. Various storage methods have been developed, including compressed hydrogen, liquefied hydrogen, and material-based storage systems, each presenting unique advantages and challenges regarding efficiency and safety [28]. For long-duration and seasonal applications, hydrogen is attractive because it can be stored at large scale with relatively low standing losses over time and can complement other flexibility options in renewable-dominated systems [86]. However, power-to-hydrogen-to-power operation typically remains less efficient than battery-based storage for short-duration and high-cycling services. For this reason, hybrid architectures that combine batteries for fast response with hydrogen for extended-duration balancing are increasingly emphasized as a practical strategy to improve overall system resilience and sustainability [23].

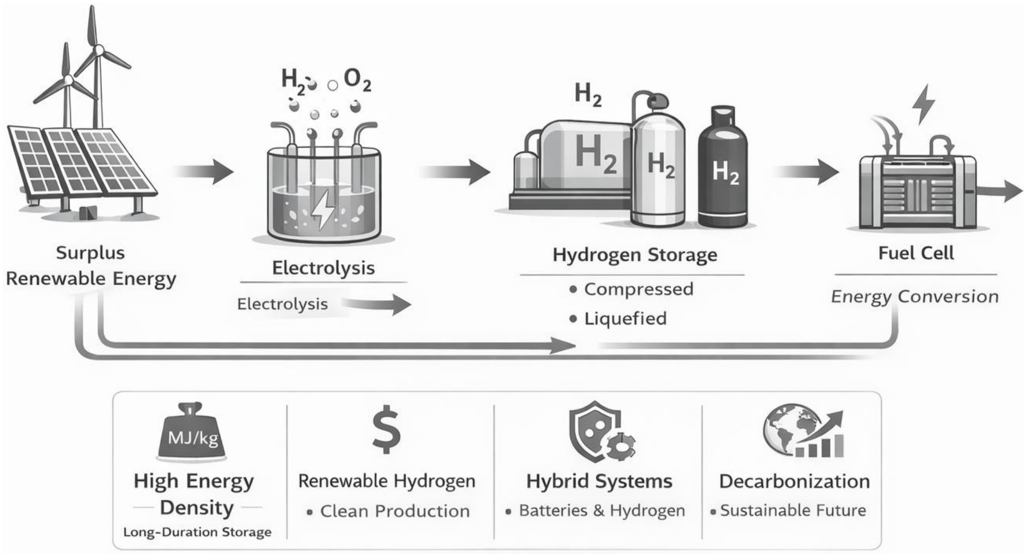


Figure 4. HES process diagram

### 6.2. Hydrogen production, storage methods, and conversion technologies

The transition toward renewable-based energy systems requires scalable and efficient pathways for hydrogen production, storage, and conversion to enable flexible operation under variable wind and solar generation [105]. Electrolysis techniques, utilizing surplus renewable electricity, represent a prominent method for hydrogen generation, while a variety of storage options ranging from compressed hydrogen tanks to advanced material-based systems enhance its viability as a long-duration energy storage solution [106]. However, recent advancements highlight the challenges and opportunities in hydrogen storage, particularly regarding safety and efficiency. Current trends showcase developments in metal hydrides and hybrid devices, offering promising avenues for future research [28]. Yet, the efficiency of hydrogen as an energy storage medium remains a concern, especially in comparisons to batteries in short-duration applications [23]. Consequently, hybrid system designs that combine hydrogen with complementary storage technologies can provide more robust solutions, using batteries for fast response and reserving hydrogen for extended-duration balancing, thereby supporting diverse energy demands while reducing dependence on fossil fuels [107].

### 6.3. Electrolysis technologies for hydrogen production using surplus renewable electricity

Electrolysis-based hydrogen production using surplus renewable electricity is increasingly viewed as a key option for managing intermittency because it converts excess generation into a storable energy carrier and expands system-level flexibility [104]. As renewable penetration grows, this power-to-hydrogen pathway can reduce curtailment and provide an additional balancing mechanism by shifting energy across longer time horizons than many short-duration storage technologies [108]. Electrolysis, which offer distinctive operational benefits, have seen significant advancements; however, challenges remain regarding efficiency and cost-effectiveness [103]. Despite these challenges, hydrogen produced via electrolysis continues to gain attention for large-scale and long-duration applications because it can be stored for extended periods and used across multiple sectors, supporting broader energy system coupling and resilience objectives [23]. Techno-economic evaluation is therefore essential to assess the feasibility of electrolysis pathways under different electricity price profiles, utilization factors, and technology configurations, with particular focus on cost, efficiency, lifetime, and operational flexibility [109]. In future renewable-dominated systems, the combination of electrolysis-driven hydrogen production with complementary storage technologies, including batteries, may enable more robust energy management strategies by matching fast-response services with long-duration balancing needs.

### 6.4. Hydrogen storage methods (compressed, liquefied, and material-based storage)

Hydrogen storage technologies are central to enabling hydrogen as a flexibility resource in renewable-integrated energy systems, particularly for long-duration and seasonal balancing applications [104]. Compressed hydrogen storage is widely used due to its technological maturity and compatibility with existing industrial practice, but it faces constraints related to volumetric energy density and safety requirements associated with high-pressure operation [103]. Conversely, liquefied hydrogen storage offers enhanced energy density but introduces complexities related to energy consumption during liquefaction and the management of boil-off losses. Material-based storage technologies, such as metal hydrides and chemical hydrides, promise safer and more compact storage solutions, yet they grapple with limitations in energy capacity and stability [110]. Technology choice therefore depends strongly on application requirements, infrastructure constraints, and system boundaries. While compressed hydrogen remains common in mobility and near-term deployment contexts, emerging work also highlights cryo-compressed concepts that aim to combine advantages of compressed and liquefied storage by improving density while managing pressure and temperature constraints [77]. Continued research is required to improve cost, safety, efficiency, and durability across these storage pathways to support a scalable hydrogen economy that complements other renewable energy technologies [103].

### 6.5. Conversion back to electricity through fuel cells or turbines

The integration of hydrogen-based ESS presents a transformative opportunity to enhance the resilience and efficiency of renewable power systems [104]. Following electrolysis, stored hydrogen can be converted back to power through fuel cells or hydrogen-capable turbines, providing dispatchable generation that supports adequacy during extended renewable shortfalls and improves system flexibility under variable operating conditions [103], [111]. Fuel cells are often preferred for smaller-scale or distributed applications due to relatively high conversion efficiency and low local emissions, whereas turbines are typically suited to higher power ratings and grid-scale operation, offering a pathway for large-capacity electricity supply during peak demand periods [22]. The ability to store hydrogen for extended periods with comparatively low standing losses strengthens its relevance for long-duration and seasonal balancing, although the overall power-to-hydrogen-to-power efficiency depends on the combined performance of electrolysis, storage, and conversion stages. Continued progress in fuel cell durability, turbine combustion characteristics, and system integration is therefore important for improving performance and cost effectiveness, reinforcing hydrogen’s potential role within future energy systems alongside complementary storage technology [9].

### 6.6. Role of hydrogen in long-duration and seasonal energy storage

The growing demand for reliable and sustainable energy systems requires storage solutions that can bridge multi-hour, multi-day, and seasonal gaps in renewable generation, especially under high wind and solar penetration [106]. Hydrogen has emerged as a promising candidate for long-duration and seasonal energy storage, primarily due to its high energy density and capacity for large-scale applications [102]. By utilizing surplus renewable electricity for hydrogen production through electrolysis, the resulting hydrogen can be stored and later converted back into electricity via fuel cells or turbines, thus addressing the intermittency associated with renewable sources [102]. While hydrogen storage technologies face challenges, including lower efficiency for frequent energy cycles, their potential in facilitating energy access and balance over extended periods cannot be overlooked [23]. Furthermore, advancements in thermal ESS, such as thermochemical processes, complement hydrogen storage by providing additional options for harnessing and preserving surplus energy [90]. Ultimately, the integration of hydrogen within a hybrid energy storage framework may enhance the overall efficacy and sustainability of renewable power systems, supporting the transition towards carbon neutrality [108]. Table 6 summarize key metrics related to hydrogen in energy systems. In the literature [112] it is stated that hydrogen has a high energy density of 120 MJ/kg $\approx$ 33.333 Wh/kg, while the production cost is relatively low at $3-5/kg [113]. Storage efficiency stands at 60%, with global demand recorded at 97 Mt. The projected market value for hydrogen is expected to exceed $20 billion, highlighting its growing importance in the energy sector.

Table 6. Key metrics related to hydrogen in energy systems

| Parameters | Values |
|---|---|
| Hydrogen energy density | 33.333 Wh/kg |
| Hydrogen production cost | 3.5/kg |
| Hydrogen storage efficiency | 70% |
| Global hydrogen demand | 97 Mt |
| Projected hydrogen market value | $20 billion |

### 6.7. Limitations of the review

Several limitations should be acknowledged when interpreting the findings of this review. First, the analysis relies exclusively on published secondary literature, and therefore inherits differences in experimental methodologies, system boundaries, and reporting practices among the original studies. Second, although representative values were harmonized using common evaluation metrics, direct quantitative comparison remains challenging because operating conditions, technology configurations, and performance definitions vary considerably across publications. Third, economic indicators such as LCOS are influenced by regional electricity prices, financing assumptions, and market conditions, which may limit the generalizability of reported cost estimates. Finally, despite efforts to include recent international studies, the available literature remains geographically uneven, with a larger proportion of published data originating from North America, Europe, and East Asia. These limitations should be considered when applying the comparative results to specific regional deployment scenarios.

## 7. CONCLUSION

This review examined AEST for renewable power systems and highlighted both their potential and the persistent barriers to large-scale, reliable integration. Across electrochemical, mechanical, thermal, and hydrogen-based pathways, storage options differ substantially in efficiency, response speed, discharge duration, scalability, cost structure, siting requirements, and maturity. These differences imply that no single technology can optimally satisfy all grid services under high renewable penetration. Instead, technology selection should be aligned with the targeted application, such as fast frequency response, daily energy shifting, or multi-day and seasonal balancing.

Summary of key findings across all storage technologies: electrochemical batteries, particularly lithium-ion, remain the leading option for short-to-medium duration services due to high efficiency and rapid controllability, although long-term scaling is affected by degradation, safety management, and material sustainability constraints. Mechanical storage, especially pumped hydro, provides proven bulk capacity and long asset life for large-scale balancing, but deployment is strongly site-dependent and influenced by environmental and permitting considerations. TES demonstrates strong relevance where heat-to-power coupling or thermal demand integration is feasible, with sensible and latent storage supporting dispatchability in applications such as CSP and district energy networks. Hydrogen-based storage is most compelling for long-duration and seasonal applications, but its competitiveness is limited by lower RTE and infrastructure complexity in frequent cycling roles. Overall, the evidence supports hybrid storage portfolios that combine complementary technologies to meet diverse grid requirements.

Comparative insights on performance, scalability, cost, and maturity: comparisons across technologies should be interpreted through consistent system boundaries and metrics. Batteries generally offer high efficiency and fast response, but cost, aging behavior, and resource considerations remain critical for long-term deployment at scale. Hydrogen enables large energy capacities and extended storage durations, yet its economic viability depends on utilization factors, electricity price profiles, and improvements in conversion efficiency and system integration. Mechanical and thermal technologies often provide long lifetimes and application-specific advantages, though they face constraints related to geography, operating temperature ranges, and integration interfaces. These trade-offs reinforce the need for standardized techno-economic evaluation when recommending storage solutions for renewable power systems.

Technical challenges, research gaps, and emerging trends: several cross-cutting challenges remain. First, improving long-duration storage efficiency and reducing lifecycle costs remain central priorities across hydrogen, thermal, and some mechanical pathways. Second, durability, safety, and circular-economy considerations are increasingly important for batteries and should be addressed through improved materials, diagnostics, recycling, and second-life strategies. Third, hybrid ESS are emerging as a practical direction for combining fast-response technologies with long-duration options, enabling more robust balancing and improved reliability under variable renewable generation. In parallel, smart grid integration, including advanced monitoring, predictive control, and optimization, is expected to improve storage dispatch, reduce curtailment, and strengthen system flexibility.

Policy, economic, and sustainability considerations for deployment: deployment at scale will also depend on supportive policy frameworks, market design, and sustainability safeguards. Investment signals that reward flexibility services, alongside standards for safety, recycling, and lifecycle emissions, will influence technology adoption. In particular, the expansion of low-carbon hydrogen requires coordinated support for electrolyze deployment, storage infrastructure, and end-use integration while ensuring environmental compliance. More broadly, aligning storage deployment with affordability, energy security, and sustainability objectives is essential for accelerating the transition toward low-carbon power systems.

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## AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
M : **M**ethodology
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D : **D**ata Curation
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E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

## ETHICAL APPROVAL

The research related to human use has been complied with all the relevant national regulations and institutional policies in accordance with the tenets of the Helsinki Declaration and has been approved by the authors' institutional review board or equivalent committee.

## DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study

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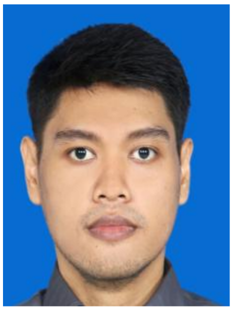

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