World Journal of Advanced Engineering Technology and Sciences
eISSN: 2582-8266
Cross Ref DOI: 10.30574/wjaets
Journal homepage: https://wjaets.com/

(REVIEW ARTICLE)

Sustaining the power grid: Breakthroughs and challenges in long-duration energy storage

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World Journal of Advanced Engineering Technology and Sciences, 2025, 15(02), 1113-1144

Publication history: Received on 04 March 2025; revised on 13 April 2025; accepted on 15 April 2025

Article DOI: https://doi.org/10.30574/wjaets.2025.15.2.0259

Abstract

The rapid shift towards renewable energy sources, particularly solar and wind power, is both a triumph and a challenge for modern energy grids. While these resources promise a cleaner future, their inherent intermittency threatens grid stability, leaving power systems vulnerable to fluctuations and supply shortfalls. Long-Duration Energy Storage (LDES) emerges as the game-changer—an indispensable solution that captures surplus energy when the sun shines and the wind blows, then delivers it precisely when demand peaks or generation falters. This review delves into the cutting-edge advancements, persistent challenges, and future prospects of LDES technologies in fortifying grid resilience. It explores a spectrum of storage solutions—chemical, mechanical, thermal, and electrochemical—analyzing their potential to replace fossil-fuel-based peaking plants, enable deep renewable integration, and revolutionize energy security. Despite its transformative promise, LDES adoption remains constrained by high capital costs, efficiency trade-offs, and policy uncertainties. Infrastructure bottlenecks, market hesitancies, and environmental considerations further complicate large-scale deployment. This paper critically evaluates these barriers while spotlighting groundbreaking innovations, including next-generation nanomaterials, AI-driven optimization, hybrid storage frameworks, and pioneering hydrogen and ammonia-based energy solutions. Global pilot projects are already proving LDES's viability, showcasing real-world applications that reinforce a cleaner, more resilient, and decentralized energy system. To accelerate progress, bold policy frameworks, strategic financial incentives, and relentless research into cost-effective storage pathways are paramount. As technology matures and regulations evolve, LDES is poised to become the backbone of a future-proof, low-carbon, and highly adaptive power grid.

Keywords: Long-Duration Energy Storage (LDES); Renewable Energy Integration; Redox Flow Batteries (RFBS); Energy Storage Technologies; Electrochemical Storage; Hydrogen and Ammonia Storage; Mechanical Energy Storage; Thermal Energy Storage; Artificial Intelligence in Energy Storage

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1. Introduction

1.1. Background on Grid Resilience

The need to cut greenhouse gas emissions and fight climate change is causing a radical transformation in the world's energy landscape towards renewable energy sources, namely solar and wind power. This transition, while environmentally beneficial, presents serious obstacles to the stability and resilience of electrical grids due to the inherent intermittency of these energy sources. Grid resilience refers to the ability of the power system to anticipate, absorb, adapt to, and rapidly recover from disruptive events, including those arising from fluctuations in energy supply. As renewable energy penetration increases, maintaining grid stability becomes a critical concern to prevent outages and ensure consistent energy delivery [1,2]. There are several obstacles to overcome when integrating renewable energy sources (RES) into the grid's current infrastructure. One primary issue is network inadequacy, where the physical capacity to accommodate supply and demand in locations with optimal renewable resources is lacking. This inadequacy can lead to voltage instabilities, frequency inconsistencies, and harmonic distortions within the power system. Additionally, the variability of RES necessitates the development of real-time network management strategies at low voltage levels to maintain high reliability standards. According to a report by McKinsey & Company, utilities face significant challenges in integrating RES due to these network inadequacies and the need for advanced management systems [3,4].

Furthermore, the current grid infrastructure sometimes lacks the adaptability needed to handle renewable energy generation's unpredictable nature. Limited transmission capacity, particularly in remote or offshore locations rich in renewable resources, hampers the efficient integration of RES into the grid. The Pacific Northwest National Laboratory highlights that current infrastructure and technology limitations, such as insufficient high-voltage direct current powerlines, pose significant challenges to renewable integration [5]. In order to maximise the potential of renewable energy sources and improve system resilience, these issues must be resolved.

1.2. Definition of Long-Duration Energy Storage (LDES)

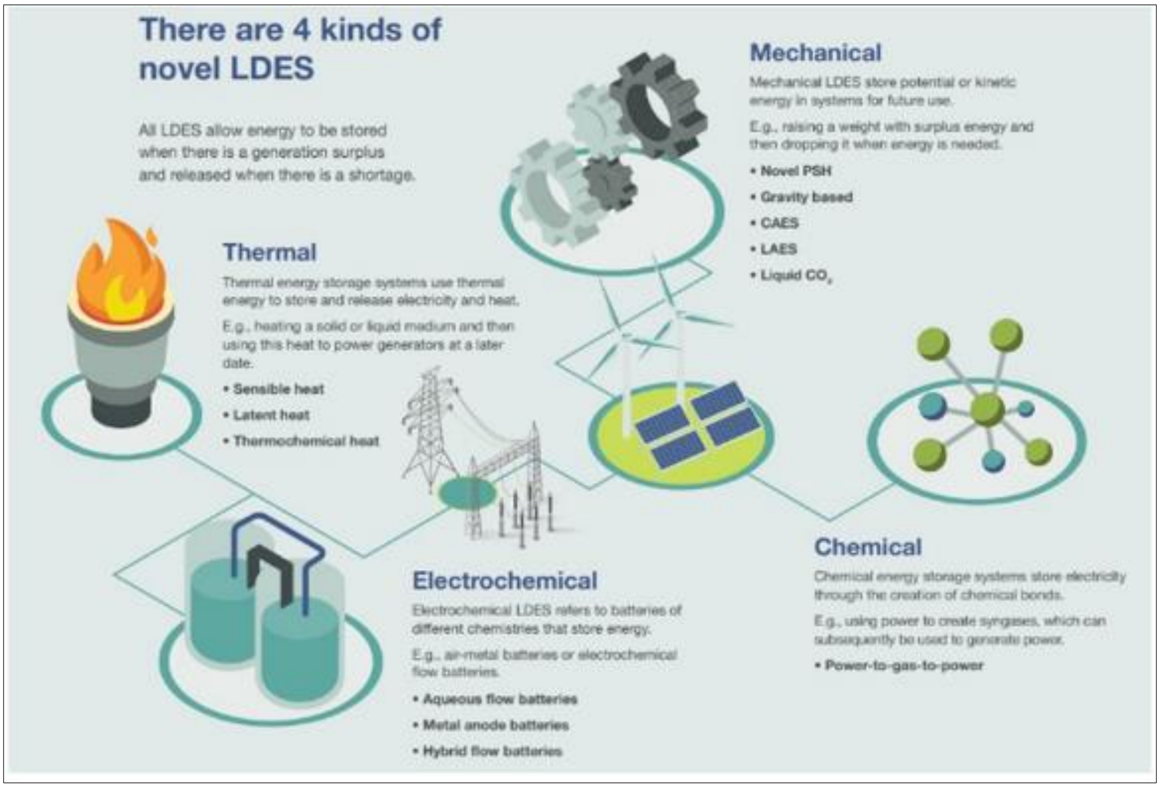

Figure 1 Illustration of Long-Duration Energy Storage (LDES) Technologies. Reproduced from Ref. [4]

Long-Duration Energy Storage (LDES) encompasses a suite of technologies designed to store energy for extended periods, typically discharging for ten hours or more. By storing extra energy produced during times of low demand and releasing it at peak usage or when renewable generation is low, these technologies play a crucial role in balancing the intermittent nature of renewable energy. LDES encompasses a number of technologies, including chemical storage (e.g., hydrogen production), mechanical storage (e.g., pumped hydro storage), thermal storage (e.g., molten salt systems), and electrochemical batteries (e.g., redox flow batteries) as illustrated in Figure 1. Each technology offers unique advantages and operational characteristics suitable for different applications within the energy system [6,7].

According to the Long Duration Energy Storage Council, LDES technologies are developing quickly as ways to allow highly variable renewable energy sources, including wind and solar, to be deeply integrated into the grid. For longer storage times—from a few hours to days, weeks, or even months—these technologies are being researched as affordable substitutes for grid-scale electrochemical batteries [8]. The diverse range of LDES technologies provides flexibility in addressing various energy storage needs, consequently, the electrical grid's resilience and dependability are improved.

1.3. Relevance of LDES

LDES technologies are integral to advancing global decarbonization efforts by making it easier for the electrical grid to incorporate large amounts of renewable energy. By providing reliable and sustained energy storage, By reducing the unpredictability of renewable energy sources, LDES lessens dependency on fossil fuels and cuts greenhouse gas emissions. The Long Duration Energy Storage Council reports that pairing LDES technologies with renewables could cut greenhouse gas emissions from industry worldwide by 65% [9]. This substantial reduction underscores the vital part LDES plays in reaching climate targets and making the shift to a low-carbon future.

In addition to environmental benefits, LDES enhances energy security by ensuring a stable energy supply, even when there are unforeseen spikes in demand or times when renewable generation is low. Because it allows energy systems to endure and recover from climate-induced disturbances, such extreme weather events, this capability is crucial for climate adaptation and enhances the overall resilience of the energy infrastructure. The Pacific Northwest National Laboratory asserts that LDES is not a luxury but a necessity for operating a fully decarbonized power grid, emphasizing its importance in maintaining grid reliability amid increasing renewable integration [10].

1.4. Objectives of the Review

This review seeks to offer a thorough examination of the developments, difficulties, and potential for the future of LDES in enhancing grid resilience. The scope encompasses a detailed examination of various LDES technologies, their operational principles, and their integration into the power grid. This review is important because it has the potential to educate researchers, industry stakeholders, and policymakers on the vital role LDES plays in creating a resilient and sustainable energy future. The methodology involves a thorough literature review of recent studies, technological assessments, and policy analyses to synthesize current knowledge and identify gaps for future research. By consolidating findings from diverse sources, this review seeks to offer valuable insights into the deployment and optimization of LDES solutions in modern energy systems.

2. Overview of Long-Duration Energy Storage Technologies

The need for energy storage systems that can sustain grid stability over long periods of time has arisen due to the growing dependence on renewable energy sources. The capacity of long-duration energy storage (LDES) technologies to store excess energy and release it when generation is insufficient makes them stand out among the rest. These systems enable the seamless integration of renewables, mitigating intermittency challenges while reducing dependence on conventional power sources. Researchers have explored diverse LDES technologies, each offering distinct operational mechanisms, energy densities, and scalability [11-13]. This section explores four primary categories of these LDES as summarized in Table 1. Electrochemical, mechanical, thermal, and chemical storage solutions are at the forefront of this transition, with ongoing innovations seeking to enhance efficiency, cost-effectiveness, and deployment feasibility. This analysis attempts to provide a thorough knowledge of these technologies' potential to improve global energy resilience by closely examining their principles of operation, current developments, and implementation obstacles.

Table 1 Comparative Analysis of Long-Duration Energy Storage Technologies

Technology	Energy Density (Wh/kg)	Round-Trip Efficiency (%)	Cycle Life (cycles)	Scalability	Cost (per kWh)
Electrochemical					
- Lithium-Ion Batteries	150–200	85–95	2,000–8,000	Modular; suitable for various applications	$200–400
- Flow Batteries (e.g., Vanadium)	10–35	65–70	12,000–14,000	Flexible energy capacity; scalable	$500–700
- Sodium-Sulfur Batteries	150–240	77–90	4,500–5,500	Suitable for large-scale stationary applications	$300–500
Mechanical					
- Pumped Storage Hydropower (PSH)	0.5–1.5	70–85	15,000–30,000	Requires specific geographic locations	$150–250
- Compressed Air Energy Storage (CAES)	2–6	40–70	10,000–30,000	Geographically constrained; large-scale	$50–150
- Flywheels	5–130	85–95	>100,000	High power density; suitable for short durations	$1,000–5,000
Thermal					
- Molten Salt Storage	N/A	70–90	10,000–15,000	Typically integrated with CSP plants	$30–80
- Liquid Air Energy Storage (LAES)	N/A	60–70	10,000–15,000	Flexible siting; large-scale potential	$200–300
Chemical					
- Hydrogen Storage	33,000 (gravimetric)	30–50	N/A	Large-scale; long-duration storage	$5–15

Note: Energy density for technologies like pumped hydro and CAES is not typically expressed in Wh/kg due to their large-scale nature.

2.1. Electrochemical Long-Duration Energy Storage (LDES)

Since electrochemical energy storage can effectively store and release energy through regulated redox processes, it is essential for long-term applications. These storage systems are particularly beneficial for adding renewable energy sources to the grid, as they offer scalability and flexible discharge durations. Unlike conventional lithium-ion batteries, which are optimized for short to medium discharge durations, electrochemical LDES technologies are designed to sustain energy output for prolonged periods ranging from a few hours to several days [12]. Various chemistries, including redox flow batteries (RFBs), sodium-based batteries, and metal-air batteries, have been extensively investigated for their potential to provide cost-effective, high-efficiency, and durable energy storage solutions [14,15]. This section focuses on redox flow batteries, detailing their working principles, efficiency, and lifespan in the context of LDES applications.

2.1.1. Redox Flow Batteries (RFBs) – Working Principles, Efficiency, Lifespan

Redox flow batteries (RFBs) are a separate type of electrochemical storage systems capable of delivering long-duration energy storage by utilizing liquid electrolytes housed in external tanks. Unlike conventional solid-state batteries, where energy storage occurs within electrode materials, RFBs store energy in two separate liquid electrolyte reservoirs, which undergo redox reactions during charge and discharge cycles [16]. The electrolytes are pumped through electrochemical cells containing inert electrodes, where the anode and cathode, respectively, experience oxidation and reduction processes. This separation of power and energy components allows independent scaling of the system, making RFBs particularly advantageous for grid-level applications (Wang et al., 2023). Fig. 1 describes a generic RFB system. An anolyte solution passes through a porous electrode in the discharge mode, where it interacts to produce electrons that go via the external circuit. The anolyte and catholyte solutions are then separated by transporting the charge-carrying species to a separator, usually an ion-exchange membrane (IEM) [17]. Two semi-reactions can be distinguished from the general reaction:

$$A^{(n-x)+} \leftrightarrow A^{n+} + x^{e-}$$

with (n>x), and

$$B^{(m+y)+} + ye^{-} \leftrightarrow B^{m+}$$

for the anolyte (negative compartment) and catholyte (positive compartment), respectively. During the discharge phase, the reaction direction is from left to right, and during the charge phase, the opposite is true [17].

Electrolyte is kept in external tanks in redox flow batteries. Through the use of pumps or other devices, the electrolyte flows throughout the stack, converting energy electrochemically. The most intriguing aspect of this type of battery is that the amount of electrolyte controls the amount of energy that can be stored; given a fixed value of active species concentration, the modularity of energy stored only depends on the volume of electrolyte [17].

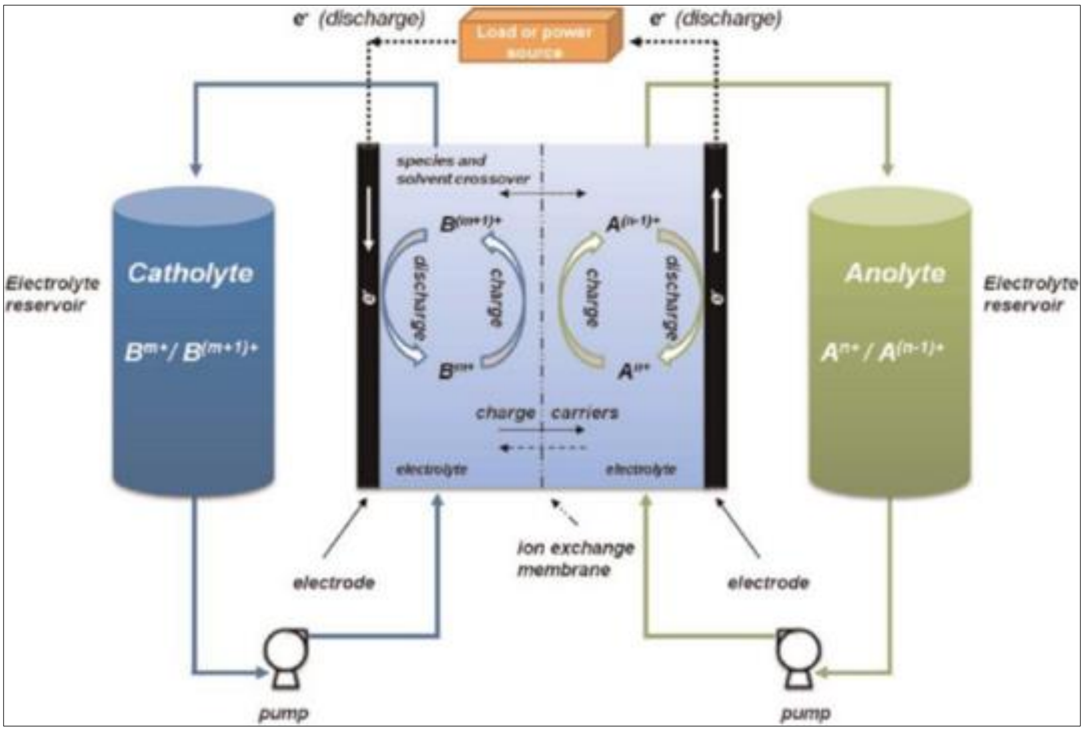

Figure 2 A schematic diagram of a redox-flow battery with electron transport in the circuit, ion transport in the electrolyte and across the membrane, active species crossover, and mass transport in the electrolyte

The vanadium redox flow battery (VRFB), which uses vanadium-based electrolytes in various oxidation states, is one of the most researched RFB technologies. According to Yuan et al. [18], VRFBs exhibit round-trip efficiencies of 70–85%, with minimal degradation over extended cycling, making them highly reliable for long-term energy storage. Additionally, they can achieve lifespans exceeding 20 years due to their ability to maintain electrolyte stability without significant capacity fade [19]. However, the high cost of vanadium and its sensitivity to temperature fluctuations have prompted researchers to explore alternative chemistries, such as iron-chromium, zinc-bromine, and organic-based flow batteries [20].

Recent developments in membrane technology and electrolyte formulation have been essential in enhancing RFB performance. Innovations in ion-selective membranes have led to reduced crossover of active species, thereby increasing energy efficiency and cycle life. Research by Tan et al. [21] demonstrated that next-generation hybrid membranes incorporating nanoporous structures can enhance selectivity while maintaining high ionic conductivity, leading to efficiency improvements of up to 10% compared to conventional membranes. Additionally, the development of low-cost, high-conductivity organic electrolytes has expanded the potential for non-vanadium-based flow batteries, addressing cost concerns associated with vanadium supply constraints [22].

Despite these advancements, several challenges continue to hinder the large-scale deployment of RFBs. The high initial capital cost is one of the main issues, driven by expensive electrolyte materials and the need for large-scale balance-of-system components. Efforts to reduce costs through alternative chemistries and manufacturing innovations are actively being pursued [23,24]. It is worthwhile to note that one critical aspect of evaluating long-duration energy storage (LDES) technologies is their cost-effectiveness, which directly impacts scalability and adoption. Each technology differs in capital investment, operational expenses, and cost per kilowatt-hour of storage, influencing its economic viability [24]. Table 2 provides a comparative breakdown of these financial aspects for RFBs as well as other leading storage technologies, offering insights into the affordability and long-term feasibility of various LDES solutions.

Beyond these, the scalability and modular nature of RFBs make them ideal for grid-level applications, particularly in scenarios requiring multi-hour to multi-day energy storage [25]. Emerging research focuses on integrating flow battery systems with artificial intelligence (AI)-based energy management algorithms to optimize charge-discharge cycles, minimize losses, and extend operational lifespans. Cavus et al. [26] highlighted that AI-driven predictive maintenance techniques could reduce operational costs by 15–20% while improving battery longevity.

Table 2 Cost Breakdown of Leading LDES Technologies

LDES Technology	Capital Cost	Operational Cost	Cost per kWh of Storage
Pumped Storage Hydropower (PSH)	- High initial investment due to large-scale infrastructure requirements, typically ranging from $1,000 to $5,000 per kilowatt (kW).	- Low operational costs owing to the mature nature of the technology and minimal maintenance needs.	- Competitive cost per kWh over the system's long lifespan, making it economically viable for large-scale storage.
Compressed Air Energy Storage (CAES)	- Moderate capital costs, approximately $1,100 to $1,500 per kW, influenced by geological site suitability and infrastructure.	- Moderate operational costs, with expenses related to compression and expansion equipment maintenance.	- Cost per kWh is favorable for bulk energy storage applications, especially when utilizing existing geological formations.
Flow Batteries (e.g., Vanadium Redox)	- Capital costs range from $300 to $1,500 per kWh, depending on system size and electrolyte materials.	- Moderate operational costs, including electrolyte management and system monitoring.	- Cost per kWh is higher compared to other technologies but offers scalability and long cycle life benefits.
Liquid Air Energy Storage (LAES)	- Capital costs are relatively high, with estimates around $1,000 per kW, due to cryogenic equipment and infrastructure.	- Operational costs are moderate, involving energy consumption for liquefaction and maintenance of cryogenic systems.	- Cost per kWh is currently higher but expected to decrease with technological advancements and economies of scale.
Hydrogen Storage	- Capital costs vary widely, from $500 to $1,500 per kW, influenced by production methods (e.g., electrolysis) and storage solutions.	- Operational costs depend on hydrogen production efficiency and storage conditions, with ongoing research aimed at cost reduction.	- Cost per kWh is currently high but has potential for reduction as hydrogen technologies mature and scale up.

Note: the costs mentioned are approximate and can vary based on factors such as location, scale, market conditions, and technological advancements. Continuous research and development are expected to influence these costs over time.

Additionally, electrolyte degradation over extended cycling remains a critical issue, particularly for non-vanadium systems. Studies by Zhou et al. [27] have explored novel electrolyte stabilization techniques, including the use of redox mediators and advanced pH control strategies, which have shown promise in enhancing long-term system stability.

Given the ongoing advancements and research efforts, RFBs continue to be a leading candidate for long-duration energy storage, offering a sustainable and flexible alternative to conventional storage technologies. However, further research is required to address cost challenges, enhance efficiency, and improve electrolyte stability to enable widespread commercial adoption.

2.1.2. Metal-Air Batteries

Because of their high theoretical energy densities and use of ambient oxygen as a reactant, metal-air batteries have become a viable class of energy storage devices with the potential for ultra-long discharge periods [28]. An electrolyte, a metal anode, and an air-breathing cathode that aids in oxygen reduction during discharge make up these batteries. They are appealing for applications needing prolonged energy supply (such as grid-scale storage and electric vehicles) because of their intrinsic design, which permits a lightweight and compact structure [28,29].

2.1.3. Working Principles and Energy Density

The fundamental operation of metal-air batteries involves the oxidation of a metal anode (e.g., zinc, aluminum, lithium) and the reduction of oxygen at the cathode. During discharge, at the anode, metal atoms liberate electrons to create metal ions, which migrate through the electrolyte. Concurrently, oxygen from the ambient air diffuses into the porous cathode, where it undergoes reduction by accepting electrons from the external circuit, forming metal-oxide or metal-hydroxide compounds. This process continues until the anode material is depleted or passivated [30,31].

The theoretical energy densities of metal-air batteries are significantly greater than those of traditional lithium-ion batteries. For example, the energy density of aluminum-air batteries is about 8.1 kWh/kg, attributed to the trivalent oxidation state of aluminum and its lightweight nature [32,33]. Similarly, lithium-air batteries exhibit theoretical energy densities up to 11.14 kWh/kg, positioning them as potential candidates for applications necessitating prolonged energy supply [34].

2.1.4. Zinc-Air Batteries

Zinc-air batteries are among the most extensively studied metal-air systems, primarily due to the abundance, low cost, and environmental benignity of zinc. These batteries have been utilized in primary (non-rechargeable) forms for hearing aids and other small devices. Recent research efforts have focused on developing rechargeable zinc-air batteries to enable their application in large-scale energy storage [35,36].

The challenges hindering the commercialization of rechargeable zinc-air batteries include the slow rates of the air cathode's oxygen evolution reaction (OER) and oxygen reduction reaction (ORR), leading to significant overpotentials and reduced round-trip efficiency. To address these issues, researchers have explored various bifunctional catalysts capable of enhancing both ORR and OER activities. For example, studies have demonstrated that doping carbon nanotube fibers with nitrogen can create self-standing air cathodes exhibiting high bifunctional catalytic activity, resulting in improved battery performance [37-39].

2.1.5. Aluminum-Air Batteries

Aluminum-air batteries have garnered attention due to aluminum's high theoretical capacity and natural abundance. These batteries can potentially deliver energy densities significantly higher than traditional battery technologies, making them suitable for applications requiring extended operational periods without recharging.

However, aluminum-air batteries face challenges such as anode corrosion and the formation of passivation layers, which impede continuous operation. Research efforts have been directed toward developing corrosion-resistant aluminum alloys and electrolytes that mitigate passivation. According to a new study, aluminum-air batteries have several benefits, including a high energy and power density that can be used in electric vehicles [40-42].

2.1.6. Iron-Air Batteries

Iron-air batteries are emerging as an economical and ecologically sustainable alternative for long-duration energy storage. Iron is abundant, inexpensive, and exhibits favorable electrochemical properties [43]. Companies like Form Energy are developing iron-air battery systems capable of delivering 100-hour discharge durations, aiming to provide a reliable and scalable solution for grid stability [44]. The primary challenge in iron-air batteries lies in enhancing the reversibility of the iron oxidation process and improving the kinetics of the air cathode reactions. Ongoing research focuses on optimizing electrode materials and electrolyte formulations to achieve efficient and durable cycling performance [45].

Despite their potential, metal-air batteries face several obstacles that need to be overcome in order to implement them in ultra-long discharge scenarios. This first notable challenge is electrode stability. Concerns about safety and capacity fade may arise from the development of dendrites and passivation layers on metal anodes. Research is still being done to create stable electrode materials and protective coatings to mitigate these issues. Quick on the heels of this challenge is air cathode catalysis. The efficiency of metal-air batteries is significantly influenced by the performance of the air cathode. Developing cost-effective, durable, and highly active bifunctional catalysts for ORR and OER remains a critical research focus. Finally, there is the challenge of electrolyte optimization. The selection of appropriate electrolytes that provide ionic conductivity while minimizing side reactions is crucial. Aqueous electrolytes are common but pose challenges related to water management and carbonation. Non-aqueous electrolytes offer alternatives but require further investigation to ensure compatibility and safety [46,47].

2.2. Mechanical Long-Duration Energy Storage (LDES)

Mechanical LDES systems harness mechanical processes to store energy, offering solutions capable of discharging over extended periods. With the growing integration of intermittent renewable energy sources, these technologies are essential for stabilising power networks [48]. Mechanical LDES systems offer a dependable and effective way to balance supply and demand by transforming electrical energy into mechanical energy and vice versa.

2.2.1. Pumped Hydro Storage (PHS)

Hydroelectric energy storage type known as pumped hydro storage (PHS) stores and produces electricity by harnessing the gravitational potential energy. Two water reservoirs at varying heights are involved. During periods of low electricity demand or excess energy production, water is pumped from the lower reservoir to the upper reservoir using surplus electrical energy. Turbines are used to release the stored water back to the lower reservoir during periods of high electrical demand, producing electricity. PHS can act like a massive battery thanks to its cyclical nature, which stores energy when supply outpaces demand and releases it when needed [49-51].

2.2.2. Global Adoption

With PHS making up more than 90% of the global energy storage capacity, it is the most extensively used type of large-scale energy storage [52]. PHS facilities have been widely installed in nations including China, the US, and Japan in order to stabilize their electrical grids and facilitate the integration of renewable energy sources [53]. In the United Kingdom, projects like the proposed 2-gigawatt Glen Earrach scheme aim to enhance energy storage capabilities, contributing to the nation's net-zero targets by providing substantial energy storage capacity [54].

2.2.3. Efficiency

The high round-trip efficiency of PHS systems, which usually ranges from 70% to 85%, is well-known. The reversible operation of pumping water to a raised reservoir during times of extra energy and releasing it to create power during peak demand is what makes this efficiency possible [49]. PHS is a desirable choice for large-scale energy storage because of the cycle's comparatively low energy loss [55].

2.2.4. Geographical Constraints

The deployment of PHS is significantly influenced by geographical factors. Suitable sites require specific topographical features, such as substantial elevation differences and the availability of water resources. In regions lacking natural elevations, constructing artificial reservoirs may result in higher capital expenses and difficulties with land use [56]. Additionally, environmental and social impacts, including potential ecological disturbances and effects on local communities, necessitate careful consideration during the planning and implementation of PHS projects. For instance, proposed hydro storage schemes around Loch Ness in Scotland have raised concerns about potential ecological disturbances, such as significant water level fluctuations affecting aquatic life [57].

2.2.5. Environmental and Social Considerations

The development of PHS projects often encounters environmental and social challenges. In Scotland, proposals for new PHS schemes around Loch Ness have raised concerns among local communities and environmental groups. Potential ecological disturbances, such as significant water level fluctuations affecting aquatic life, have been highlighted. For example, the recent operation of the Foyer station led to a 14 cm drop in Loch Ness's water level, prompting discussions about the environmental impact of such projects [57].

2.2.6. Future Prospects

Advancements in PHS technology aim to mitigate some of the existing limitations. Among the innovations are the creation of closed-loop systems that minimize environmental impact by reducing reliance on natural water bodies. Additionally, PHS integration with renewable energy sources, such solar and wind, can improve power systems' overall sustainability and efficiency. Financial mechanisms, including government subsidies and innovative funding models, are being explored to attract private investment and support the expansion of PHS infrastructure. For instance, the UK government plans to support pumped hydro storage projects using a "cap and floor" mechanism, guaranteeing revenues if prices fall but limiting charges during high prices [57].

2.3. Compressed Air Energy Storage (CAES)

In times when there is little demand for electricity, compressed air energy storage (CAES) devices compress air and store it in subterranean caves or reservoirs (see figure 3) [58]. When the need for electricity increases, the high-pressure air that has been stored is brought down to the surface, heated, and expanded using turbines to produce energy [58]. This process enables supply and demand to be balanced, enhancing grid reliability and making it easier to incorporate alternative energy sources.

2.3.1. Recent Advancements in CAES

Significant progress has been made in CAES technology in recent years leading to improved efficiency and expanded deployment. A notable development is the commissioning of a large-scale CAES project in Hubei, China, with a 300 MW capacity and 1,500 MWh of energy storage capacity [59]. This facility utilizes abandoned salt mines for air storage and was completed within two years, demonstrating the feasibility of rapid deployment [59].

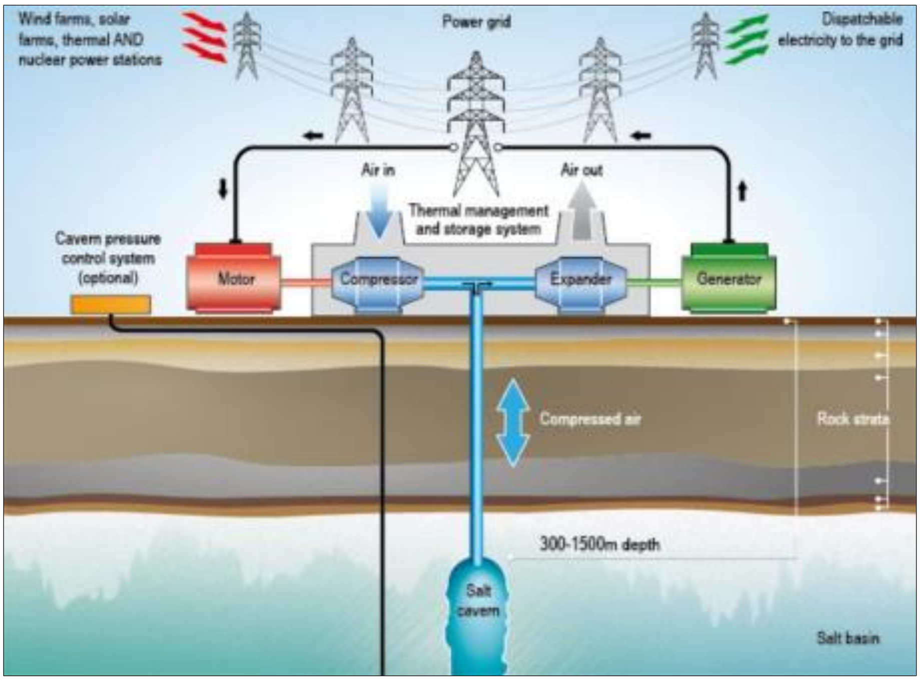

Figure 3 Compressed Air Energy Storage System. Reproduced from Ref. [60] with permission

2.3.2. Hybrid CAES Systems

The creation of hybrid systems is the result of the combination of CAES with other energy technologies, aiming to enhance overall efficiency and sustainability. One such innovation One such invention is the hybrid adiabatic compressed air energy storage system (HA-CAES), which combines advanced adiabatic CAES (AA-CAES) with solar thermal collectors (STC) [61]. This configuration leverages solar thermal energy to heat the compressed air, reducing greenhouse gas emissions and dependence on fossil fuels [61]. Additionally, the concept of underwater CAES has been explored, where compressed air is stored in flexible containers anchored to the seabed [62]. This approach benefits from the natural hydrostatic pressure of deep water, potentially reducing infrastructure costs and environmental impact.

2.4. Liquid Air Energy Storage (LAES)

One promising method for large-scale energy storage is liquid air energy storage (LAES), utilizing the thermodynamic properties of air to store and release energy. This technology turns ambient air into a liquid condition for storage by cooling it to cryogenic temperatures. When energy demand rises, the liquid air is reheated, expanded, and converted back into electricity through a series of thermodynamic processes [63,64]. LAES offers several advantages, including high energy density, geographical flexibility, and the use of readily available materials, positioning it as a workable way to incorporate renewable energy sources into the electrical system [64].

2.4.1. Working Principle

The LAES process comprises three main stages: liquefaction, storage, and power recovery as illustrated in Figure 4. During the liquefaction phase, ambient air is compressed and cooled to approximately -196°C (-320°F), causing it to liquefy. After that, this liquid air is kept in low-pressure, insulated tanks, where it can remain for extended periods with minimal energy loss [65]. When electricity is needed, the liquid air is rapidly expanded into a gaseous condition after being pumped under high pressure and exposed to waste heat or the environment. This expansion drives turbines connected to generators, producing electricity. The efficiency of LAES systems can be enhanced by integrating thermal energy storage to capture and recycle the heat and cold produced by the expansion and liquefaction processes, respectively [66,67].

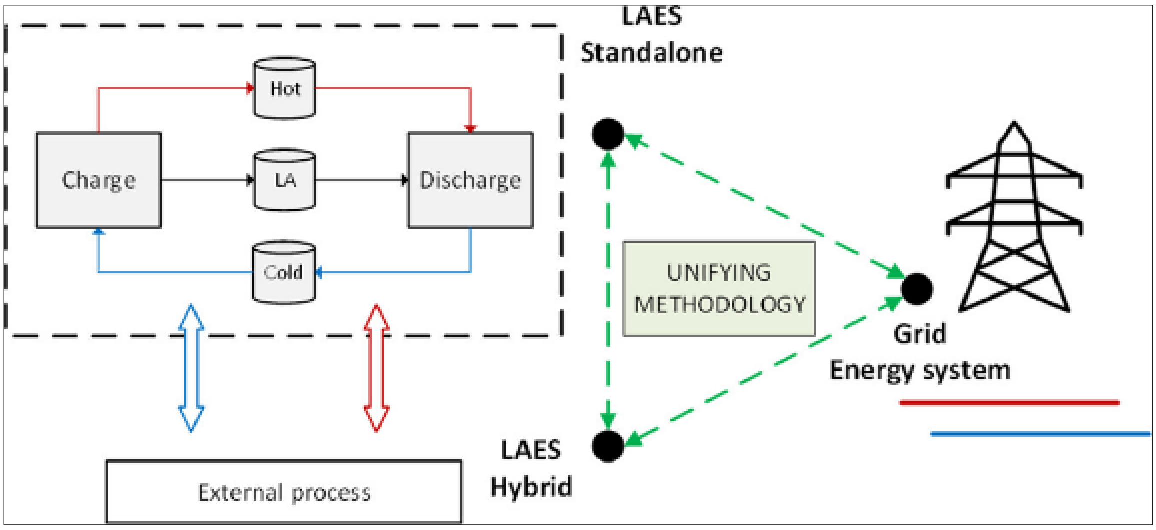

Figure 4 Schematic Representation of Liquid Air Energy Storage (LAES) in Standalone and Hybrid Configurations for Grid Integration. Reproduced with permission from Ref. [67]

2.4.2. Efficiency and Performance

LAES systems usually have a round-trip efficiency of 50% to 70%, depending on system design and integration with external heat sources. The efficiency is influenced by elements such the quality of heat integration, the efficiency of thermal energy storage, and the liquefaction and expansion processes' operating parameters [68,69]. Recent studies have focused on optimizing system configurations and enhancing thermal energy storage to improve overall efficiency. For instance, integrating waste heat from industrial processes or power plants can significantly boost the efficiency of LAES systems by providing additional energy during the expansion phase [70].

2.4.3. Applications and Advantages

LAES systems are especially appropriate for situations involving extensive energy storage, offering several key advantages. One notable benefit is the geographical flexibility. Unlike pumped hydro storage, which requires specific topographical features, LAES plants can be sited in various locations, including urban areas, due to their relatively small footprint and minimal environmental impact [71]. Similarly, the scalable nature of LAES systems comes with great benefits. LAES systems can be scaled to match different energy storage requirements, from small-scale installations to grid-scale facilities, providing flexibility in addressing various energy demands [71]. Additionally, resource availability gives the LAES system a great standing as an impressive LDES technology. The primary working fluid, air, is abundant and free, eliminating the need for scarce or hazardous materials and reducing environmental concerns associated with resource extraction and disposal. Finally, LAES systems utilize established components from the industrial gas and power generation sectors, contributing to robust performance and extended operational lifespans [71].

2.5. Thermal LDES

Thermal Long-Duration Energy Storage (LDES) contributes significantly to contemporary energy systems by facilitating the storage and controlled release of thermal energy over extended durations. This category of storage technology is particularly advantageous in balancing fluctuations in energy supply, particularly when combined with renewable energy sources like wind and solar. Thermal energy storage systems generally operate by capturing heat and preserving it in several ways, including thermochemical storage, perceptible heat, and latent heat [72-74]. Raising the temperature of a storage medium—like concrete or molten salts—without causing a phase shift is known as sensible heat storage. Phase-change materials, which absorb or release heat during the transition between solid and liquid states, are essential to latent heat storage. Conversely, thermochemical storage relies on reversible chemical reactions that enable energy to be stored as chemical bonds and released as required. These technologies collectively enhance the efficiency and flexibility of energy utilization, supporting grid stability and energy security [52,74].

Thermal energy grid storage (TEGS), inspired by multijunction photovoltaics (MPV), represents an emerging technology that leverages MPVs to generate heat for TEG systems. In this approach, the thermal energy grid (TEG) system is charged using surplus electricity, which is directed through a refractory heating element with high electrical resistance, such as tungsten or graphite. This heating element produces heat that is subsequently transferred through pumped liquid tin. Tin is particularly advantageous due to its high thermal diffusivity and its ability to remain in a liquid state over a broad temperature range (232–2600 °C). The generated heat is then stored within the grid storage system, which consists of insulated graphite blocks—a cost-effective material for retaining thermal energy. When needed, the stored heat is converted back into electricity using thermophotovoltaic (TPV) cells [75,76]. Figure 5 provides an illustration of the TEGS concept.

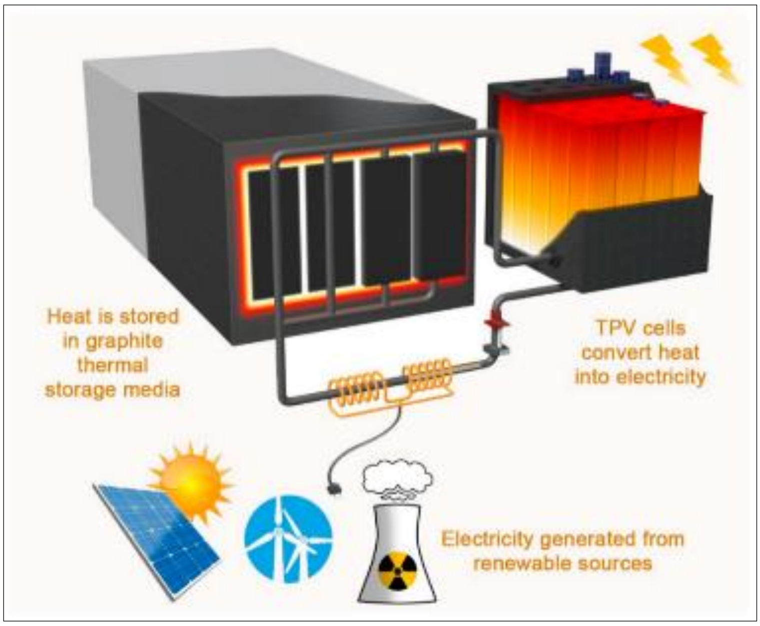

Figure 5 Thermal Energy Grid Storage (TEGS) Working Principle. Reproduced with permission from Ref. [74]

2.5.1. Molten Salt Storage

One of the most widely implemented thermal LDES technologies is molten salt storage, which has becoming more popular in large-scale applications, especially in facilities that use concentrated solar power (CSP) [77]. This technology functions by using a eutectic mixture of salts, commonly composed of sodium nitrate and potassium nitrate, which can be heated to high temperatures and retain thermal energy for extended periods. In a typical molten salt storage system, solar radiation is concentrated onto a receiver that transfers heat to the molten salt, raising its temperature to around 565°C [78]. The heated salt is then stored in an insulated high-temperature reservoir, where it retains energy with minimal thermal losses. When electricity generation is required, a heat exchanger converts the molten salt's stored thermal energy into water, creating steam that powers a turbine to produce electricity. After this process, the cooled salt is stored in a separate low-temperature reservoir, ready for reheating and reuse [78].

Molten salt storage offers several advantages that make it an effective way to store energy on a vast scale. One of its key benefits is its capacity to hold energy for long periods of time, often exceeding 10 hours, making it well-suited for overnight energy supply in solar power plants. Additionally, the technology boasts high thermal efficiency, with energy retention rates exceeding 99% over extended storage periods. The relatively low cost and widespread availability of the salts used in this system further enhance its economic viability, making it a desirable choice for energy storage that is sustainable [77,78]. However, certain challenges must be addressed to optimize its performance and reliability. One significant issue is the high operating temperature required to maintain the molten state of the salts, necessitating the use of specialized containment materials that can withstand thermal stress. Another critical concern is the risk of freezing, as molten salts solidify at temperatures around 131°C, potentially causing operational disruptions if not properly managed. Additionally, prolonged exposure to high-temperature molten salts can lead to corrosion in storage tanks and piping, necessitating the development of advanced corrosion-resistant materials to improve system longevity [78].

The application of molten salt storage has been demonstrated in several large-scale projects worldwide, highlighting its potential in renewable energy integration. One such example in Spain is the Gemasolar power plant, featuring a molten salt storage system that has enabled continuous electricity generation, including a record-breaking 36 consecutive days of uninterrupted operation [79]. Similarly, the Cerro Dominador solar thermal plant in Chile, commissioned in 2021, incorporates a molten salt storage system with a capacity of 17.5 hours, allowing it to provide stable power output even in the absence of sunlight [80]. The goal of ongoing research is to further improve the longevity and effectiveness of molten salt storage by developing new salt formulations with lower melting points and improved thermal properties. Additionally, advancements in insulation materials and containment technologies aim to reduce thermal losses and mitigate corrosion-related challenges, thereby extending the operational lifespan of these storage systems [81].

2.6. Phase Change Materials (PCMs) and Sensible Heat Storage

Sensible Heat Storage and Phase Change Materials (PCMs) are two essential methods for thermal energy storage that allow for controlled heat release and effective energy retention over long periods of time. The latent heat of fusion is used by PCMs to facilitate phase transitions, usually from solid to liquid and vice versa. On the other hand, sensible heat storage depends on raising or lowering a storage medium's temperature without causing a phase shift. Both approaches are essential for increasing the adaptability and effectiveness of energy systems, especially when it comes to incorporating renewable energy sources and boosting energy security [82].

PCMs leverage the ability of certain substances to absorb and release significant amounts of heat when undergoing phase transitions. Thermal energy is stored while the material melts during the charging process, and during discharging, the material solidifies, releasing stored heat. This process allows for high-energy density storage within a relatively small volume, making PCMs suitable for applications requiring stable temperature maintenance. Various organic, inorganic, and eutectic PCMs have been investigated for their thermal storage potential. Fatty acids and paraffin waxes are examples of organic PCMs that are distinguished by their non-corrosive properties and chemical stability. Higher thermal conductivity and energy storage density are provided by inorganic PCMs, especially salt hydrates and metallic alloys, however they may have problems with phase segregation and subcooling. Researchers have explored hybrid PCM formulations that combine the desirable properties of organic and inorganic materials to enhance performance [83].

PCMs have been widely adopted in building energy management, concentrated solar power (CSP) plants, and industrial waste heat recovery. In building applications, they are integrated into walls, ceilings, and floors to regulate indoor temperatures, reducing heating and cooling demands. In CSP plants, PCMs are used to store excess solar energy during peak radiation hours and release it during low solar intensity periods, ensuring continuous power generation [84,85]. Additionally, industrial facilities use PCMs to capture waste heat from high-temperature processes, enhancing overall energy efficiency. However, these materials also present several limitations, including low thermal conductivity, which slows down heat exchange rates. Efforts to improve thermal conductivity involve embedding PCMs with highly conductive materials, such as graphene, metal foams, and carbon nanotubes [86,87]. Another challenge is long-term stability, as repeated phase transitions may lead to material degradation and reduced storage efficiency. Sensible heat storage, on the other hand, involves raising the temperature of a storage medium, such as water, rocks, or concrete, without inducing a phase change. The energy stored depends on the specific heat capacity of the material and the temperature range it can withstand. This method is widely utilized due to its simplicity, low cost, and scalability. Water-based sensible heat storage systems are commonly employed in district heating networks, while high-temperature storage using solid media is integrated into CSP plants. Thermal storage in large-scale rock beds has been explored for seasonal energy storage, allowing excess summer heat to be conserved for winter heating demands [87].

Despite its widespread adoption, sensible heat storage exhibits limitations that can affect its efficiency. One major drawback is the relatively low energy density compared to latent heat storage, requiring large storage volumes to achieve high capacity. Heat losses over time, particularly in long-duration applications, also pose a challenge, necessitating advanced insulation materials to mitigate energy dissipation. Additionally, the temperature gradient across the storage medium can lead to thermal stratification, which impacts the efficiency of heat retrieval. Researchers continue to investigate novel materials and system designs to optimize sensible heat storage performance, including the development of thermally enhanced concrete and encapsulated phase change hybrids to improve energy retention [88].

Both PCMs and sensible heat storage contribute significantly to the advancement of long-duration thermal energy storage technologies. Ongoing research efforts aim to address existing limitations by improving thermal conductivity, material stability, and system integration. These advancements will further enhance the viability of thermal LDES in enabling renewable energy deployment and reducing reliance on fossil-fuel-based energy sources [88,89].

2.7. Chemical Long-Duration Energy Storage (LDES)

Chemical energy storage represents a transformative approach to long-duration energy storage (LDES) by converting electrical energy into chemical bonds, which can later be reversed to release energy when needed. This method provides high energy density and extended discharge durations, making it particularly suitable for balancing fluctuations in renewable energy generation. Unlike other LDES technologies that store energy in physical forms such as heat or gravitational potential, chemical storage facilitates energy retention in molecular structures, allowing for efficient transport and utilization [90].

Among the various chemical storage technologies, hydrogen-based systems and metal-based energy carriers have gained prominence due to their potential to provide large-scale, long-term energy storage solutions [52,91]. Hydrogen storage, in particular, has been extensively investigated due to its role in the power-to-gas (P2G) concept and its integration with fuel cell technology [92]. Additionally, alternative chemical storage methods, such as ammonia and liquid organic hydrogen carriers (LOHCs), are being explored to enhance storage efficiency and transportability. The effectiveness of chemical LDES depends on the efficiency of conversion processes, storage safety, and economic feasibility. While these technologies offer significant promise, challenges related to efficiency losses, infrastructure development, and material stability continue to be the focus of research efforts [92].

2.7.1. Hydrogen Storage – Power-to-Gas (P2G) and Hydrogen Fuel Cells

Hydrogen storage plays a crucial role in the integration of renewable energy by offering a means to convert excess electricity into storable hydrogen through electrolysis. The power-to-gas (P2G) concept involves splitting water into hydrogen and oxygen using surplus renewable electricity, effectively mitigating curtailment issues associated with wind and solar power generation [93]. The stored hydrogen can then be used in multiple applications, including direct combustion, industrial processes, and electricity regeneration through fuel cells. This versatility makes hydrogen a key enabler of deep decarbonization in sectors that are difficult to electrify, such as heavy industry, long-haul transportation, and grid-scale energy storage [94,95].

Hydrogen storage can be achieved through various means, including compressed gas storage, liquid hydrogen storage, and solid-state storage using metal hydrides or chemical compounds (see Table 3). Compressed hydrogen storage is the most commonly deployed method due to its relatively mature technology and scalability [96]. However, it requires high-pressure containment systems, typically ranging from 350 to 700 bar, which impose engineering and cost challenges. Liquid hydrogen storage, which involves cryogenic cooling to temperatures below -253°C, offers higher energy density but faces energy losses due to boil-off effects. Solid-state hydrogen storage, involving metal hydrides and chemical carriers such as ammonia or LOHCs, provides a promising alternative with improved safety and energy density, though challenges related to reaction kinetics and reversibility remain active areas of research [97,98].

Hydrogen fuel cells enable the efficient conversion of stored hydrogen back into electricity, playing a critical role in long-duration energy applications. Proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) are among the most widely studied fuel cell technologies for grid and transport applications. PEMFCs operate at relatively low temperatures, making them suitable for mobility solutions, while SOFCs function at high temperatures, enhancing their efficiency in stationary power generation. Research efforts have focused on improving catalyst materials, membrane durability, and system integration to enhance fuel cell longevity and cost-effectiveness. Recent advancements in platinum-free catalysts and high-temperature polymer electrolyte membranes have contributed to the development of more efficient and sustainable hydrogen fuel cell systems [96].

Despite its significant potential, hydrogen storage and conversion technologies face several challenges that must be addressed to enable widespread adoption (see Table 3). Energy losses associated with electrolysis, storage, and fuel cell conversion reduce the overall efficiency of the hydrogen cycle, necessitating improvements in electrolyzer performance and advanced storage materials. Additionally, the development of hydrogen infrastructure, including transport and refueling networks, remains a major bottleneck in achieving large-scale deployment. Ongoing research aims to address these issues by exploring innovative storage solutions, enhancing hydrogen production efficiency, and optimizing integration with renewable energy systems [99].

Table 3 Advantages and Challenges of Hydrogen Storage Methods

Storage Method	**Energy Efficiency**	**Storage Conditions**	**Advantages**	**Drawbacks**
Compressed Gas Storage	Moderate	- Pressure: 350–700 bar - Temperature: Ambient	- Mature technology - Scalable for various applications - Relatively straightforward implementation	- High energy requirement for compression - Safety concerns due to high-pressure storage - Bulky storage vessels
Liquid Hydrogen Storage	Moderate to High	- Temperature: -253°C (20 K) - Pressure: Near atmospheric	- Higher energy density than compressed gas - Effective for large-scale storage and transport	- Significant energy required for liquefaction - Boil-off losses due to evaporation - Requires advanced insulation and cryogenic handling
Metal Hydride Storage	Variable	- Temperature: Typically, 20–300°C - Pressure: 1–10 bar	- High volumetric energy density - Operates at lower pressures - Enhanced safety profile due to solid-state storage	- Heavy storage systems - Thermal management needed for hydrogen absorption/desorption - High material costs and potential degradation over time
Chemical Hydride Storage	Variable	- Temperature: Varies depending on the chemical reaction - Pressure: Typically, near ambient	- High hydrogen storage capacity - Stable under ambient conditions - Potential for high energy density	- Complex hydrogen release mechanisms - Regeneration of spent materials can be costly and energy-intensive - Byproduct management required

2.8. Ammonia and Synthetic Fuels – Emerging Alternatives for Grid Resilience

The exploration of alternative chemical energy carriers has intensified as the energy sector seeks efficient long-duration storage solutions that complement intermittent renewable generation. Ammonia and synthetic fuels have gained recognition as viable vectors for storing and transporting renewable energy while offering the advantage of established industrial infrastructure. These energy carriers facilitate long-term storage by converting electricity into high-energy-density compounds, which can be utilized for power generation, transportation, and industrial applications. Compared to hydrogen, ammonia and synthetic fuels exhibit favorable handling properties and higher storage efficiency, making them practical alternatives for large-scale energy storage and grid stability [99].

2.8.1. Ammonia as an Energy Carrier

Ammonia presents a promising energy storage medium due to its high hydrogen content, ease of liquefaction under mild pressure, and well-established production and distribution networks. Produced through the Haber-Bosch process using renewable hydrogen and nitrogen from the air, ammonia serves as a carbon-free fuel that can be directly combusted in gas turbines or re-converted into hydrogen via catalytic cracking. The ability to store ammonia as a liquid at moderate pressures enables cost-effective energy retention over extended periods, positioning it as an attractive option for seasonal energy storage and transcontinental energy transport [100].

Recent studies have demonstrated that ammonia-fueled gas turbines can achieve high combustion efficiencies while reducing carbon emissions. However, challenges related to NOx emissions during ammonia combustion necessitate the development of advanced catalysts and optimized combustion strategies. Additionally, ongoing research into ammonia electrolysis aims to enhance efficiency and reduce the energy intensity of hydrogen recovery. Despite these technical hurdles, several demonstration projects are underway to integrate ammonia into power generation systems, with Japan and Europe leading initiatives to deploy ammonia-cofired power plants and maritime fuel applications [101,102].

2.8.2. Synthetic Fuels and Their Role in Grid Resilience

Synthetic fuels, also known as e-fuels, are liquid hydrocarbons produced using renewable electricity, captured carbon dioxide, and hydrogen through power-to-liquid (PtL) processes. These fuels offer a drop-in solution for existing transportation and industrial fuel infrastructure, enabling decarbonization without requiring significant modifications to engines or distribution networks. The production of synthetic methane, methanol, and Fischer-Tropsch fuels relies on well-established chemical pathways, allowing for scalable deployment in energy-intensive sectors such as aviation, shipping, and backup power generation [103].

The integration of synthetic fuels into energy storage systems enhances grid resilience by providing dispatchable power that complements variable renewable energy sources. Unlike battery storage, which is limited by capacity constraints, synthetic fuels can be stockpiled indefinitely, ensuring reliable energy supply during prolonged periods of low renewable generation. Moreover, advancements in carbon capture and utilization (CCU) technologies are improving the efficiency of synthetic fuel synthesis, reducing lifecycle emissions, and enhancing economic viability. Research continues to focus on optimizing catalyst materials, reactor designs, and process efficiency to accelerate the commercial adoption of synthetic fuels in energy storage applications [103,104].

2.9. Challenges and Future Prospects

Despite their advantages, ammonia and synthetic fuels face technical and economic barriers that must be addressed to facilitate widespread deployment. Ammonia combustion requires stringent control of NOx emissions, necessitating innovations in burner design and exhaust treatment technologies. Additionally, the high energy demand of ammonia and synthetic fuel production presents efficiency trade-offs that impact overall cost competitiveness. Policy support, investment in green hydrogen production, and advancements in energy conversion technologies will be critical in driving the adoption of these alternative chemical storage solutions. Ongoing research efforts aim to improve ammonia synthesis efficiency, develop novel catalysts for synthetic fuel production, and enhance combustion performance for energy applications. Collaborative initiatives between industry and academia are accelerating the commercialization of these technologies, positioning ammonia and synthetic fuels as essential components of future grid stability and decarbonization strategies. As renewable energy penetration increases, these alternative energy carriers are expected to play a crucial role in achieving a reliable, low-carbon energy system [102,105].

3. Role of LDES in Enhancing Grid Resilience

The stability of modern power grids is increasingly challenged by the growing integration of variable renewable energy sources, extreme weather events, and rising electricity demand. As conventional baseload power plants are phased out to meet decarbonization targets, maintaining grid reliability requires advanced energy storage solutions capable of providing sustained power over extended durations. Long-duration energy storage (LDES) plays a crucial role in addressing these challenges by mitigating supply-demand imbalances, stabilizing voltage and frequency fluctuations, and enhancing the flexibility of grid operations [106,107]. By enabling the efficient storage and dispatch of surplus renewable energy, LDES technologies contribute to energy security, reduce reliance on fossil-fuel-based peaking plants, and strengthen the resilience of power systems against disruptions.

This section explores the diverse functions of LDES in fortifying grid infrastructure, including its role in balancing intermittent generation, ensuring reliability during extreme weather conditions, and supporting the transition to a low-carbon energy system. Additionally, it examines the capacity of LDES to provide ancillary services, improve power quality, and facilitate energy arbitrage, all of which are essential for the stability and economic viability of future grids. Through an analysis of real-world applications and recent advancements in storage technology, this discussion highlights the transformative impact of LDES on grid resilience and long-term sustainability.

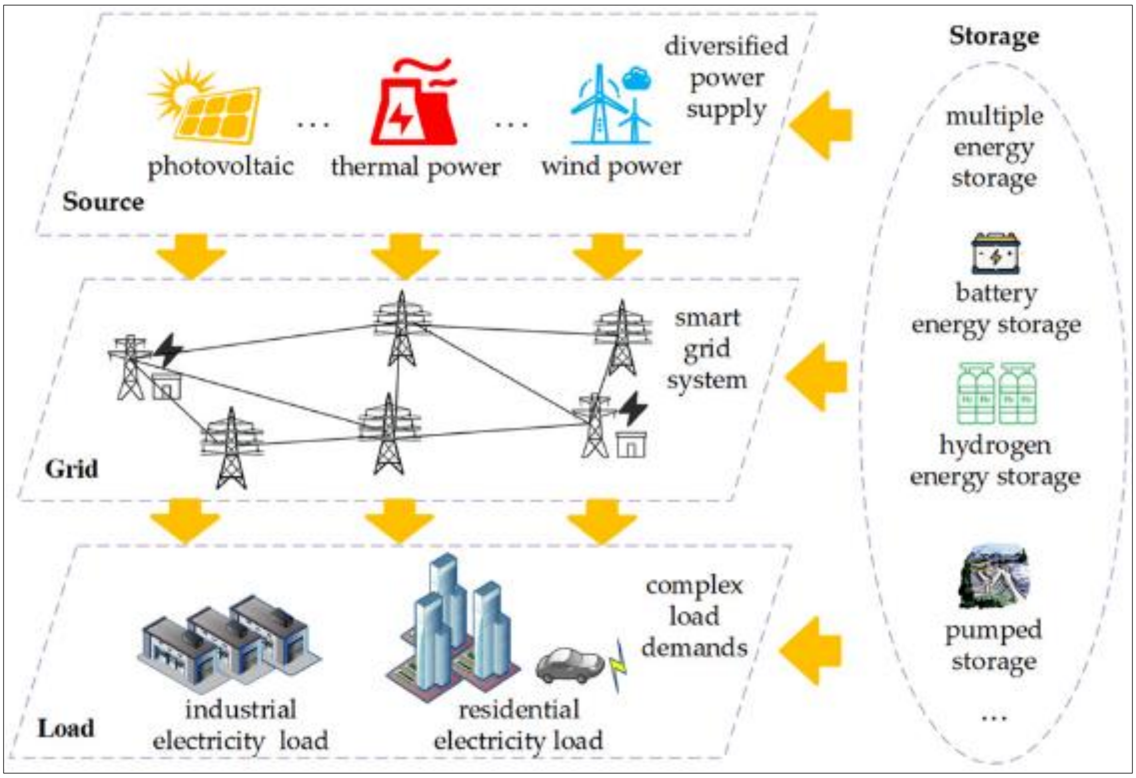

Figure 6 LDES integration into the power grid to enhance resilience, improve reliability, and stabilize supply-demand imbalances. Reproduced with permission from Ref. [108]

3.1. Frequency Regulation and Grid Stability

The integration of renewable energy sources introduces variability into power generation, leading to fluctuations that can challenge the stability of electrical grids. Long-duration energy storage (LDES) systems play a pivotal role in mitigating these fluctuations by providing frequency regulation and enhancing grid stability (see Figure 6).

3.1.1. Frequency Regulation

Maintaining a consistent frequency is essential for the reliable operation of power systems. Deviations from the standard frequency can result in equipment malfunctions and power outages. LDES systems contribute to frequency regulation by rapidly absorbing excess energy during periods of overgeneration and supplying energy during deficits, thereby balancing supply and demand in real-time. This capability ensures that the grid frequency remains within acceptable limits, supporting overall system reliability [108,109].

3.1.2. Grid Stability

Beyond frequency regulation, LDES systems enhance grid stability by offering services such as voltage support and spinning reserve capabilities. By providing a steady flow of energy, these systems help maintain the necessary voltage levels and ensure that there is a ready reserve of power to address sudden changes in demand or supply. This flexibility is crucial for integrating higher proportions of renewable energy, which are inherently variable and can otherwise destabilize the grid [110].

3.1.3. Mitigating Renewable Energy Fluctuations

The intermittent nature of renewable energy sources like wind and solar can lead to supply fluctuations that challenge grid stability. LDES systems mitigate these fluctuations by storing surplus energy generated during periods of high renewable output and releasing it during periods of low generation. This storage and discharge process smooths out the variability in renewable energy supply, ensuring a consistent and reliable power flow to the grid [111].

In summary, LDES systems are integral to modern power grids, providing essential services that maintain frequency regulation and overall stability amidst the increasing integration of renewable energy sources.

3.2. Energy Arbitrage and Demand Shifting

As highlighted previously, the increasing penetration of renewable energy sources has led to significant fluctuations in electricity generation, resulting in periods of excess supply and sudden shortages. These imbalances create volatility in electricity prices, making energy arbitrage an essential mechanism for optimizing grid economics. Long-duration energy storage (LDES) enables the strategic storage of surplus electricity during times of low demand and its release when demand peaks, thereby reducing costs and improving the overall efficiency of power systems [52]. By capitalizing on price differentials between off-peak and peak periods, LDES facilitates a more balanced energy market while minimizing reliance on expensive and carbon-intensive peaking plants [105].

Recent studies indicate that LDES technologies, particularly electrochemical and chemical storage systems, have demonstrated significant potential for demand shifting applications. According to Zhu et al. [112], redox flow batteries (RFBs) and metal-air batteries provide extended discharge durations that allow grid operators to shift large-scale energy consumption patterns over several hours or even days. Similarly, hydrogen storage systems, through power-to-gas conversion and subsequent electricity generation, offer a promising pathway for long-term energy arbitrage, particularly in regions with high renewable energy penetration [113]. The long-duration energy storage (LDES) market has been experiencing rapid expansion, driven by the increasing penetration of renewable energy sources, the need for grid stability, and supportive government policies. Market projections indicate significant growth in both installed capacity and investment, with the sector expected to see substantial advancements in the coming years. Table 4 provides a comprehensive overview of key market trends, highlighting past and projected figures for installed capacity, market valuation, and major industry developments.

Table 4 Global Market Trends and Forecasts for LDES

Year	Installed Capacity (GWh)	Market Value (USD Billion)	Notable Trends and Insights
2023	24	256.45	- Significant growth in large-scale battery storage, with a 71% increase from the previous year, totaling 24 GWh. California led with over 11 GWh, followed by Texas (6 GWh), Arizona (2 GWh), and Nevada (1.1 GWh). - Global LDES market valued at $256.45 billion.
2024	Data not specified	4.84	- Projected market value of $4.84 billion, driven by increasing demand for grid stability and renewable energy integration.
2025	20	350.00	- UK government introduces "cap and floor" mechanism to support pumped hydro storage projects, aiming to manage supply and demand volatility as renewable energy integration increases.
2030	Data not specified	605.10	- Market projected to reach $605.10 billion, with a compound annual growth rate (CAGR) of 13.6% from 2024 to 2030.

The role of LDES in demand shifting extends beyond economic optimization, as it also alleviates stress on transmission and distribution infrastructure. By flattening load curves and reducing peak demand, these storage technologies help defer costly grid upgrades and improve overall system stability [114]. Additionally, large-scale energy storage deployments enhance the resilience of power networks by mitigating the impact of supply-demand mismatches, which are exacerbated by extreme weather conditions and grid disturbances [115]. Empirical evidence from real-world implementations further underscores the effectiveness of LDES in energy arbitrage strategies. In California, the deployment of long-duration battery storage systems has contributed to grid stabilization by storing excess solar energy generated during midday and discharging it in the evening when consumption surges [116]. Similar trends have been observed in European markets, where pumped hydro storage and thermal energy storage facilities are increasingly utilized to optimize electricity pricing structures and enhance system flexibility.

As energy markets continue to evolve, the integration of LDES in arbitrage and demand-shifting applications is expected to play a pivotal role in shaping a cost-effective and resilient electricity grid. Advancements in storage efficiency, coupled with declining technology costs, will further expand the feasibility of large-scale deployment, making LDES a cornerstone of modern grid operations.

3.3. Blackout Prevention and Disaster Recovery: LDES as a Backup During Grid Failures and Extreme Weather Events

The increasing frequency and intensity of extreme weather events pose significant challenges to the reliability of power grids. Hurricanes, wildfires, and other natural disasters can disrupt electricity supply, leading to prolonged outages that affect communities and critical infrastructure. Long-duration energy storage (LDES) systems play a pivotal role in enhancing grid resilience by providing reliable backup power during such events, thereby mitigating the impact of blackouts and facilitating efficient disaster recovery efforts.

3.3.1. Enhancing Grid Resilience

LDES systems, such as battery energy storage systems (BESS), can stabilize the grid by balancing supply and demand, reacting swiftly to unforeseen incidents, and providing balancing energy. This capability effectively prevents power outages and enhances the overall resilience of the power system [117].

3.3.2. Case Study: Alaska's Battery Energy Storage System

A notable example is the BESS installed in Fairbanks, Alaska, which has significantly strengthened grid resilience. Shortly after its installation, the system prevented approximately 30,000 power outages, achieving a 90% reduction in power supply interruptions. This underscores the effectiveness of LDES in maintaining continuous power supply during emergencies [118].

3.3.3. Role in Disaster Recovery

Beyond blackout prevention, LDES systems are integral to disaster recovery strategies. By ensuring a stable power supply, they support critical infrastructure and services during natural disasters, thereby reducing the time required for first responders to commence recovery efforts [119].

3.4. Enhancing Renewable Energy Integration

The increasing penetration of renewable energy sources, particularly solar and wind power, presents a fundamental challenge to grid stability due to their variable and weather-dependent nature. Unlike conventional thermal power plants, which can provide consistent electricity generation, solar and wind output fluctuates based on environmental conditions, creating imbalances between supply and demand. Long-duration energy storage (LDES) plays a crucial role in mitigating these fluctuations by storing excess renewable energy during periods of high generation and releasing it when production declines, thereby ensuring a continuous and stable power supply [120].

LDES technologies such as redox flow batteries, pumped hydro storage, and hydrogen-based systems enable the efficient temporal shifting of renewable energy, extending the availability of solar and wind power beyond daylight hours or calm periods. Research conducted by IRENA (2023) highlights that grid-scale LDES can significantly reduce curtailment of excess renewable energy, improving the overall efficiency of energy utilization. By integrating LDES with renewable generation assets, grids can absorb surplus electricity during peak production and dispatch it during high-demand periods, minimizing reliance on fossil-fuel-based backup generation and accelerating the transition to a low-carbon energy mix [121].

Beyond balancing supply and demand, LDES contributes to frequency and voltage stabilization, essential for maintaining grid reliability amid increasing renewable integration. Case studies on hybrid renewable energy systems incorporating LDES have demonstrated improved grid performance and resilience in regions with high solar and wind penetration [122,123]. Furthermore, policy frameworks promoting the deployment of LDES have been shown to enhance energy security by reducing dependency on imported fuels and mitigating risks associated with energy market volatility. Continued research and investment in advanced LDES technologies will be essential for realizing fully renewable-powered grids capable of delivering reliable and sustainable electricity worldwide [122].

4. Techno-Economic and Policy Challenges of LDES Deployment

The widespread adoption of long-duration energy storage (LDES) is integral to achieving a reliable, decarbonized energy grid. However, its deployment is constrained by a combination of technological, economic, and regulatory barriers that influence its feasibility and scalability. The high capital costs associated with LDES technologies, along with uncertainties in long-term cost reductions, pose challenges for investment and commercialization. Additionally, efficiency limitations, material availability, and the complexity of integrating these storage solutions with existing grid infrastructure hinder widespread implementation [114].

Economic challenges, including uncertain revenue streams and the lack of well-defined market structures for valuing long-duration storage services, further complicate the financial viability of LDES. Regulatory frameworks and energy policies often lag behind technological advancements, creating barriers to grid interconnection, market participation, and incentive structures that could otherwise support LDES deployment. Policy interventions, such as capacity market reforms, investment subsidies, and carbon pricing mechanisms, play a crucial role in mitigating these barriers and fostering an environment conducive to large-scale storage adoption [124]. This section explores the key techno-economic and policy challenges affecting LDES, providing an in-depth analysis of technology performance limitations, cost dynamics, investment risks, and regulatory hurdles. Understanding these constraints is essential for developing strategies that enable the large-scale deployment of LDES as a cornerstone of future energy systems.

4.1. Cost and Market Competitiveness

The deployment of long-duration energy storage (LDES) technologies is significantly influenced by their economic viability, encompassing capital expenditures, levelized cost of storage (LCOS), and prevailing investment challenges. Capital costs remain one of the primary obstacles, as many LDES systems require substantial initial investments. Technologies such as compressed air energy storage (CAES) and pumped storage hydropower (PSH) demand high infrastructure costs due to their reliance on large-scale facilities. In contrast, battery-based storage solutions, including lithium-ion and flow batteries, are undergoing continuous advancements to reduce these capital requirements. Despite these ongoing developments, lowering the financial burden associated with LDES technologies remains a critical objective for ensuring large-scale adoption [125].

Another crucial economic factor is the levelized cost of storage (LCOS), which evaluates the total cost of building and operating an energy storage facility over its lifetime, divided by the total energy stored and discharged. The LCOS of LDES technologies varies significantly depending on the storage type, efficiency levels, system lifespan, and operational factors. Current estimates indicate that LCOS for LDES solutions must be further reduced to reach grid parity with conventional energy storage and generation technologies. The U.S. Department of Energy has set a cost reduction target of $0.05/kWh by 2030, emphasizing the necessity for ongoing technological innovation to meet this benchmark [126].

Investment in LDES technologies faces several barriers, including concerns over technological uncertainty, market structures, and regulatory policies. Many emerging LDES solutions are still in their early stages of development, raising investor apprehensions regarding their long-term reliability and commercial viability. Additionally, existing energy markets often fail to adequately compensate the grid-balancing services provided by LDES, limiting the financial incentives for deployment. The absence of clear policies and dedicated incentives further compounds these investment challenges, as financial stakeholders seek assurances of viable returns. Overcoming these barriers requires collaboration between policymakers, industry leaders, and financial institutions to create investment-friendly regulatory frameworks that promote LDES development while mitigating financial risks [127].

4.2. Efficiency and Technological Maturity

The efficiency and technological readiness of LDES systems play a pivotal role in their widespread adoption, with factors such as round-trip efficiency, degradation rates, and operational constraints significantly influencing their performance. Round-trip efficiency (RTE), which measures the proportion of energy recovered from storage relative to the energy initially input, varies considerably among different LDES technologies. Pumped storage hydropower (PSH), one of the most established storage solutions, achieves RTE values between 70% and 85%, while compressed air energy storage (CAES) typically operates with efficiencies ranging from 42% to 55%. Flow batteries, another promising LDES category, currently demonstrate efficiencies of around 60% to 70%, though further improvements are actively being pursued. Higher RTE values are desirable as they indicate more efficient energy conversion, directly impacting the economic and environmental feasibility of storage technologies [128].

In addition to efficiency, degradation and operational limitations present significant challenges for LDES technologies. The longevity of these systems depends on cycle life, capacity retention, and maintenance requirements. Over prolonged use, energy storage devices may experience capacity fade, leading to diminished storage efficiency and increased operational costs. Technologies with higher cycle lives demonstrate greater long-term value, as they require less frequent replacements and incur lower maintenance expenses. Some LDES systems also demand continuous upkeep to manage wear and tear, particularly in mechanical storage solutions such as CAES and PSH. A clear understanding of these degradation factors is essential for accurately forecasting system performance and determining overall lifecycle costs [129].

The technological maturity of LDES solutions varies widely across different energy storage approaches. Pumped storage hydropower is the most established, with extensive global deployment, while lithium-ion batteries, though dominant in short-duration applications, are still undergoing modifications for use in long-duration scenarios. Flow batteries and alternative chemistries, including metal-air and solid-state batteries, are still in pilot or early commercial phases, requiring further research and development before large-scale implementation. Increasing the technological maturity of these emerging solutions is essential to improve their reliability, efficiency, and cost-effectiveness, ultimately enabling broader integration into the energy grid [130]. Addressing the techno-economic and policy challenges of LDES deployment is critical to ensuring their role in future energy systems. Advancements in cost reduction, efficiency improvements, and regulatory support will determine how effectively these technologies contribute to grid stability and renewable energy integration.

4.3. Regulatory and Policy Barriers

The expansion of long-duration energy storage (LDES) is closely tied to the regulatory and policy landscape, which influences market viability and investment attractiveness. Many existing energy market structures were developed around conventional power generation systems, failing to fully accommodate the operational dynamics of LDES. One of the major challenges is the lack of clear policies that define storage as a distinct asset class within electricity markets. Without proper classification, LDES technologies struggle to access revenue streams comparable to traditional generation and transmission assets, limiting their ability to compete on equal footing [114].

A critical regulatory gap lies in the absence of long-term market incentives that support the financial sustainability of LDES. Unlike short-duration storage solutions, which can benefit from frequent charge-discharge cycles and ancillary service payments, LDES systems are designed to store energy over extended periods, making their revenue models less immediate. Current market mechanisms often do not compensate the full value that LDES provides in terms of grid stability, renewable energy integration, and resilience against outages. Government-backed incentives, such as tax credits, direct subsidies, and capacity payments, could encourage investment in LDES, but such policies remain fragmented across different regions. Some jurisdictions have introduced pilot programs to assess the feasibility of incorporating LDES within capacity markets, but a globally coherent approach is still lacking [114].

In addition to market-based incentives, regulatory frameworks must address permitting challenges and standardization issues. The deployment of large-scale LDES projects often requires extensive environmental and safety assessments, which can delay implementation and increase costs. Standardized permitting processes and streamlined regulatory pathways could significantly reduce these barriers. Furthermore, technical standards for interoperability, safety, and performance benchmarks are necessary to create a competitive and reliable LDES market. Regulatory bodies must work in coordination with industry stakeholders to establish frameworks that facilitate the deployment of these technologies while ensuring operational security and compliance with environmental regulations [127].

4.4. Infrastructure and Deployment Constraints

The large-scale implementation of LDES technologies is often hindered by infrastructure limitations, siting challenges, and environmental considerations. Many storage technologies require significant land, specialized geological conditions, or extensive transmission network integration, making deployment complex and geographically constrained. Pumped storage hydropower (PSH), one of the most widely deployed LDES solutions, necessitates reservoirs and elevation differentials, restricting its feasibility to specific locations. Similarly, compressed air energy storage (CAES) depends on underground caverns, limiting its application to regions with suitable geological formations [128].

Land use and permitting challenges further complicate LDES deployment, particularly in densely populated regions where space constraints are significant. Large-scale battery storage systems and thermal energy storage installations require designated sites with appropriate zoning, safety clearances, and infrastructure support. The process of obtaining permits for these projects is often lengthy, involving multiple regulatory bodies and environmental impact assessments. In some cases, community opposition due to concerns over land repurposing, ecological disruptions, and safety risks further delays project approvals. Addressing these concerns requires better community engagement, transparent impact assessments, and compensation mechanisms that ensure local benefits [130].

Environmental impact is another critical factor influencing the scalability of LDES technologies. While these systems contribute to decarbonization by enabling greater integration of renewable energy, their material sourcing, land transformation, and operational emissions must be carefully managed. Some storage technologies, such as lithium-ion and flow batteries, involve the extraction of critical minerals, raising concerns about resource depletion and supply chain sustainability. Other systems, including thermal energy storage, may require extensive water resources for heat transfer processes, leading to potential conflicts in water-scarce regions. The development of more sustainable materials, recycling strategies, and life-cycle assessments can help mitigate these environmental challenges and enhance the overall viability of LDES solutions [129]. The environmental impact of long-duration energy storage (LDES) technologies is a critical factor in assessing their sustainability and feasibility for large-scale deployment. Each technology presents unique challenges and benefits concerning land use, resource extraction, emissions, and disposal. Table 5 provides a comparative analysis of these environmental considerations, offering insights into how different storage methods affect ecosystems, carbon footprints, and long-term sustainability.

Table 5 Environmental Impact of Various LDES Technologies

LDES Technology	Land Use	Resource Extraction	Emissions	End-of-Life Disposal
Pumped Storage Hydropower (PSH)	- Large-scale land alteration due to reservoir creation, impacting ecosystems and habitats.	- Extensive use of concrete and steel, leading to significant environmental footprint.	- Minimal operational emissions; however, construction phase can produce substantial CO_2 emissions.	- Long lifespan reduces frequency of disposal concerns; decommissioning can impact local environments.
Compressed Air Energy Storage (CAES)	- Requires underground caverns or aquifers, potentially disrupting geological formations.	- Materials for compressors and expanders involve mining and processing activities.	- Operational emissions depend on energy source; construction phase has associated emissions.	- Equipment recycling is possible, but site restoration may be necessary.
Flow Batteries (e.g., Vanadium Redox)	- Compact footprint suitable for urban settings; minimal land disruption.	- Vanadium extraction can be environmentally intensive; electrolyte production requires chemical processing.	- Low operational emissions; production phase involves emissions from material processing.	- Potential for electrolyte recycling; proper disposal of hazardous materials is essential.
Liquid Air Energy Storage (LAES)	- Moderate land use; facilities can be integrated into existing industrial sites.	- Requires materials for cryogenic tanks and liquefaction equipment, involving standard industrial processes.	- Emissions depend on electricity source; liquefaction process can be energy-intensive.	- Equipment can be dismantled and recycled; minimal hazardous waste concerns.
Hydrogen Storage (e.g., Underground Caverns)	- Utilizes existing geological formations; minimal surface land use.	- Hydrogen production methods vary; electrolysis requires water and electricity, while steam methane reforming involves natural gas.	- Emissions depend on production method; 'green' hydrogen has low emissions, whereas 'grey' hydrogen is carbon-intensive.	- Cavern repurposing or sealing required; minimal solid waste.

Overcoming infrastructure and deployment constraints will require coordinated efforts between governments, industry stakeholders, and research institutions. Advances in siting methodologies, grid planning strategies, and environmentally friendly storage solutions can contribute to more efficient and sustainable LDES implementation. Policy measures that streamline permitting processes, provide incentives for responsible land use, and support research into alternative materials will be essential in addressing these barriers [122].

5. Emerging Innovations and Future Research Directions

The rapid expansion of renewable energy has underscored the necessity for advanced long-duration energy storage (LDES) solutions capable of ensuring grid stability and reliability. While existing technologies provide viable storage options, ongoing research is focused on enhancing efficiency, scalability, and cost-effectiveness. Innovations in material science, electrochemistry, and system design are driving the next generation of LDES, with researchers exploring novel chemistries, high-performance electrolytes, and hybrid storage configurations. Additionally, artificial intelligence and machine learning are being integrated into energy management systems to optimize storage operations and improve forecasting accuracy [121,131].

Beyond technological advancements, future research is expected to address sustainability challenges, particularly in relation to resource utilization, recyclability, and lifecycle emissions. The exploration of alternative materials with lower environmental footprints, coupled with advances in manufacturing techniques, aims to reduce dependency on critical minerals and enhance the circular economy within the storage sector. At the policy level, research is shifting toward market mechanisms that incentivize innovation and support the deployment of next-generation LDES technologies. As global energy systems transition toward higher renewable penetration, the role of cutting-edge storage solutions will become increasingly pivotal in shaping a more resilient and decarbonized grid [114,132].

5.1. Advanced Materials for LDES

Advancements in nanomaterials and novel electrolytes are pivotal in enhancing the performance of long-duration energy storage (LDES) systems. Nanomaterials, due to their unique properties, offer improved ionic transport and electronic conductivity compared to traditional battery materials. This enhancement allows for higher specific capacities and faster ion diffusion, enabling electrodes to tolerate high currents, which is essential for efficient energy storage [133]. Additionally, the development of polymer-ceramic hybrid nanofiber separators has been shown to improve the safety and efficiency of lithium-ion batteries, a common technology in LDES applications.

In parallel, research into novel electrolytes, such as solid-state electrolytes, aims to address safety concerns and increase energy densities. Ceramic-based electrolytes, synthesized using green chemistry methods, have demonstrated notable ionic conductivity and durability, offering a pathway to safer and more efficient energy storage solutions [134]. These advancements in materials science are critical for the evolution of LDES technologies, as they directly impact the efficiency, safety, and overall performance of energy storage systems.

5.2. AI and Machine Learning in LDES Optimization

Artificial intelligence (AI) and machine learning (ML) are increasingly integral to optimizing LDES systems. By analyzing large datasets, AI can predict battery health, optimize charging methods, and extend battery life, thereby enhancing overall system performance [135]. Moreover, AI-based control strategies facilitate intelligent and flexible responses to complex energy management challenges, enabling more efficient energy dispatch and grid balancing [136]. The integration of AI in energy storage extends to the development phase, where AI accelerates materials discovery and system design. Surrogate models powered by machine learning can simulate high-fidelity scenarios at reduced computational costs, expediting the identification of optimal materials and configurations for energy storage [135]. As renewable energy sources become more prevalent, AI's role in forecasting energy generation and managing grid integration becomes increasingly vital, ensuring that LDES systems operate efficiently within the broader energy infrastructure [135].

5.3. Hybrid LDES Systems

Hybrid long-duration energy storage systems, which combine electrochemical, mechanical, and thermal storage technologies, are emerging as a strategy to optimize performance and address the limitations inherent in individual storage methods. By integrating different storage mechanisms, hybrid systems can leverage the strengths of each technology to achieve higher efficiency, flexibility, and reliability [137].

For instance, combining battery storage with thermal energy systems can provide both rapid response capabilities and long-term energy retention, catering to varying grid demands. Additionally, integrating mechanical storage solutions, such as flywheels, with electrochemical batteries can enhance the system's ability to manage short-term fluctuations and maintain long-term energy supply. Ongoing research and development in hybrid LDES systems focus on optimizing these integrations to create more resilient and efficient energy storage solutions, capable of supporting the evolving needs of modern power grids [122].

5.4. Next-Generation Hydrogen and Ammonia Storage

Advancements in hydrogen and ammonia storage technologies are transforming their role in long-duration energy storage (LDES), with recent breakthroughs enhancing storage efficiency, cost-effectiveness, and scalability. Hydrogen storage remains a central challenge due to the element’s low volumetric density, necessitating high-pressure tanks, cryogenic liquefaction, or solid-state storage solutions. Research into metal-organic frameworks (MOFs) and advanced hydrides is addressing these limitations by offering high-capacity and reversible hydrogen storage at lower pressures and ambient temperatures. Studies have demonstrated that nanostructured magnesium hydrides and borohydrides exhibit improved hydrogen absorption and desorption kinetics, making them viable candidates for next-generation hydrogen storage applications [122]. Additionally, innovations in liquid organic hydrogen carriers (LOHCs) provide a chemically stable medium for hydrogen transport and release, enabling safer and more efficient storage solutions [138].

Fuel cell technologies are evolving in parallel with storage advancements, with solid oxide fuel cells (SOFCs) and proton exchange membrane fuel cells (PEMFCs) achieving higher efficiencies and durability. Recent developments in catalyst materials, such as platinum-free electrodes and high-performance ceramic electrolytes, are significantly reducing costs while improving energy conversion efficiency [139]. Moreover, hydrogen compression and distribution strategies are being optimized to align with grid-scale energy storage needs, ensuring the integration of hydrogen-based LDES into renewable energy systems.

Ammonia is emerging as a promising alternative for hydrogen storage due to its higher energy density and established production and distribution infrastructure. Unlike pure hydrogen, ammonia can be liquefied at moderate pressures, simplifying storage and transport. Research into ammonia cracking technologies, which facilitate the efficient release of hydrogen from ammonia at lower temperatures, is enhancing its viability as a large-scale energy carrier [140]. Additionally, direct ammonia fuel cells (DAFCs) are undergoing significant improvements in membrane electrode assembly designs, reducing ammonia crossover and enhancing overall performance. These innovations position ammonia as a viable medium for grid-scale energy storage, complementing hydrogen in the transition to sustainable energy systems [140].

5.5. Global Research and Pilot Projects

The deployment of long-duration energy storage (LDES) is gaining momentum globally, with multiple research initiatives and pilot projects demonstrating the feasibility of various storage technologies in different energy markets (see Table 6). These projects aim to improve grid reliability, optimize renewable energy integration, and support decarbonization efforts. One of the most notable initiatives is the European Union’s STORE&GO project, which integrates power-to-gas (P2G) technology with existing natural gas infrastructure. This project has demonstrated how surplus renewable electricity can be converted into synthetic methane via electrolysis and methanation, offering a scalable solution for seasonal energy storage [131]. Similarly, Germany's Energiewende strategy has supported multiple LDES demonstrations, including the installation of large-scale hydrogen storage facilities that leverage underground salt caverns for high-capacity storage with minimal energy loss [141].

In the United States, the Pacific Northwest National Laboratory (PNNL) is leading an initiative to evaluate the viability of iron-air batteries for grid-scale applications. The project has yielded promising results, with recent studies indicating that iron-air batteries can achieve energy densities up to ten times higher than conventional lithium-ion technologies while significantly reducing costs [142]. Meanwhile, the California Energy Commission has funded the deployment of compressed air energy storage (CAES) systems in abandoned natural gas fields, demonstrating their potential for bulk energy storage and peak-load management [143].

China has invested heavily in molten salt storage as part of its concentrated solar power (CSP) expansion strategy. The 100 MW Dunhuang molten salt tower plant has successfully demonstrated round-the-clock electricity generation by utilizing high-temperature molten salt to store excess solar energy during the day and release it at night [144]. Additionally, China’s recent pilot projects in redox flow batteries are proving their viability for stabilizing power fluctuations in wind-heavy regions such as Inner Mongolia [145].

In Australia, the government has partnered with private sector stakeholders to explore ammonia-based energy storage solutions. The H2U Eyre Peninsula Gateway project aims to develop a 75 MW electrolysis plant that will produce green hydrogen and convert it into ammonia for long-term storage and export applications. This initiative represents a step toward building an integrated hydrogen economy that supports grid stability and energy security [146,147].

These global projects illustrate the potential of LDES technologies to support a more resilient and sustainable energy future. Continued research and pilot demonstrations will play a critical role in refining these technologies, reducing costs, and expanding their adoption across diverse energy markets.

Table 6 Global LDES Pilot Projects and Demonstrations

Project Name	Location	Technology Used	Storage Capacity	Key Findings
Highview Power LAES Plant	Carrington, UK	Liquid Air Energy Storage (LAES)	300 MWh	Demonstrated the feasibility of large-scale LAES, providing grid stability and supporting renewable integration.
Energy Vault GESS	Rudong, China	Gravity Energy Storage Solution (GESS)	100 MWh	Validated the use of gravity-based storage by lifting and lowering heavy blocks, offering an alternative to chemical batteries.
Form Energy Iron-Air Battery Pilot	Cambridge, Minnesota, USA	Iron-Air Battery	1 MW / 150 MWh	Showcased 100-hour storage capability, addressing intermittency of renewable energy sources and enhancing grid reliability.
Hydrostor A-CAES Pilot	Goderich, Canada	Advanced Compressed Air Energy Storage	1.75 MW / 10 MWh	Demonstrated the viability of compressed air storage in underground caverns, providing emission-free long-duration storage.
Neoen Hornsdale Power Reserve Expansion	South Australia	Lithium-Ion Battery Storage	150 MW / 194 MWh	Expanded world's largest lithium-ion battery, improving grid stability and integrating renewable energy sources.
PGE Battery Storage Initiative	Poland	Various Battery Technologies	17,000 MWh	Aimed to support Poland's transition from coal to renewables by investing in large-scale battery storage projects.
TotalEnergies Battery Storage Projects	Germany	Battery Storage	221 MW	Part of strategy to establish a comprehensive electricity value chain in Germany, enhancing grid flexibility.
Highview Power LAES Plant at Hunterston	Hunterston, UK	Liquid Air Energy Storage (LAES)	2.5 GWh	Planned to contribute significantly to the UK's net-zero targets by providing large-scale energy storage without batteries.

6. Conclusion

Long-duration energy storage (LDES) presents a transformative opportunity to enhance grid resilience by mitigating the intermittency of renewable energy sources and enabling a more reliable, flexible, and sustainable energy infrastructure. These technologies facilitate large-scale energy storage over extended periods, ensuring a stable power supply during peak demand or periods of low renewable generation. By integrating LDES, energy systems can achieve higher penetration of renewables, reduce dependency on fossil fuel-based backup power, and support decarbonization goals. Various storage approaches, including electrochemical, thermal, mechanical, and chemical methods, have demonstrated potential in addressing the challenges associated with energy variability and system stability. Advances in materials science, artificial intelligence, and hybrid storage systems continue to refine LDES performance, increasing efficiency and cost-effectiveness.

Despite the promising benefits, multiple challenges hinder the widespread adoption of LDES. High capital costs and the levelized cost of storage (LCOS) remain key economic barriers, limiting large-scale deployment. Technological constraints such as efficiency losses, degradation, and operational limitations affect performance and long-term feasibility. Infrastructure-related concerns, including land use and environmental impacts, require careful consideration to optimize deployment. Regulatory uncertainties and the lack of well-defined market incentives further complicate investment in LDES solutions. Addressing these issues demands targeted research, industrial collaborations, and supportive policy frameworks that enhance financial viability while accelerating technological advancements.

A coordinated effort among governments, research institutions, and private stakeholders is essential to unlock the full potential of LDES. Policymakers must develop structured regulatory mechanisms that incentivize investment, while technological advancements should focus on improving efficiency, scalability, and lifecycle sustainability. Future innovations in hydrogen storage, ammonia-based fuels, and multi-modal storage systems hold the potential to drive the next wave of LDES evolution. As the energy transition progresses, establishing an integrated approach that combines policy support, market incentives, and breakthrough research will be instrumental in realizing a resilient and sustainable energy future.

Compliance with ethical standards

Acknowledgments

The authors wish to acknowledge the collaborative effort of all contributing scholars and colleagues who jointly authored and edited this review paper. This work was conducted entirely through the intellectual and academic contributions of the authoring team, without external funding or assistance from any individual, institution, or organization.

Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., ... & Jaszczur, M. (2024). The renewable energy role in the global energy Transformations. Renewable Energy Focus, 48, 100545.

[2] Kabeyi, M. J. B., & Olanrewaju, O. A. (2022). Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Frontiers in Energy research, 9, 743114.

[3] Basit, M. A., Dilshad, S., Badar, R., & Sami ur Rehman, S. M. (2020). Limitations, challenges, and solution approaches in grid-connected renewable energy systems. International Journal of Energy Research, 44(6), 4132-4162.

[4] Barth, A., González, D., Gonzalez, J. L., Hanzlík, V., Pinheiro, G., Tai, H., & Weiss, A. (2024, February 8). How grid operators can integrate the coming wave of renewable energy. McKinsey & Company. https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/how-grid-operators-can-integrate-the-coming-wave-of-renewable-energy

[5] Pacific Northwest National Laboratory. (n.d.). Renewable Integration. Retrieved March 29, 2025, from https://www.pnnl.gov/explainer-articles/renewable-integration

[6] Shan, R., Reagan, J., Castellanos, S., Kurtz, S., & Kittner, N. (2022). Evaluating emerging long-duration energy storage technologies. Renewable and Sustainable Energy Reviews, 159, 112240.

[7] Aspitarte, L., & Woodside, C. R. (2024). A techno-economic survey of energy storage media for long-duration energy storage applications. Cell Reports Sustainability, 1(1).

[8] LDES Council. (n.d.). The Long Duration Energy Storage Council. https://www.ldescouncil.com/

[9] Long-Duration Energy Storage Council. (2024, May). Industrial decarbonization: The critical role of long-duration energy storage in global net zero goals. LDES Council.

[10] Pacific Northwest National Laboratory. (2023, May 25). Long-duration energy storage: The time is now. https://www.pnnl.gov/news-media/long-duration-energy-storage-time-now

[11] Zhu, X., Zhang, X., Gong, P., & Li, Y. (2023). A review of distributed energy system optimization for building decarbonization. Journal of Building Engineering, 73, 106735.

[12] Albertus, P., Manser, J. S., & Litzelman, S. (2020). Long-duration electricity storage applications, economics, and technologies. Joule, 4(1), 21-32.

[13] Guven, A. F., Abdelaziz, A. Y., Samy, M. M., & Barakat, S. (2024). Optimizing energy Dynamics: A comprehensive analysis of hybrid energy storage systems integrating battery banks and supercapacitors. Energy Conversion and Management, 312, 118560.

[14] Park, M., Ryu, J., Wang, W., & Cho, J. (2016). Material design and engineering of next-generation flow-battery technologies. Nature Reviews Materials, 2(1), 1-18.

[15] Ragupathy, P., Bhat, S. D., & Kalaiselvi, N. (2023). Electrochemical energy storage and conversion: An overview. Wiley Interdisciplinary Reviews: Energy and Environment, 12(2), e464.

[16] Olabi, A. G., Allam, M. A., Abdelkareem, M. A., Deepa, T. D., Alami, A. H., Abbas, Q., ... & Sayed, E. T. (2023). Redox flow batteries: recent development in main components, emerging technologies, diagnostic techniques, large-scale applications, and challenges and barriers. Batteries, 9(8), 409.

[17] Dassisti, M., Mastrorilli, P., Rizzuti, A., Cozzolino, G., Chimienti, M., Olabi, A. G., ... & Ramadan, M. (2021). Vanadium: A transition metal for sustainable energy storing in redox flow batteries. Encyclopedia of Smart Materials, 208-229.

[18] Yuan, X. Z., Song, C., Platt, A., Zhao, N., Wang, H., Li, H., ... & Jang, D. (2019). A review of all-vanadium redox flow battery durability: Degradation mechanisms and mitigation strategies. International Journal of Energy Research, 43(13), 6599-6638.

[19] Wang, Y., Mu, A., Wang, W., Yang, B., & Wang, J. (2024). A Review of Capacity Decay Studies of All-vanadium Redox Flow Batteries: Mechanism and State Estimation. ChemSusChem, 17(14), e202301787.

[20] Su, L., Kowalski, J. A., Carroll, K. J., & Brushett, F. R. (2015). Recent developments and trends in redox flow batteries. Rechargeable Batteries: Materials, Technologies and New Trends, 673-712.

[21] Tan, R., Wang, A., Malpass-Evans, R., Williams, R., Zhao, E. W., Liu, T., ... & Song, Q. (2020). Hydrophilic microporous membranes for selective ion separation and flow-battery energy storage. Nature materials, 19(2), 195-202.

[22] Li, L., Zhang, X., Lu, Y., Chen, X., Cheng, H., & Lu, Y. (2024). Recent advances and future perspectives of membranes in iron-based aqueous redox flow batteries. Energy Material Advances, 5, 0118.

[23] Li, W., & Jin, S. (2020). Design principles and developments of integrated solar flow batteries. Accounts of Chemical Research, 53(11), 2611-2621.

[24] Zheng, M., Sun, J., Meinrenken, C. J., & Wang, T. (2019). Pathways toward enhanced techno-economic performance of flow battery systems in energy system applications. Journal of Electrochemical Energy Conversion and Storage, 16(2), 021001.

[25] Kanti Hazra, S., Kim, H., Meskher, H., Singh, P., Kansara, S., Kumar Thakur, A., ... & Hwang, J. Y. (2024). Lithium-free redox flow batteries: challenges and future prospective for safe and efficient energy storage. Batteries & Supercaps, 7(7), e202400100.

[26] Cavus, M., Dissanayake, D., & Bell, M. (2025). Next Generation of Electric Vehicles: AI-Driven Approaches for Predictive Maintenance and Battery Management. Energies, 18(5), 1041.

[27] Zhou, T., Gui, C., Sun, L., Hu, Y., Lyu, H., Wang, Z., ... & Yu, G. (2023). Energy applications of ionic liquids: recent developments and future prospects. Chemical Reviews, 123(21), 12170-12253.

[28] Zou, X., Lu, Q., Liao, K., & Shao, Z. (2022). Towards practically accessible aprotic Li-air batteries: Progress and challenges related to oxygen-permeable membranes and cathodes. Energy Storage Materials, 45, 869-902.

[29] Das, S., Kundu, A., Kuila, T., & Murmu, N. C. (2023). Recent advancements on designing transition metal-based carbon-supported single atom catalysts for oxygen electrocatalysis: Miles to go for sustainable Zn-air batteries. Energy Storage Materials, 61, 102890.

[30] Liu, Q., Pan, Z., Wang, E., An, L., & Sun, G. (2020). Aqueous metal-air batteries: Fundamentals and applications. Energy Storage Materials, 27, 478-505.

[31] Dilshad, K. A. J., & Rabinal, M. K. (2023). Review on Molecularly Controlled Design of Electrodes for Metal–Air Batteries: Fundamental Concepts and Future Directions. Energy & Fuels, 37(8), 5689-5711.

[32] Shahzad, K., & Cheema, I. I. (2024). Aluminum batteries: Unique potentials and addressing key challenges in energy storage. Journal of Energy Storage, 90, 111795.

[33] Rajore, S. M., Kanwade, A. R., Satrughna, J. A. K., Tiwari, M. K., & Shirage, P. M. (2024). A comprehensive review on advancements in catalysts for aluminum-air batteries. Journal of Power Sources, 616, 235101.

[34] Lei, J., Gao, Z., Tang, L., Zhong, L., Li, J., Zhang, Y., & Liu, T. (2022). Coupling Water-Proof Li Anodes with LiOH-Based Cathodes Enables Highly Rechargeable Lithium–Air Batteries Operating in Ambient Air. Advanced Science, 9(4), 2103760.

[35] Yang, D., Tan, H., Rui, X., & Yu, Y. (2019). Electrode materials for rechargeable zinc-ion and zinc-air batteries: current status and future perspectives. Electrochemical Energy Reviews, 2, 395-427.

[36] Iqbal, A., El-Kadri, O. M., & Hamdan, N. M. (2023). Insights into rechargeable Zn-air batteries for future advancements in energy storing technology. Journal of Energy Storage, 62, 106926.

[37] Wang, Q., Kaushik, S., Xiao, X., & Xu, Q. (2023). Sustainable zinc–air battery chemistry: advances, challenges and prospects. Chemical Society Reviews, 52(17), 6139-6190.

[38] Meng, F. L., Liu, K. H., Zhang, Y., Shi, M. M., Zhang, X. B., Yan, J. M., & Jiang, Q. (2018). Recent advances toward the rational design of efficient bifunctional air electrodes for rechargeable Zn–air batteries. Small, 14(32), 1703843.

[39] Nazir, G., Rehman, A., Lee, J. H., Kim, C. H., Gautam, J., Heo, K., ... & Park, S. J. (2024). A review of rechargeable zinc–air batteries: Recent progress and future perspectives. Nano-Micro Letters, 16(1), 138.

[40] Wu, S., Zhang, Q., Ma, J., Sun, D., Tang, Y., & Wang, H. J. M. T. E. (2020). Interfacial design of Al electrode for efficient aluminum-air batteries: issues and advances. Materials Today Energy, 18, 100499.

[41] Nayem, S. A., Islam, S., Mohamed, M., Shaheen Shah, S., Ahammad, A. S., & Aziz, M. A. (2024). A Mechanistic Overview of the Current Status and Future Challenges of Aluminum Anode and Electrolyte in Aluminum-Air Batteries. The Chemical Record, 24(1), e202300005.

[42] Ikeuba, A. I., Njoku, C. N., Ekerenam, O. O., Njoku, D. I., Udoh, I. I., Daniel, E. F., ... & Okonkwo, B. O. (2024). A review of the electrochemical and galvanic corrosion behavior of important intermetallic compounds in the context of aluminum alloys. RSC advances, 14(43), 31921-31953.

[43] Ikeuba, A. I., Iwuji, P. C., Nabuk, I. I. E., Obono, O. E., Charlie, D., Etim, A. A., ... & Amajama, J. (2024). Advances on lithium, magnesium, zinc, and iron-air batteries as energy delivery devices—a critical review. Journal of Solid State Electrochemistry, 28(9), 2999-3025.

[44] GreenPower Nigeria. (2023). Form Energy to deploy 100-hour iron-air battery system in Georgia. GreenPower Nigeria.

[45] McKerracher, R. D., Ponce de Leon, C., Wills, R. G. A., Shah, A. A., & Walsh, F. C. (2015). A review of the iron–air secondary battery for energy storage. ChemPlusChem, 80(2), 323-335.

[46] Wang, Q., Kaushik, S., Xiao, X., & Xu, Q. (2023). Sustainable zinc–air battery chemistry: advances, challenges and prospects. Chemical Society Reviews, 52(17), 6139-6190.

[47] Lu, Y. T. (2022). Oxygen Electrochemistry in Divalent Metal-Air Batteries. The University of Liverpool (United Kingdom).

[48] Michaelides, E. E. (2021). Thermodynamics, energy dissipation, and figures of merit of energy storage systems—A critical review. Energies, 14(19), 6121.

[49] Mahfoud, R. J., Alkayem, N. F., Zhang, Y., Zheng, Y., Sun, Y., & Alhelou, H. H. (2023). Optimal operation of pumped hydro storage-based energy systems: A compendium of current challenges and future perspectives. Renewable and Sustainable Energy Reviews, 178, 113267.

[50] Alnaqbi, S. A., Alasad, S., Aljaghoub, H., Alami, A. H., Abdelkareem, M. A., & Olabi, A. G. (2022). Applicability of hydropower generation and pumped hydro energy storage in the Middle East and North Africa. Energies, 15(7), 2412.

[51] Ji, X. (2019). A paradigm of storage batteries. Energy & Environmental Science, 12(11), 3203-3224.

[52] Gür, T. M. (2018). Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. Energy & environmental science, 11(10), 2696-2767.

[53] Barbour, E., Wilson, I. G., Radcliffe, J., Ding, Y., & Li, Y. (2016). A review of pumped hydro energy storage development in significant international electricity markets. Renewable and sustainable energy reviews, 61, 421-432.

[54] International Water Power & Dam Construction. (2024, May 17). Glen Earrach Energy announces £3 Billion Loch Ness pumped storage project. https://www.waterpowermagazine.com/news/glen-earrach-energy-announces-3-billion-loch-ness-pumped-storage-project/

[55] Mahela, O. P., & Shaik, A. G. (2016). Comprehensive overview of grid interfaced wind energy generation systems. Renewable and Sustainable Energy Reviews, 57, 260-281.

[56] Lu, X., & Wang, S. (2017). A GIS-based assessment of Tibet's potential for pumped hydropower energy storage. Renewable and Sustainable Energy Reviews, 69, 1045-1054.

[57] Carrell, S. (2025, March 12). Balance of power: Loch Ness hydro storage schemes fuel local anxiety. The Guardian. https://www.theguardian.com/environment/2025/mar/12/loch-ness-hydro-storage-schemes-scotland

[58] Pacific Northwest National Laboratory. (2013). Techno-economic performance evaluation of compressed air energy storage in the Pacific Northwest. U.S. Department of Energy. Retrieved from https://caes.pnnl.gov/pdf/PNNL-22235.pdf

[59] Murray, C. (2024, April 10). 'World's largest' compressed air energy storage project connects to the grid in China. Energy Storage News.

[60] Olabi, A. G., Wilberforce, T., Ramadan, M., Abdelkareem, M. A., & Alami, A. H. (2021). Compressed air energy storage systems: Components and operating parameters–A review. Journal of Energy Storage, 34, 102000.

[61] Jia, Q., Liu, T., Chen, X., Chen, L., Si, Y., & Mei, S. (2021). Optimized regulation of hybrid adiabatic compressed air energy storage system for zero-carbon-emission micro-energy network. Frontiers in Energy Research, 9, 745457.

[62] Wikipedia contributors. (2025, March 11). Compressed-air energy storage. In Wikipedia, The Free Encyclopedia. Retrieved 13:51, March 31, 2025, from https://en.wikipedia.org/w/index.php?title=Compressed-air_energy_storage&oldid=1280005943

[63] Rabi, A. M., Radulovic, J., & Buick, J. M. (2023). Comprehensive review of liquid air energy storage (LAES) technologies. Energies, 16(17), 6216.

[64] Liang, T., Zhang, T., Lin, X., Alessio, T., Legrand, M., He, X., ... & Ding, Y. (2023). Liquid air energy storage technology: a comprehensive review of research, development and deployment. Progress in Energy, 5(1), 012002.

[65] Wen, N., & Tan, H. (2022). Modelling and optimization of liquid air energy storage systems with different liquefaction cycles. Energy Conversion and Management, 271, 116321.

[66] Yang, Y., Tong, L., Liu, Y., Guo, W., Wang, L., Qiu, Y., & Ding, Y. (2023). A novel integrated system of hydrogen liquefaction process and liquid air energy storage (LAES): energy, exergy, and economic analysis. Energy Conversion and Management, 280, 116799.

[67] Vecchi, A., Li, Y., Ding, Y., Mancarella, P., & Sciacovelli, A. (2021). Liquid air energy storage (LAES): A review on technology state-of-the-art, integration pathways and future perspectives. Advances in Applied Energy, 3, 100047.

[68] Liang, T., Zhang, T., Lin, X., Alessio, T., Legrand, M., He, X., ... & Ding, Y. (2023). Liquid air energy storage technology: a comprehensive review of research, development and deployment. Progress in Energy, 5(1), 012002.

[69] Burian, O., & Dančová, P. (2023). Compressed air energy storage (CAES) and liquid air energy storage (LAES) technologies—a comparison review of technology possibilities. Processes, 11(11), 3061.

[70] Damak, C., Leducq, D., Hoang, H. M., Negro, D., & Delahaye, A. (2020). Liquid Air Energy Storage (LAES) as a large-scale storage technology for renewable energy integration–A review of investigation studies and near perspectives of LAES. International Journal of Refrigeration, 110, 208-218.

[71] Ali, S., Stewart, R. A., Sahin, O., & Vieira, A. S. (2023). Integrated GIS-AHP-based approach for off-river pumped hydro energy storage site selection. Applied Energy, 337, 120914.

[72] Sayed, E. T., Olabi, A. G., Alami, A. H., Radwan, A., Mdallal, A., Rezk, A., & Abdelkareem, M. A. (2023). Renewable energy and energy storage systems. Energies, 16(3), 1415.

[73] Suberu, M. Y., Mustafa, M. W., & Bashir, N. (2014). Energy storage systems for renewable energy power sector integration and mitigation of intermittency. Renewable and Sustainable Energy Reviews, 35, 499-514.

[74] Elkhatat, A., & Al-Muhtaseb, S. A. (2023). Combined "renewable energy–thermal energy storage (RE–TES)" systems: a review. Energies, 16(11), 4471.

[75] Atomistic Simulation & Energy Research Group. Thermal Energy Grid Storage (TEGS) Concept. Available online: https://ase.mit.edu/projects/thermal-energy-grid-storage-tegs/ (accessed on 31 March 2025).

[76] Amy, C.; Seyf, H.R.; Steiner, M.A.; Friedman, D.J.; Henry, A. Thermal energy grid storage using multi-junction photovoltaics. Energy Environ. Sci. 2019, 12, 334–343.

[77] Abir, F. M., Altwarah, Q., Rana, M. T., & Shin, D. (2024). Recent advances in molten salt-based nanofluids as thermal energy storage in concentrated solar power: A comprehensive review. Materials, 17(4), 955.

[78] González-Roubaud, E., Pérez-Osorio, D., & Prieto, C. (2017). Review of commercial thermal energy storage in concentrated solar power plants: Steam vs. molten salts. Renewable and sustainable energy reviews, 80, 133-148.

[79] Energy Monitor. (2012, April 29). Gemasolar Concentrated Solar Power, Seville. https://www.energymonitor.ai/projects/gemasolar-concentrated-solar-power-seville/

[80] Internationale Klimaschutzinitiative (IKI). (2021, June 11). First CSP plant in South America. Internationale Klimaschutzinitiative (IKI). https://www.international-climate-initiative.com/en/iki-media/news/first_csp_plant_in_south_america/

[81] de Figueiredo Luiz, D., Boon, J., Rodriguez, G. O., & van Sint Annaland, M. (2024). Review of the molten salt technology and assessment of its potential to achieve an energy efficient heat management in a decarbonized chemical industry. Chemical Engineering Journal, 155819.

[82] Nazir, H., Batool, M., Osorio, F. J. B., Isaza-Ruiz, M., Xu, X., Vignarooban, K., ... & Kannan, A. M. (2019). Recent developments in phase change materials for energy storage applications: A review. International Journal of Heat and Mass Transfer, 129, 491-523.

[83] Shu, G., Xiao, T., Guo, J., Wei, P., Yang, X., & He, Y. L. (2023). Effect of charging/discharging temperatures upon melting and solidification of PCM-metal foam composite in a heat storage tube. International Journal of Heat and Mass Transfer, 201, 123555.

[84] Jarimi, H., Aydin, D., Yanan, Z., Ozankaya, G., Chen, X., & Riffat, S. (2019). Review on the recent progress of thermochemical materials and processes for solar thermal energy storage and industrial waste heat recovery. International Journal of Low-Carbon Technologies, 14(1), 44-69.

[85] Zhang, C., Pomianowski, M., Heiselberg, P. K., & Yu, T. (2020). A review of integrated radiant heating/cooling with ventilation systems-Thermal comfort and indoor air quality. Energy and Buildings, 223, 110094.

[86] Royo, P., Acevedo, L., Ferreira, V. J., García-Armingol, T., López-Sabirón, A. M., & Ferreira, G. (2019). High-temperature PCM-based thermal energy storage for industrial furnaces installed in energy-intensive industries. Energy, 173, 1030-1040.

[87] Dal Magro, F., Xu, H., Nardin, G., & Romagnoli, A. (2018). Application of high temperature phase change materials for improved efficiency in waste-to-energy plants. Waste Management, 73, 322-331.

[88] Memon, S. A., Cui, H. Z., Zhang, H., & Xing, F. (2015). Utilization of macro encapsulated phase change materials for the development of thermal energy storage and structural lightweight aggregate concrete. Applied Energy, 139, 43-55.

[89] Gautam, A., & Saini, R. P. (2020). A review on sensible heat based packed bed solar thermal energy storage system for low temperature applications. Solar Energy, 207, 937-956.

[90] Zeng, Y., Zhou, T., Wang, T., Zhang, M., Zhang, S., & Yang, H. (2025). Long-Duration Energy Storage: A Critical Enabler for Renewable Integration and Decarbonization. Energies, 18(3), 466.

[91] Lin, A., & Bagnato, G. (2024). Revolutionising energy storage: The Latest Breakthrough in liquid organic hydrogen carriers. International Journal of Hydrogen Energy, 63, 315-329.

[92] Mehrjerdi, H., Saboori, H., & Jadid, S. (2022). Power-to-gas utilization in optimal sizing of hybrid power, water, and hydrogen microgrids with energy and gas storage. Journal of Energy Storage, 45, 103745.

[93] Hossain, M. A., Islam, M. R., Hossain, M. A., & Hossain, M. J. (2023). Control strategy review for hydrogen-renewable energy power system. Journal of Energy Storage, 72, 108170.

[94] Beckford, T., Jackson-Johns, G., Daoud, A., Finn, G., & Dowden, T. (2023). The Role of Hydrogen and Batteries in Delivering Net Zero in the UK by 2050.

[95] Arent, D. J., Green, P., Abdullah, Z., Barnes, T., Bauer, S., Bernstein, A., ... & Turchi, C. (2022). Challenges and opportunities in decarbonizing the US energy system. Renewable and Sustainable Energy Reviews, 169, 112939.

[96] Rusman, N. A. A., & Dahari, M. (2016). A review on the current progress of metal hydrides material for solid-state hydrogen storage applications. International Journal of Hydrogen Energy, 41(28), 12108-12126.

[97] Hamdy, S. (2019). Cryogenic energy storage systems: An exergy-based evaluation and optimization. Technische Universitaet Berlin (Germany).

[98] Lin, A., & Bagnato, G. (2024). Revolutionising energy storage: The Latest Breakthrough in liquid organic hydrogen carriers. International Journal of Hydrogen Energy, 63, 315-329.

[99] Sun, H., Wang, Z., Meng, Q., & White, S. (2025). Advancements in hydrogen storage technologies: Enhancing efficiency, safety, and economic viability for sustainable energy transition. International Journal of Hydrogen Energy, 105, 10-22.

[100] Aziz, M., Wijayanta, A. T., & Nandiyanto, A. B. D. (2020). Ammonia as effective hydrogen storage: A review on production, storage and utilization. Energies, 13(12), 3062.

[101] Stocks, M., Fazeli, R., Hughes, L., & Beck, F. J. (2022). Global emissions implications from co-combusting ammonia in coal fired power stations: An analysis of the Japan-Australia supply chain. Journal of Cleaner Production, 336, 130092.

[102] Chavando, A., Silva, V., Cardoso, J., & Eusebio, D. (2024). Advancements and challenges of ammonia as a sustainable fuel for the maritime industry. Energies, 17(13), 3183.

[103] Dell'Aversano, S., Villante, C., Gallucci, K., Vanga, G., & Di Giuliano, A. (2024). E-fuels: a comprehensive review of the most promising technological alternatives towards an energy transition. Energies, 17(16), 3995.

[104] Javadi, E. A., Joorabian, M., & Barati, H. (2022). A sustainable framework for resilience enhancement of integrated energy systems in the presence of energy storage systems and fast-acting flexible loads. Journal of Energy Storage, 49, 104099.

[105] Čuček, L., Klemeš, J. J., & Kravanja, Z. (2012). Carbon and nitrogen trade-offs in biomass energy production. Clean Technologies and Environmental Policy, 14, 389-397.

[106] Liang, X. (2016). Emerging power quality challenges due to integration of renewable energy sources. IEEE Transactions on Industry Applications, 53(2), 855-866.

[107] Stephanie, F., & Karl, L. (2020). Incorporating Renewable Energy Systems for a New Era of Grid Stability. Fusion of Multidisciplinary Research, An International Journal, 1(01), 37-49.

[108] Zang, T., Wang, S., Wang, Z., Li, C., Liu, Y., Xiao, Y., & Zhou, B. (2024). Integrated planning and operation dispatching of source–grid–load–storage in a new power system: A coupled socio–cyber–physical perspective. Energies, 17(12), 3013.

[109] Edison Electric Institute. (n.d.). Issues & Policy in Energy storage. https://www.eei.org/en/issues-and-policy/energy-storage

[110] InfoLink. (2025, February 3). Understanding long duration energy storage: Technologies shaping the future of energy. InfoLink. https://www.infolink-group.com/energy-article/Long-Duration-Energy-Storage

[111] Anderson, A. (n.d.). Long-duration energy storage for clean energy. Greenhouse Communications. Retrieved April 2, 2025, from https://greenhouse.agency/blog/long-duration-energy-storage-clean-energy-future/

[112] Zhu, Z., Jiang, T., Ali, M., Meng, Y., Jin, Y., Cui, Y., & Chen, W. (2022). Rechargeable batteries for grid scale energy storage. Chemical Reviews, 122(22), 16610-16751.

[113] Escamilla, A., Sánchez, D., & García-Rodríguez, L. (2022). Assessment of power-to-power renewable energy storage based on the smart integration of hydrogen and micro gas turbine technologies. International Journal of Hydrogen Energy, 47(40), 17505-17525.

[114] McNamara, J. W., DeAngelis, V., Byrne, R. H., Benson, A., Chalamala, B. R., & Masiello, R. (2022). Long-duration energy storage in a decarbonized future: Policy gaps, needs, and opportunities. MRS Energy & Sustainability, 9(2), 142-170.

[115] Shen, C., Zhu, W., Tang, X., Du, W., Wang, Z., Xu, S., & Yao, K. (2024). Risk assessment and resilience enhancement strategies for urban power supply-demand imbalance affected by extreme weather: A case study of Beijing. International Journal of Disaster Risk Reduction, 106, 104471.

[116] CSE. (2025, February 12). How battery storage is powering California's solar revolution. Centre for Sustainability and Excellence. https://cse-net.org/california-solar-battery-storage-growth/

[117] Kyon Energy. (2023, August 17). How energy storage devices avoid blackouts. Kyon Energy. https://www.kyon-energy.de/en/blog/wie-energiespeicher-blackouts-vermeiden

[118] Hitachi Energy. (2019, December). Avoiding blackouts due to immediate support from battery energy storage. Hitachi Energy. https://www.hitachienergy.com/us/en/news-and-events/customer-success-stories/avoiding-blackouts-due-to-immediate-support-from-battery-energy-storage

[119] National Electrical Manufacturers Association. (n.d.). The Role of Energy Storage in Disaster Recovery and Prevention. NEMA. Retrieved from https://www.nema.org/storm-disaster-recovery/microgrids-and-energy-storage/the-role-of-energy-storage-in-disaster-recovery-and-prevention

[120] Rahman, A., Farrok, O., & Haque, M. M. (2022). Environmental impact of renewable energy source based electrical power plants: Solar, wind, hydroelectric, biomass, geothermal, tidal, ocean, and osmotic. Renewable and sustainable energy reviews, 161, 112279.

[121] Shahzad, S., Abbasi, M. A., Shahid, M. B., & Guerrero, J. M. (2024). Unlocking the potential of long-duration energy storage: Pathways to net-zero emissions through global innovation and collaboration. Journal of Energy Storage, 97, 112904.

[122] Adeyinka, A. M., Esan, O. C., Ijaola, A. O., & Farayibi, P. K. (2024). Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration. Sustainable Energy Research, 11(1), 26.

[123] Shafiei, K., Zadeh, S. G., & Hagh, M. T. (2024). Planning for a network system with renewable resources and battery energy storage, focused on enhancing resilience. Journal of Energy Storage, 87, 111339.

[124] International Renewable Energy Agency. (2023). World Energy Transitions Outlook 2023: 1.5°C Pathway. https://www.irena.org/Digital-Report/World-Energy-Transitions-Outlook-2023

[125] U.S. Department of Energy. (2024). Achieving the promise of low-cost long duration energy storage. https://www.energy.gov/sites/default/files/2024-08/Achieving%20the%20Promise%20of%20Low-Cost%20Long%20Duration%20Energy%20Storage_FINAL_08052024.pdf

[126] Martucci, B. (2024, August 13). Further innovation required to achieve $0.05/kWh target for long-duration storage: DOE. Utility Dive. https://www.utilitydive.com/news/innovation-long-duration-energy-storage-cost-reduction-flow-battery-compressed-air-pumped-hydro/724121/

[127] Long Duration Energy Storage Council, & McKinsey & Company. (2021). Net-zero power: Long-duration energy storage for a renewable grid. McKinsey & Company. https://www.mckinsey.com/capabilities/sustainability/our-insights/net-zero-power-long-duration-energy-storage-for-a-renewable-grid

[128] Clima Now. (2024). Deep Dive: Long Duration Energy Storage. Clima Now. https://climanow.ch/media/cabinet/2024/04/ClimaNow_Deep_Dive_Long_Duration_Energy_Storage_202404.pdf

[129] Center for Sustainable Systems. (2023). U.S. grid energy storage factsheet. University of Michigan. https://css.umich.edu/publications/factsheets/energy/us-grid-energy-storage-factsheet

[130] Ho, C. (2021). The Value of Long-Duration Energy Storage: Policy and Perception (Conference presentation). Sandia National Laboratories. https://www.osti.gov/biblio/1889548

[131] Selänniemi, A., Hellström, M., & Björklund-Sänkiaho, M. (2025). Long-duration energy storage technology adoption: Insights from US energy industry experts. Energy Reports, 13, 378-396.

[132] Adnan, M., Zahid, H., Zulfiqar, A., Iqbal, M. S., Shah, A., & Fida, K. (2024). Global Renewable Energy Transition: A Multidisciplinary Analysis of Emerging Computing Technologies, Socio-Economic Impacts, and Policy Imperatives.

[133] Smdani, G., Islam, M. R., Ahmad Yahaya, A. N., & Bin Safie, S. I. (2023). Performance evaluation of advanced energy storage systems: a review. Energy & Environment, 34(4), 1094-1141.

[134] Bashir, S., & Liu, J. L. (2024). Design and evaluations of nano-ceramic electrolytes used for solid-state lithium battery. npj Materials Sustainability, 2(1), 37.

[135] Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T. C., & Madyira, D. M. (2024). Optimizing renewable energy systems through artificial intelligence: Review and future prospects. Energy & Environment, 35(7), 3833-3879.

[136] Jabakumar, A. K. (2024). Optimizing Energy Storage Systems with AI-Based Control Strategies. Research Journal of Computer Systems and Engineering, 5(1), 95-105.

[137] Adebayo, D. H., Ajiboye, J. A., Okwor, U. D., Muhammad, A. L., Ugwuijem, C. D., Agbo, E. K., & Stephen, V. I. (2025). Optimizing energy storage for electric grids: Advances in hybrid technologies. management, 10, 11.

[138] Lin, A., & Bagnato, G. (2024). Revolutionising energy storage: The Latest Breakthrough in liquid organic hydrogen carriers. International Journal of Hydrogen Energy, 63, 315-329.

[139] Qasem, N. A., & Abdulrahman, G. A. (2024). A recent comprehensive review of fuel cells: history, types, and applications. International Journal of Energy Research, 2024(1), 7271748.

[140] Asif, M., Bibi, S. S., Ahmed, S., Irshad, M., Hussain, M. S., Zeb, H., ... & Kim, J. (2023). Recent advances in green hydrogen production, storage and commercial-scale use via catalytic ammonia cracking. Chemical Engineering Journal, 473, 145381.

[141] Herrmann, S., Kahlert, S., Wuerth, M., & Spliethoff, H. (2017). Thermo-economic evaluation of novel flexible caes/ccpp concept. Journal of Energy Resources Technology, 139(1), 011902.

[142] Mohanty, P., Chojkiewicz, E., Sarkar, E. M., Laumas, R., Saraf, A., Satheesh, A., & Abhyankar, N. (2023). Review of Grid-Scale Energy Storage Technologies Globally and in India.

[143] Matos, C. R., Silva, P. P., & Carneiro, J. F. (2022). Overview of compressed air energy storage projects and regulatory framework for energy storage. Journal of Energy Storage, 55, 105862.

[144] Zhuang, X., Xu, X., Liu, W., & Xu, W. (2019). LCOE analysis of tower concentrating solar power plants using different molten-salts for thermal energy storage in China. Energies, 12(7), 1394.

[145] CNESA Admin. (2024, May 16). China's first vanadium battery industry-specific policy issued. China Energy Storage Alliance. https://en.cnesa.org/new-blog/2024/5/16/chinas-first-vanadium-battery-industry-specific-policy-issued

[146] Government of South Australia. (2025, March 14). The Hydrogen Utility (H2U) Eyre Peninsula Gateway. Energy & Mining. https://www.energymining.sa.gov.au/industry/hydrogen-and-renewable-energy/hydrogen-in-south-australia/hydrogen-projects-in-south-australia/the-hydrogen-utility-h2u-eyre-peninsula-gateway

[147] Khan, M. H. A. (2024). Technical, Environmental and Economic Assessment Frameworks and Tools for Low Emission Hydrogen Production-A Case Study of Australia (Doctoral dissertation, University of New South Wales (Australia)).