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REVIEW

Advances in Energy Storage Technologies for Renewable Energy Systems: Bridging Intermittency and Sustainable Integration

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Abstract

The increasing use of renewable energy sources, such as solar, hydropower, and wind, has prompted the need for advanced energy storage technologies to address the intermittent challenges associated with these sources. Effective energy storage solutions are essential for ensuring grid stability, enhancing energy security, and facilitating the large-scale integration of renewables. The present study explores recent advancements in energy storage technologies, focusing on electrochemical, mechanical, thermal, and hydrogen-based storage systems. Lithium-ion batteries continue to dominate the market due to their high efficiency and energy density. However, emerging alternatives, including solid-state batteries, sodium-ion batteries, and redox flow batteries, offer promising improvements in cost, safety, and sustainability. Hydrogen storage techniques and supercapacitors are also gaining attention as complementary solutions. This study examines the role of hybrid storage systems and smart energy management strategies in optimizing energy utilization. A critical analysis of the latest developments is presented, along with an assessment of existing challenges and future research directions.

Keywords: Renewable energy, Energy storage, Clean technologies, Solar systems, Batteries

1. Introduction

The detrimental effects of climate change on the environment, and the unsustainable nature of fossil fuel resources have necessitated the decarbonization of the energy sector. Over the centuries, fossil fuels have constituted the foundation of global industrial advancement, leading to a significant depletion of their reserves. Emissions from fossil fuel combustion account for approximately 75 % of global greenhouse gas emissions [1–3]. Renewable energy sources provide a clean and sustainable means of energy generation. These include solar, wind, hydroelectric, and geothermal energy, all of which are essential components of global mitigation strategies aimed at addressing climate change [4–8]. However, a complete shift towards a sustainable energy transition has been unrealistic due to several constraints, including intermittency, low energy efficiency, and high startup capital.

Incorporating renewable energy into current energy systems presents significant challenges. Among these, the intermittency of renewable energy sources stands out as a major concern. While fossil fuels can be combusted on demand to generate electricity, renewable resources are constrained by environmental conditions that dictate their availability. Solar energy is limited to daylight hours and further affected by weather fluctuations, whereas wind energy depends on sufficient wind velocities to operate turbines [8–10]. A temporal misalignment between energy generation and consumption poses challenges to grid stability, particularly as renewables become a major component of national and regional energy markets. Addressing intermittency

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often necessitates reliance on supplementary systems such as fossil-fuel-powered plants, which, in turn, diminishes the environmental benefits of transitioning to renewable energy sources [11—13]. Thus, energy storage systems provide a reliable solution to minimize the effects of intermittency. Excess energy generated during peak production periods can be stored in energy storage systems (ESS). The stored energy can be released during times of high demand or low generation, thereby mitigating fluctuations in energy supply and demand. Besides stabilizing the grid, ESS are crucial in enhancing the overall efficiency of renewable energy systems and facilitating the transition to decentralized off-grid renewable energy solutions [14,15]. Table 1 provides an overview of CO_2 emissions across different countries (Table 1 has been adopted from Ahmed et al. [16]).

The data presented in Table 1 reveals the uneven distribution of emissions across different regions of the world, and highlights the urgent need for targeted energy strategies to support climate mitigation. This can be achieved via the deployment of renewable energy systems and energy storage technologies. The United States and European Union collectively contribute approximately 47 % of global CO_2 emissions, reflecting their historically high dependence on fossil fuels. Despite advancements in renewable energy adoption, their continued emission levels indicate the need for accelerated integration of large-scale ESS to enhance grid reliability, minimize fossil fuel backup reliance, and support de-carbonization goals. China, accounting for 12.7 % of global emissions, is a unique case, being both the largest absolute emitter and the leading investor in renewable energy. Its coal-dominant energy mix and rapid industrialization necessitate widespread deployment of long-duration and grid-scale ESS to address variability in renewable energy generation. India and Brazil, with contributions of 3 and 0.9 % respectively, are representative of rapidly growing economies with increasing energy demands. These countries have the opportunity to avoid fossil fuel dependency by integrating decentralized renewable energy systems supported by scalable and cost-effective storage technologies. High-emission countries with significant fossil fuel reserves, such as the Russian Federation, Iran, Saudi Arabia, and South Africa, contribute between 6 and 1.3 % of global emissions. Despite their renewable potential, the slow adoption of ESS in these regions has limited the effectiveness of renewable integration, often necessitating continued reliance on fossil fuel-based peaking systems. Other contributors such as Canada, Mexico, Australia, and Ukraine, each accounting for between 1 and 2 % of global emissions, face distinct energy challenges related to infrastructure, policy, or geopolitical factors. In these contexts, modular and hybrid ESS can provide critical support in stabilizing energy systems, promoting energy independence, and enabling the transition to decentralized renewable energy networks.

Table 1. Cumulative CO_2 emissions across various countries of the world.

Country	Total CO_2 emissions (Billions Metric Tons)	Percentage (%) CO_2 global emission
United States	399	25
European Union	353	22
People's Republic of China	200	12.7
Russian Federation	101	6
Japan	62	4
India	48	3
Canda	32	2
South Africa	19.8	1.3
Mexico	19	1.2
Ukraine	19	1.2
Australian	17.4	1.1
Iran	17	1
Korea	16	1
Brazil	14.2	0.9
Saudi Arabia	14	0.9

The emission trend in Table 1 also shows a global mismatch between emission responsibility and renewable infrastructure readiness. While some high-emission countries have made progress in clean energy development, others lag behind in implementing energy storage solutions necessary for achieving energy security and sustainability. This highlights the importance of coordinated international efforts, technology transfer, and financial mechanisms to ensure equitable access to advanced energy storage technologies. Integration of renewable energy sources is constrained by their intermittent nature, necessitating robust and flexible energy storage systems. The countries identified in Table 1, regardless of their emission levels, require tailored ESS strategies to align energy supply with demand, ensure grid stability, and support the decarbonization of power systems. Technologies such as lithium-ion, redox flow, solid-state batteries, and hydrogen storage offer scalable solutions suited to different national contexts. Thus, hybrid configurations that combine electrochemical, thermal, and mechanical storage can address complex challenges related to variability and energy management. As countries transition toward cleaner energy systems, the strategic deployment of ESS will be essential in bridging the gap between renewable energy intermittency and long-term sustainability.

This review study employed rigorous literature selection from key scientific databases (Scopus, Web of Science, Google Scholar, and ScienceDirect) using keywords including “renewable energy,” “energy storage,” “solid-state batteries,” and “grid integration.” The search process applied strict inclusion criteria limiting sources to peer-reviewed articles, authoritative reports, patents, and reviews published within the last two decades to ensure currency and reliability. Additionally, both backward and forward citation analyses were conducted to capture seminal works and recent advancements, creating a comprehensive examination that reflects current knowledge while identifying emerging trends and challenges in integrating advanced energy storage systems with renewable energy networks. The present study provides an overview of the current state-of-the-art advancements in energy storage technologies, focusing on their integration with renewable energy systems. It analyzes key breakthroughs in electrochemical, mechanical, chemical, and thermal storage technologies.

2. Renewable energy systems and their storage needs

2.1. Current state of renewable energy deployment

Fig. 1 illustrates the distribution of public awareness regarding various renewable energy sources. The profile reveals notable disparities in recognition, which can influence both the pace of adoption and the effectiveness of policy implementation in the renewable energy sector. Solar energy demonstrates the highest level of public awareness, accounting for 32 % of the total responses. This is likely attributable to the widespread deployment of rooftop solar systems, high media visibility, and growing governmental support through subsidies and incentives. The prominence of solar energy in public discourse and education further reinforces its dominant position in awareness metrics. Wind energy follows with 21 %, reflecting considerable public familiarity due to the increasing visibility of wind turbines in rural and coastal landscapes. Wind projects, particularly in developed countries, have been extensively promoted as sustainable alternatives to conventional power generation, contributing to greater public exposure. Small hydropower and bio-gas technologies account for 20 and 17 %, respectively. These figures suggest moderate awareness, which may be attributed to their more localized applications and limited mainstream visibility. While small hydro systems contribute to rural electrification, their environmental and geographical constraints restrict widespread implementation. Similarly, biogas, though important in agricultural and waste management contexts, remains underrepresented in public narratives related to mainstream energy transition. Waste-to-energy technology records the lowest awareness level at 10 %. This limited recognition reflects the relatively low deployment of such systems in many regions and a general lack of public understanding of their role in circular economy models. Despite its potential to address both energy generation and waste reduction, waste-to-energy is often overlooked due to misconceptions about environmental impacts and operational complexity.

Public perception plays a crucial role in shaping energy policies and community acceptance of renewable projects. Technologies with lower visibility may face greater resistance or slower adoption due to knowledge gaps and misinformation. Therefore, increasing public literacy in emerging renewable technologies, particularly those beyond solar and wind, is essential for fostering broad-based support and accelerating the energy transition [18—20]. From a policy and planning perspective, understanding public awareness trends allows for more effective engagement strategies. Tailored communication, community involvement, and demonstration projects can enhance acceptance and promote behavioral shifts toward sustainable energy

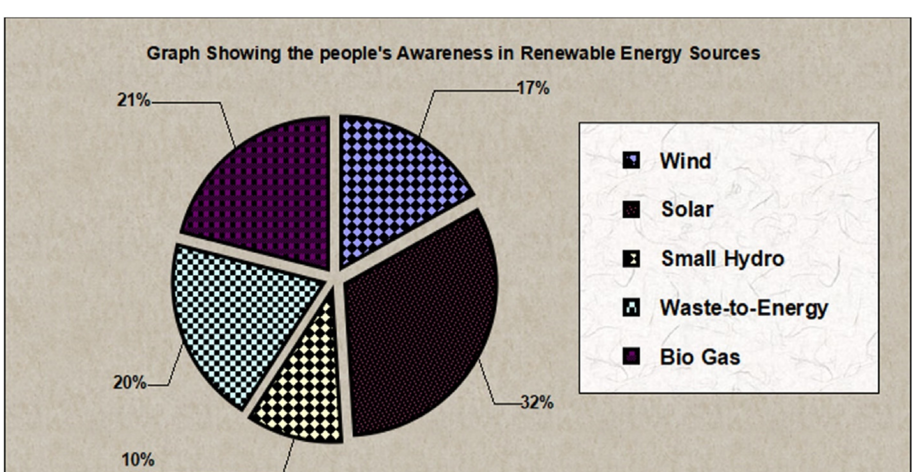

Fig. 1. Graph showing the people's awareness of renewable energy resources [17].

use. Moreover, integrating awareness programs within national energy strategies can bridge the gap between technological advancement and societal readiness, ensuring that innovations in energy storage and generation are matched by informed public support [21,22].

Despite the encouraging levels of awareness for solar and wind energy reflected in Fig. 1, it is important to recognize that public perception may not fully capture the underlying economic and technical advancements driving the energy transition. This advancement is facilitated by the decreasing expenses associated with renewable technology. Since 2010, the Levelized Cost of Energy (LCOE) for solar photovoltaic systems has decreased by almost 85 %, while onshore wind costs have declined by about 50 %, rendering these technologies comparable to or less expensive than fossil fuels in numerous areas [23,24]. These cost reductions have contributed to increased adoption and visibility, which in turn reinforces public awareness, particularly of solar and wind energy. Nevertheless, despite these advancements, a primary hurdle to the incorporation of renewables into energy systems is the variability of energy generation. As discussed, public awareness remains limited for other critical technologies, such as waste-to-energy and biogas, which could play a key role in enhancing energy diversity and stability when integrated with effective energy storage systems.

2.2. Intermittency challenges

Fig. 2 shows the inherent variability and temporal mismatch of renewable energy sources relative to electricity demand. In Fig. 2(A), the seasonal profiles of solar (orange), wind (blue), and demand (black) highlight distinct patterns. Solar energy peaks during mid-year (summer months), corresponding to longer daylight hours, while wind energy exhibits higher variability throughout the year with less predictable spikes and troughs. Notably, demand remains relatively steady with modest seasonal variation, suggesting that neither solar nor wind production consistently aligns with consumption patterns. This is a fundamental challenge, while solar energy generation surges during sunny periods, it may not coincide with the peak electricity demand, particularly in the evening when solar output drops to zero. Fig. 2(B) further emphasizes this mismatch. Solar generation exhibits a well bend curve, peaking around midday when sunlight is most intense, but falling to zero during the evening and nighttime hours, precisely when electricity demand often rises. In contrast, wind energy maintains a more variable profile but does not consistently align with demand peaks either. Demand, represented by the black line, remains relatively stable with modest peaks in the morning and evening, revealing the misalignment with the generation profiles of variable renewables.

The profile in Fig. 2(A and B) illustrates the critical point that renewable energy availability is dictated by environmental conditions that do not necessarily correspond to consumption needs. The disparity between energy supply and demand profiles, both seasonally and within a single day, reinforces the necessity for robust energy storage solutions and grid flexibility. Without such systems, surplus energy during periods of high renewable generation risks being wasted, while shortfalls during peak demand times would require reliance on backup generation, often from fossil fuels. Thus, the profiles vividly demonstrate the operational challenges of integrating high shares of intermittent renewables into the energy system.

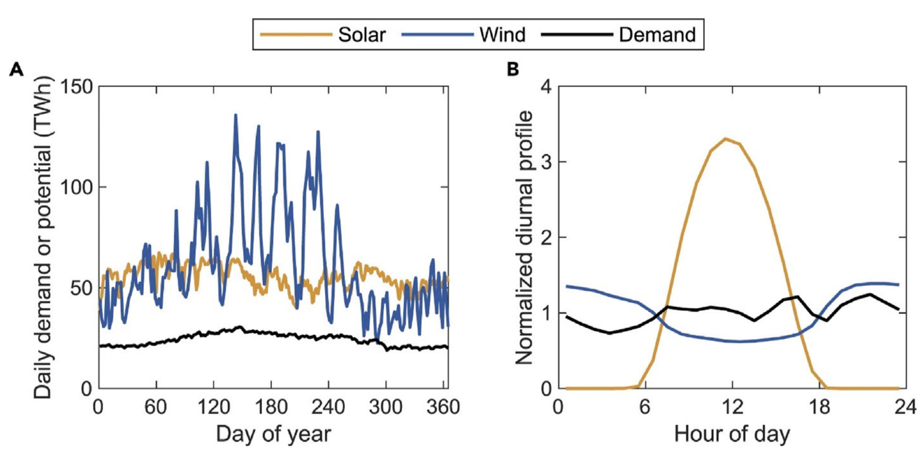

Fig. 2. The potential for national solar and wind power and the demand projections for 2050 are shown in two parts: (A) Daily fluctuations in terawatt-hours (TWh) and (B) the annual average normalized daily profile. The daily profiles are adjusted (y-axis is unitless) based on the 24-h average values [25].

2.3. Energy storage requirements

Energy storage technologies are the key to addressing the intermittency challenges associated with renewable energy sources, paving the way for a reliable, flexible, and sustainable energy system. As renewable generation is inherently variable and often mismatched with consumption patterns, effective storage solutions are indispensable for balancing supply and demand across temporal and spatial scales [26—29]. Any robust energy storage system must satisfy a number of critical technical, economic, and environmental requirements to support widespread deployment and grid integration. These include the following essential criteria:

I. Scalability

Energy storage systems must be inherently versatile, with the capacity to scale across a broad spectrum of applications, from small-scale residential installations to large, utility-level grid support. Residential solar users frequently rely on lithium-ion batteries due to their compact size, high energy density, and ease of integration with rooftop solar panels [30]. However, for utility-scale applications, technologies like Pumped Hydro Storage (PHS) and Compressed Air Energy Storage (CAES) demonstrate greater economic and technical feasibility, owing to their ability to store vast quantities of energy over longer durations [31—33]. The scalability of energy storage systems not only enables wider adoption but also ensures adaptability to diverse regional energy landscapes and evolving demands, which is crucial as energy systems transition toward higher penetrations of renewables.

II. Efficiency

The round-trip efficiency of an energy storage system, which is the ratio of energy retrieved to the energy originally stored, is a critical measure of system performance. High efficiency minimizes energy losses, thereby improving overall system economics and sustainability. Lithium-ion batteries and flywheel energy storage systems are among the leading technologies in this regard, consistently achieving efficiencies between 80 percent and 95 percent [34,35]. These high-efficiency solutions are particularly well-suited for applications requiring rapid charge-discharge cycles, such as frequency regulation and peak shaving. As energy storage technologies evolve, further improvements in efficiency will directly contribute to reducing operational costs and enhancing the feasibility of renewable integration.

III. Cost

While the declining costs of solar photovoltaic and wind energy have made renewable generation increasingly competitive, the high capital expenditures associated with energy storage technologies remain a significant barrier to large-scale deployment. Cost factors include raw materials, manufacturing processes, installation, maintenance, and eventual decommissioning or recycling. Encouragingly, emerging storage solutions such as solid-state batteries and flow batteries are demonstrating the potential for lower lifecycle costs and extended operational lifespans compared to conventional lithium-ion systems [36,37]. Flow batteries, in particular, offer advantages in scalability and durability, making them well-suited for grid-level applications where long-duration storage is required. Continuous innovation and economies of scale are expected to further drive down costs, making storage technologies more accessible and economically viable worldwide.

IV. Sustainability

Despite technical and economic considerations, the environmental footprint of energy storage systems is increasingly recognized as a key factor in their long-term viability. Current concerns include the reliance on finite and geopolitically sensitive resources, such as cobalt and lithium, as well as the environmental impacts associated with mining, manufacturing, and end-of-life disposal. Addressing these issues, research is advancing toward alternative chemistries like sodium-ion and organic batteries, which utilize more abundant and environmentally benign materials [38,39]. Furthermore, advancements in recycling technologies for lithium-ion batteries aim to reduce dependence on virgin materials, decrease manufacturing emissions, and promote circular economy principles within the energy sector. Prioritizing sustainability not only mitigates environmental impacts but also enhances supply chain resilience, a critical factor in the global energy transition.

Table 2 provides detailed information on the requirements of various energy storage systems. Achieving these interconnected criteria of scalability, efficiency, cost-effectiveness, and sustainability, energy storage systems can serve as a vital tool for integrating renewable energy into power systems. As the demand for clean energy solutions continues to accelerate, the role of advanced storage technologies becomes increasingly pivotal in ensuring a resilient, flexible, and low-carbon energy future. Consequently, sustained investment in research, development, and deployment of innovative storage solutions will be essential to realizing the full potential of renewable energy on a global scale.

Table 2. Comparison of energy storage requirements.

Technology	Scalability	Efficiency	Cost	Sustainability	Ref.
Lithium-ion Batteries	Suitable for residential to utility-scale applications	High (80—95 % round-trip efficiency)	Moderate to High (declining with R&D)	Relies on scarce materials like lithium and cobalt; recycling is challenging but improving	[40]
Solid-State Batteries	Promising for grid and high-demand applications	Very High (potentially >95 %)	High (due to nascent stage)	Lower reliance on flammable components; potential for better recyclability	[41]
Flow Batteries	Ideal for large-scale, long-duration storage	Moderate (60—80 % round-trip efficiency)	High (initial investment)	Long lifespan; vanadium extraction poses environmental concerns but can be recycled	[42]
Pumped Hydro Storage	Limited to locations with suitable geography	High (70—85 % efficiency)	Low to Moderate (once installed)	Minimal environmental impact during operation; significant ecological footprint during setup	[43]
Compressed Air Energy Storage (CAES)	Scalable for utility-level storage	Moderate (40—60 % efficiency)	Moderate	Lower material requirements; site-specific environmental impact	[44]
Flywheel Energy Storage	Best for short-term storage and grid frequency regulation	Very High (>85% efficiency)	Moderate	Durable and recyclable; minimal reliance on rare or hazardous materials	[45]
Hydrogen Storage	Highly scalable for grid and transportation	Low to Moderate (30—50% efficiency)	High (electrolysis and storage costs)	Significant potential as a clean energy carrier; challenges with production and storage efficiency	[46]
Molten Salt Storage	Scalable for concentrated solar power (CSP) systems	Moderate (60—70 % efficiency)	Moderate	High recyclability; issues with material corrosion over time	[47]

A critical overview of Table 2 shows that lithium-ion batteries have emerged as a flexible option, effectively bridging residential and utility-scale applications. Their high round-trip efficiency, typically ranging from 80 to 95 %, makes them particularly attractive for integrating intermittent renewables such as solar and wind. However, despite declining costs due to intensive research and development efforts, lithium-ion systems remain constrained by their reliance on scarce materials like lithium and cobalt. Although recycling techniques are advancing, the environmental and geopolitical challenges associated with raw material extraction and processing remain significant concerns. Solid-state batteries represent an evolution of lithium-ion technology, offering even higher efficiencies potentially exceeding 95 % [48]. Their solid electrolytes enhance safety by reducing flammability risks and promise better recyclability. However, these advantages are tempered by their high production costs, which reflect the nascent stage of commercial development. Solid-state batteries hold substantial promises for high-demand applications, including grid-level storage, provided that manufacturing scalability and material sourcing challenges are overcome.

Flow batteries, especially vanadium-based systems, offer an appealing solution for large-scale, long-duration storage. Their capacity is decoupled from power output, allowing independent scaling of energy and power ratings. While they offer a long operational lifespan and recyclability of active materials, their moderate efficiency (60—80 %) and high upfront capital costs are notable drawbacks. Furthermore, environmental concerns associated with vanadium mining and processing warrant continued research into alternative chemistries and recycling methods. Pumped hydro storage (PHS) remains the most established form of large-scale energy storage. It combines high efficiency (70—85%) with low operational costs once installed [49]. However, its applicability is geographically constrained to sites with suitable topography, and initial construction can cause significant ecological disruption. Nonetheless, PHS offers minimal environmental impact during operation and provides essential grid services, making it a cornerstone of many national energy strategies. Compressed air energy storage (CAES) offers utility-scale potential, with moderate costs and lower material intensity compared to battery technologies. Its moderate efficiency range of 40—60 % reflects thermodynamic limitations, particularly in conventional systems without thermal energy recovery. Site-specific geological requirements, such as suitable caverns or aquifers, also restrict CAES deployment [50,51]. Nevertheless, its ability to provide long-duration storage positions CAES as a valuable complement to other technologies in hybrid energy storage solutions.

Flywheel energy storage systems excel in applications requiring high power output over short durations, such as grid frequency regulation. With efficiencies exceeding 85 %, robust durability, and minimal reliance on rare materials, flywheels offer an environmentally friendly solution for ancillary services. However, their limited energy capacity restricts their role in bulk energy storage, confining their utility to niche but critical grid support functions. Hydrogen storage presents a highly scalable option for both grid-level applications and transportation fuel. Its potential as a clean energy carrier is compelling, particularly when produced through renewable-powered electrolysis. However, the low to moderate efficiency (30—50 %) of hydrogen systems, combined with high costs associated with production, compression, and storage, represent significant barriers. Ongoing advancements in electrolyze technology and storage materials are crucial to unlocking hydrogen's full potential in future energy systems. Molten salt storage is primarily deployed alongside concentrated solar power (CSP) systems, enabling thermal energy storage for electricity generation during periods of low solar irradiance. Its moderate efficiency range (60—70 %) and high recyclability offer environmental benefits. However, challenges related to material corrosion and thermal management over extended periods must be addressed to enhance reliability.

3. Energy storage technologies

Energy storage systems are indispensable components in the transition towards a sustainable energy future, particularly for addressing the inherent intermittency of renewable energy sources such as solar and wind power [52—54]. Using excessive energy generated during periods of low demand and releasing it during peak consumption times, these systems contribute to balancing supply and demand, thereby enhancing grid stability and operational reliability. Moreover, energy storage supports the integration of decentralized energy resources, facilitates frequency regulation, and contributes to the overall resilience of the power infrastructure against disruptions. This section provides a comprehensive investigation of the diverse categories of energy storage technologies currently in use and under development. It explores traditional methods such as pumped hydro storage and advanced batteries, alongside emerging solutions like flow batteries, supercapacitors, and hydrogen-based storage systems [55]. Special attention is given to recent innovations that aim to improve efficiency, scalability, and cost-effectiveness. Additionally, the discussion highlights critical challenges, including material limitations, lifecycle concerns, environmental impacts, and economic viability. This section outlines future prospects and research directions that could pave the way for next-generation storage solutions, fostering greater deployment of renewable energy systems on a global scale.

3.1. Electrochemical energy storage

3.1.1. Lithium-ion batteries

Fig. 3 illustrates the operating mechanism and internal structure of a lithium-ion battery (LIB), highlighting both the charging and discharging processes. Lithium-ion batteries (LIBs) dominate the energy storage sector due to their high energy density, excellent efficiency, and steadily declining production costs. The fundamental architecture of LIBs comprises a cathode, typically made of lithium-metal oxides, an anode composed of carbon-based materials such as graphite or lithium-

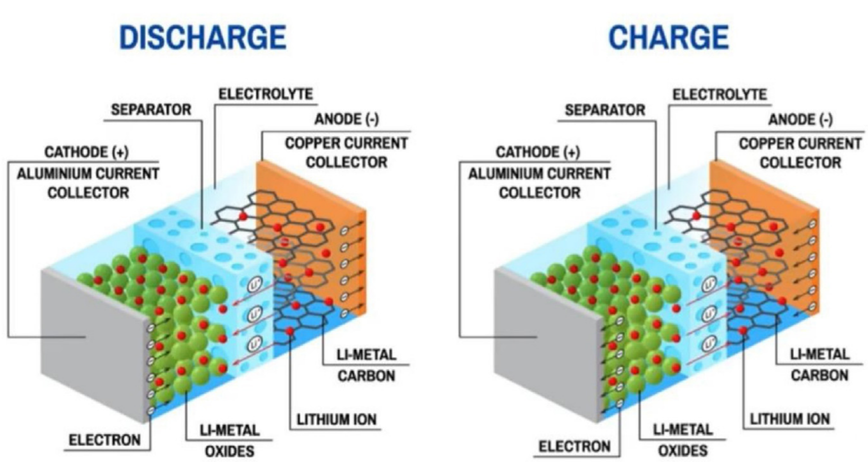

Fig. 3. Operating mechanism and design of a lithium-ion battery [59].

metal composites, and an electrolyte that facilitates lithium-ion transport between the electrodes [56—58]. Current collectors, specifically aluminium for the cathode and copper for the anode, enable efficient electron flow through the external circuit. During discharge, lithium ions migrate from the anode to the cathode through the electrolyte, while electrons flow externally from the anode to the cathode via the copper and aluminium current collectors, delivering useable electrical energy to the connected load. Conversely, during charging (Fig. 3, right), an external power source drives lithium ions back from the cathode to the anode, where they intercalate into the carbon structure. Simultaneously, electrons travel through the external circuit in the opposite direction. Significant progress has been made in enhancing LIB performance through material innovations. Nickel-rich layered oxides in the cathode and silicon-enhanced anodes have notably increased both the energy density and cycle life of the batteries [59]. In parallel, advancements in electrolyte formulations and separator technologies have improved the safety profile of LIBs by reducing the risk of dendrite formation and thermal runaway, a critical hazard in high-energy systems. The integration of sophisticated battery management systems (BMS) enables real-time monitoring of voltage, current, and temperature, thereby enhancing operational safety and prolonging battery lifespan.

Several studies [56,60,61] have successfully demonstrated the sustainability of LIB batteries, and their wide spectrum of applications, ranging from small-scale residential energy storage to large-scale grid integration projects aimed at stabilizing renewable energy inputs. Nevertheless, several challenges continue to impede broader adoption. Among these are the reliance on scarce and geopolitically sensitive raw materials, such as cobalt, and the complex processes involved in recycling and reusing end-of-life batteries to reduce environmental impacts.

3.1.2. Solid-state batteries

Among the various emerging technologies, solid-state batteries (SSBs) are widely regarded as one of the most promising advancements in the future of energy storage, offering energy densities that exceed those of conventional LIBs [62,63]. By replacing flammable liquid electrolytes with solid-state materials, SSBs significantly enhance safety, effectively mitigating risks such as leakage, thermal runaway, and combustion. This improved safety profile renders them particularly attractive for high-demand applications, including electric vehicles (EVs), aerospace systems, and large-scale grid storage. Recent progress in solid electrolyte development, particularly in sulphide-based and oxide-based materials, has shown substantial promise in achieving high ionic conductivity comparable to or surpassing that of liquid electrolytes [56,64]. Sulphide electrolytes, in particular, exhibit exceptional lithium-ion conductivity and favorable mechanical properties, which facilitate better contact with electrodes and improved performance at room temperature. Oxide electrolytes, while typically less conductive, offer superior chemical stability and are less sensitive to moisture, which is advantageous for long-term operational reliability and simplified handling during manufacturing.

Innovations in composite electrolytes have contributed to reducing interfacial resistance, a critical challenge that impedes ion transfer efficiency between the electrolyte and electrodes. Techniques such as surface coatings, the use of buffer layers, and the optimization of electrode microstructures are being actively explored to enhance interfacial compatibility and mechanical integrity [65]. Despite these advancements, significant challenges remain, particularly in scaling up production processes to meet commercial demands. The fabrication of dense, defect-free solid electrolytes requires precise control over material synthesis and processing conditions, which currently limits manufacturing scalability and increases production costs. Additionally, maintaining stable electrode-electrolyte interfaces during repeated charge-discharge cycles remains a challenge, as mechanical stress and volume changes can lead to interface degradation and performance decline over time. While SSBs represent a potential step toward safer, higher-capacity energy storage systems, continued study and development efforts are essential to overcome current material and engineering limitations before widespread commercial deployment can be realized.

3.1.3. Flow batteries

Flow batteries, particularly vanadium redox flow batteries (VRFBs), represent a highly promising solution for grid-scale energy storage, primarily due to their exceptional cycle life, scalability, and the decoupling of energy and power capacities. As illustrated in Fig. 4, a typical VRFB system comprises two external electrolyte tanks: one for the catholyte (V^{4+}/V^{5+}) and one for the anolyte (V^{2+}/V^{3+}) [66]. These tanks circulate vanadium-based electrolytes through a central electrochemical cell stack by means of pumps. The core of the system features an ion-selective membrane that permits proton (H^{+}) transfer while preventing the cross-mixing of vanadium ions, thereby maintaining electrochemical stability and efficiency. During the charging process, electrical energy from an external grid is applied to drive the oxidation of V^{3+} to V^{4+} at the cathode and the reduction of V^{4+} to V^{2+} at the anode, effectively storing energy in the chemical states of the electrolyte solutions. Conversely, during

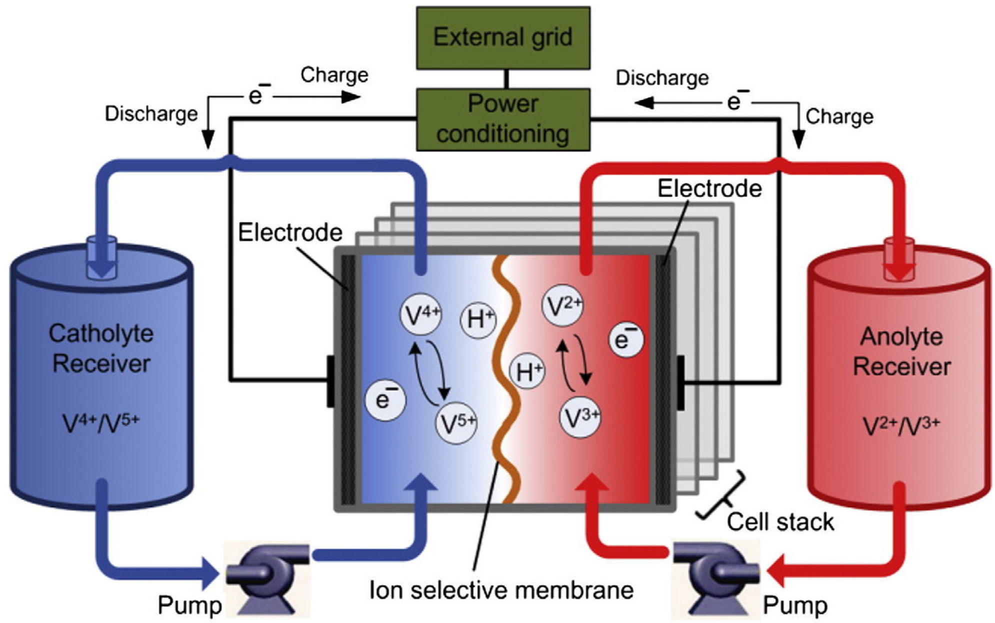

Fig. 4. Schematic diagram and structure of a vanadium redox flow battery [66].

discharge, the reverse reactions occur, releasing stored energy to the grid. This architecture allows the energy capacity to be scaled by simply increasing the volume of electrolyte stored in the external tanks. In contrast, the power output is determined by the size and number of cell stacks.

Sharma et al. [67] investigated the use of vanadium to enhance energy density and reduce overall system costs. The study proposes the development of mixed-acid electrolytes and the use of advanced supporting salts to stabilize higher concentrations of vanadium ions, thereby improving the volumetric energy capacity. Current studies aim to reduce the cost of vanadium and the membrane by exploring alternative redox couples and low-cost ion-exchange membranes, without compromising system longevity and efficiency [68,69]. Flow batteries generally exhibit lower volumetric energy density compared to LIBs, their ability to store vast quantities of energy over extended periods makes them particularly well suited for stationary applications such as renewable energy integration. They can effectively buffer the intermittent nature of solar and wind power, facilitating stable and reliable energy supply to the grid.

3.2. Mechanical energy storage

3.2.1. Pumped hydroelectric storage

Pumped hydro storage (PHS) remains the dominant form of large-scale energy storage, accounting for over 90 % of the total global storage capacity [70,71]. The operational principle of PHS, as illustrated in Fig. 5, involves two water reservoirs positioned at different elevations, an upper reservoir and a lower reservoir. During periods of surplus electricity generation, particularly from renewable sources such as wind and solar power, water is pumped from the lower reservoir to the upper reservoir using excess grid energy. This process effectively stores energy in the form of gravitational potential energy. When electricity demand rises, or during peak consumption periods, water is released from the upper reservoir. It flows through a control valve and descends towards the lower reservoir, passing through turbines that convert the kinetic energy of flowing water into mechanical energy. This mechanical energy is subsequently transformed into electrical energy by the generator, with the output transmitted to the grid via a transformer. The surge chamber, illustrated in the system layout, plays a critical role in regulating pressure fluctuations, thereby protecting the infrastructure and ensuring operational stability.

PHS systems exhibit high round-trip efficiency, typically ranging from 70 to 85 %, and are capable of providing both rapid response times and large-scale energy capacity. These characteristics make PHS an essential asset for grid balancing, frequency regulation, and supporting the integration of intermittent renewable energy sources. Furthermore, PHS offers operational flexibility, allowing for prolonged discharge durations that are ideal for daily load shifting and seasonal storage needs. However, despite these technical advantages, the widespread deployment of PHS is constrained by significant geographic and

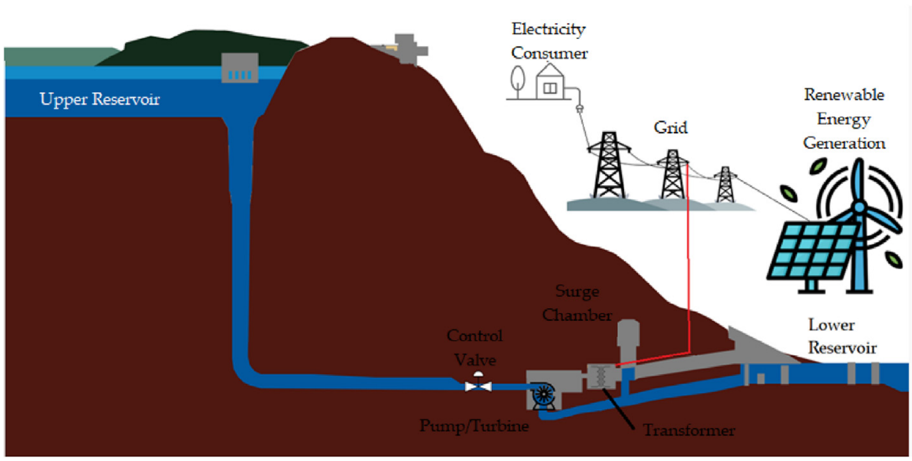

Fig. 5. A potential design for a pumped hydro storage (PHS) system [72].

environmental factors. The necessity for suitable topographical features, such as steep elevation differences and the availability of water resources, limits site selection. Additionally, ecological concerns, including potential impacts on aquatic ecosystems, land use conflicts, and the risk of habitat disruption, necessitate thorough environmental assessments prior to development. Emerging innovations, such as closed loop and underground PHS systems, are being explored to mitigate these limitations by decoupling system design from natural water bodies and sensitive habitats.

3.2.2. Compressed air energy storage

Compressed Air Energy Storage (CAES) operates by compressing air and storing it in subterranean caverns, typically in salt formations gas fields, before releasing it to drive turbines and generate electricity during periods of peak demand. This approach allows for the decoupling of energy generation from consumption, aiding grid balancing and integration of variable renewable sources. Recent advancements include the development of adiabatic CAES systems, which capture and reuse the heat generated during the compression phase, substantially improving overall energy efficiency and reducing dependency on external thermal inputs [73,74]. Fig. 6 shows the basic cycle layout of Diabatic Compressed Air Energy Storage. Additionally, research into isothermal compression processes and advanced thermodynamic cycle designs further promises to minimize energy losses. However,

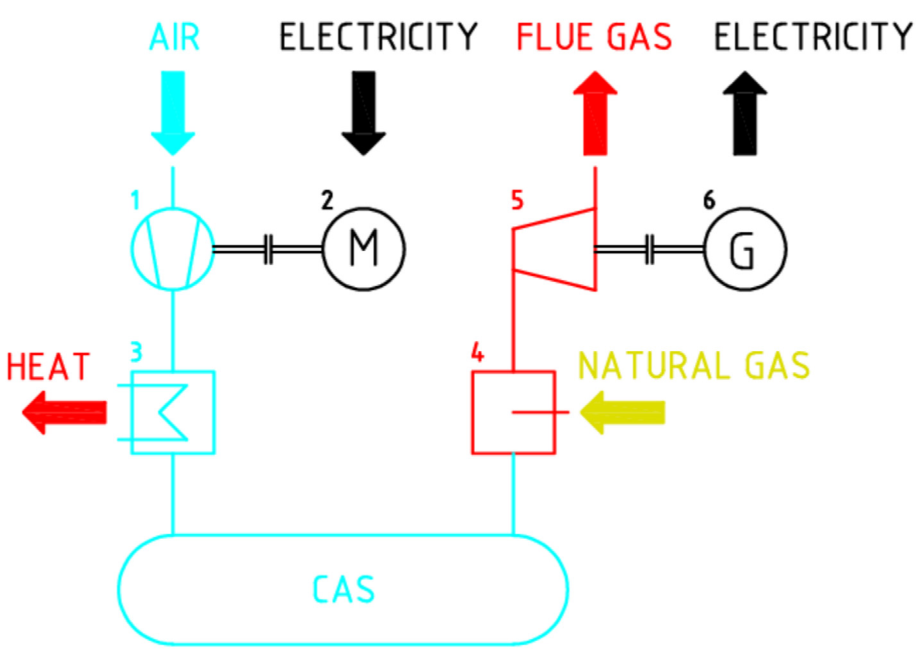

Fig. 6. Schematic representation of the basic D-CAES cycle 1) compressor; 2) electric motor for compressor; 3) aftercooler; 4) combustion chamber; 5) gas expansion turbine; 6) electric generator [75].

CAES remain constrained by geographic limitations, as suitable underground formations are not universally available. Despite technological improvements, inherent energy losses during the compression and expansion cycles continue to pose challenges to achieving optimal round-trip efficiencies.

3.2.3. Flywheel energy storage

Flywheel energy storage systems store energy in the form of rotational kinetic energy by accelerating a rotor to very high speeds within a low-friction environment. With round-trip efficiencies exceeding 85 %, minimal maintenance requirements, and exceptional response times, flywheels are especially suited for high-power, short-duration applications, such as frequency regulation, voltage stabilization, and uninterruptible power supply system's [76—78]. Recent material innovations, notably the utilization of carbon fibre composite rotors, have enabled higher rotational speeds and energy densities while maintaining structural integrity. Moreover, the incorporation of magnetic bearings and vacuum enclosures has significantly reduced mechanical losses, thereby extending the operational lifespan of these systems. As research continues, the integration of flywheels with smart grid technologies and hybrid energy systems is being explored to enhance grid flexibility and resilience.

3.3. Chemical energy storage

3.3.1. Hydrogen

Hydrogen is emerging as a versatile and clean energy vector, with applications spanning grid-scale energy storage, transportation fuels, and industrial processes. Green hydrogen, produced through water electrolysis powered by renewable electricity, is particularly promising for achieving deep decarbonization targets across multiple sectors. Technological advancements in electrolyzes, particularly proton exchange membrane (PEM) and solid oxide electrolyzer cells (SOEC), have improved system efficiencies, reduced operational costs, and enhanced scalability [79—82]. In parallel, breakthroughs in storage technologies, including the development of metal hydrides, high-pressure tanks, and liquid organic hydrogen carriers (LOHCs), address the critical challenges of hydrogen's low volumetric energy density and associated safety concerns.

3.3.2. Synthetic fuels

Synthetic fuels synthesized from renewable electricity and captured carbon dioxide, offer a sustainable pathway for storing surplus renewable energy in chemical form. These fuels, including methanol, ammonia, and synthetic hydrocarbons, are compatible with existing storage, transport, and end-use infrastructures, making them particularly attractive for sectors that are difficult to electrify, such as maritime shipping, aviation, and heavy industry [83,84]. In addition to their energy storage capacity, synthetic fuels contribute to carbon circularity by reusing CO_2 emissions as a feedstock, thus promoting climate mitigation efforts.

3.4. Thermal energy storage

3.4.1. Phase-change materials

Phase Change Materials (PCMs) store thermal energy by exploiting the latent heat associated with phase transitions, predominantly between solid and liquid phases [85—87]. During the melting process, PCMs absorb a substantial amount of heat at a nearly constant temperature, which is later released upon solidification, providing a reliable mechanism for thermal energy storage. This characteristic makes them highly suitable for integration into solar thermal systems, as they enhance efficiency by mitigating the intermittency of solar irradiance. Such systems can supply consistent thermal energy for both residential heating, including space and water heating, and industrial processes that require moderate temperature ranges. Advancements in PCM technology have significantly broadened their applicability and performance. Inorganic PCMs, particularly salt hydrates, offer high volumetric energy storage density and relatively sharp phase transition temperatures. However, challenges such as subcooling, phase segregation, and corrosivity necessitate careful material selection and encapsulation strategies [88]. In contrast, organic PCMs, including paraffins and fatty acids, provide improved thermal and chemical stability, exhibit minimal supercooling, and possess self-nucleating properties, although they generally have lower thermal conductivity compared to their inorganic counterparts.

Recent research focuses on enhancing PCM thermal conductivity through the incorporation of high-conductivity additives such as metal foams, carbon nanotubes, and graphene nanoplatelets. Furthermore, micro- and macro-encapsulation techniques are employed to prevent leakage during phase transitions and to improve the durability and cycling stability of PCMs under repeated thermal loads [89,90]. These developments not only increase the overall efficiency of solar thermal energy systems but also extend the operational lifespan of the materials, contributing to the commercial viability of PCM-based thermal energy storage solutions.

3.4.2. Molten salt storage

Molten salt systems have become one of the most mature and widely implemented technologies for high-temperature thermal energy storage in concentrated solar power (CSP) plants [91]. These systems typically utilize a mixture of nitrate salts, such as sodium nitrate ($NaNO_3$) and potassium nitrate (KNO_3), which are chosen for their high thermal stability, favorable thermophysical properties, and relatively low cost [92]. The molten salts serve as both the heat transfer fluid and the storage medium, allowing for efficient collection, transfer, and storage of thermal energy at operating temperatures ranging from approximately 290 to 565 °C, depending on the specific salt formulation [93,94]. Storing thermal energy accumulated during periods of peak solar irradiance, molten salt systems enable the dispatchability of CSP plants, thereby supporting continuous power generation and enhancing grid reliability. The stored heat is subsequently used to produce steam that drives conventional turbines to generate electricity during periods of low or no sunlight, such as at night or during cloudy conditions. This capability significantly improves the capacity factor of CSP facilities, bringing them closer to base-load power generation performance.

The deployment of molten salt systems faces several technical challenges, primarily related to material compatibility and thermal losses. Corrosion of structural components, especially storage tanks, piping, and heat exchangers, is a major concern due to the aggressive chemical environment at elevated temperatures. Research and development efforts are currently focused on the development of corrosion-resistant alloys and protective coatings, such as ceramic linings and advanced surface treatments, to extend component lifespan and reduce maintenance costs. In addition, thermal losses over extended storage durations, particularly from hot and cold tanks, can impact overall system efficiency. Advances in high-performance thermal insulation materials, including vacuum-insulated panels and aerogels, have been implemented to minimize heat dissipation. Furthermore, innovations in heat transfer fluid formulations, including the exploration of chloride-based salts and eutectic mixtures, aim to achieve higher operating temperatures beyond 600 °C, which would increase the thermodynamic efficiency of the power cycle.

4. Integration of energy storage with renewable energy grids

The integration of energy storage technologies with renewable energy networks is a pivotal enabler for achieving a sustainable and resilient energy future. As the global deployment of variable renewable energy (VRE) sources, such as solar photovoltaic (PV) and wind power, accelerates, ESS play a critical role in addressing their inherent intermittency and variability [95,96]. These storage solutions contribute to maintaining grid stability by providing services such as frequency regulation, voltage support, peak shaving, and spinning reserve capacity. They enhance grid flexibility, enabling the dynamic balancing of supply and demand across diverse temporal and spatial scales, while also optimizing energy utilization by facilitating load shifting and maximizing renewable energy self-consumption. From a technological perspective, a broad portfolio of energy storage systems is being integrated into renewable energy networks, each with distinct characteristics suited to specific applications. Electrochemical storage systems, particularly lithium-ion batteries, dominate short-duration storage due to their high energy density, fast response times, and declining costs [78]. For longer-duration storage, technologies such as flow batteries, CAES, and pumped hydroelectric storage are employed, offering large-scale capacity and extended discharge durations. Emerging innovations, such as solid-state batteries, metal-air chemistries, and thermochemical storage, hold the potential to further diversify the storage landscape and address current limitations related to scalability, cost, and environmental impact. Operational integration of storage with renewable generation entails sophisticated energy management systems (EMS) and advanced control algorithms that optimize the dispatch of storage assets based on real-time grid conditions, weather forecasts, and market signals. The implementation of smart grids and digitalization, including the use of artificial intelligence and machine learning, enhances predictive maintenance, state-of-charge estimation, and optimal scheduling of energy storage systems, thereby improving reliability and economic performance.

Strategically, successful deployment of integrated storage solutions requires alignment with supportive policy frameworks, market incentives, and regulatory structures that value the multifaceted benefits of energy storage beyond simple energy arbitrage. Time-of-use pricing, capacity remuneration mechanisms, and ancillary service markets are crucial for unlocking the full value proposition of storage technologies. Notable success stories, such as the Hornsdale Power Reserve in Australia and the deployment of utility-scale battery systems in California, demonstrate the effectiveness of integrated storage in stabilizing grids with high renewable penetration, mitigating curtailment, and enhancing energy security. Despite these advancements, several challenges persist, including high upfront capital costs, lifecycle management of storage components, environmental considerations associated with material extraction and disposal, and the need for harmonized technical standards.

4.1. Smart grid systems

Fig. 7 illustrates the role of AI control strategies as the central intelligence in orchestrating the integration of diverse energy sources and consumers within a smart grid ecosystem. Smart grids rely on advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), and big data analytics to seamlessly coordinate energy storage systems with variable renewable energy inputs and dynamic consumption demands across sectors [97—99]. AI algorithms serve as the brain of the smart grid. They enable precise real-time forecasting of renewable energy generation, especially for intermittent sources such as solar photovoltaics (PV) and wind energy. Processing vast datasets, including weather forecasts and historical production data, AI models optimize the dispatch of energy to meet demand efficiently. In particular, AI supports predictive load balancing, ensuring that surplus energy generated during peak sunlight or wind conditions is stored to meet consumption needs in sectors like industrial manufacturing and commercial buildings, as illustrated. The integration of IoT-connected devices is to ensure seamless connectivity between generation sources, storage units, and end-users like smart homes, electric vehicles, and smart subways. IoT sensors and actuators continuously monitor grid conditions, battery states of charge, and energy consumption patterns. These devices transmit real-time data to central AI platforms, enabling adaptive control responses such as demand-side management and automated load shedding during grid stress periods.

Fig. 7 also highlights smart homes and smart vehicles as crucial distributed energy resources and flexible loads. AI-enabled home energy management systems adjust appliance operation and vehicle charging in response to real-time energy prices and grid conditions. For example, during periods of high renewable generation, smart homes can priorities energy-intensive tasks, while smart vehicles can act as mobile storage units, feeding power back into the grid when necessary. Advanced machine learning models, referenced in both the text and visually implied by the central AI control strategies, have already demonstrated success in wind-solar hybrid systems. These models synchronize renewable generation forecasts with battery storage operations, significantly reducing energy wastage and enhancing overall grid stability.

4.2. Grid stability and flexibility

Energy storage devices are critical to overcoming the intermittent nature of renewable energy sources, ensuring a stable and reliable power supply by capturing surplus energy during periods of low demand and releasing it during peak consumption times [101]. Battery technologies, notably lithium-ion and flow batteries, have seen increasing deployment for short-term balancing of supply and demand fluctuations. Meanwhile, long-duration solutions such as pumped hydro storage and compressed air energy storage address seasonal mismatches between energy generation and consumption. The integration of these storage solutions with renewable energy systems significantly enhances grid flexibility, allowing utilities to swiftly adjust power outputs in response to dynamic grid conditions. This flexibility is instrumental in delivering ancillary services, including frequency regulation and voltage stabilisation, which are particularly critical in networks with a high penetration of variable renewable sources like solar and wind energy,

Fig. 7. Smart grid AI control schemes [100].

where output can experience rapid and unpredictable changes [102,103].

A crucial consideration in energy storage deployment lies in the distinction between distributed and centralized storage systems, each offering unique advantages depending on the grid architecture, demand patterns, and geographic factors. Distributed storage encompasses smaller-scale installations, such as residential battery systems and community storage hubs, positioned close to the point of consumption. This decentralized approach mitigates transmission losses, enhances energy security, and empowers consumers to actively participate in energy markets [104]. For instance, solutions such as Tesla's Powerwall enable households to store electricity generated from rooftop solar panels and feed excess power back into the grid, thereby contributing to the resilience and decentralization of the energy system. In contrast, centralized storage systems, exemplified by large-scale battery farms and pumped hydro facilities, are designed to manage substantial energy volumes at the grid level. These systems benefit from economies of scale and play a vital role in integrating utility-scale renewable energy projects, such as expansive solar farms and offshore wind arrays, into the broader grid infrastructure. However, centralized storage solutions demand significant capital investments and are often subject to geographical and environmental constraints that can limit their deployment.

5. Conclusion, limitation and future perspectives

Energy storage technologies have emerged as a key factor in the pursuit of a sustainable and reliable energy future. The present study highlighted significant advancements across electrochemical, mechanical, chemical, and thermal storage systems, revealing their critical role in addressing the intermittent challenges posed by renewable energy sources such as solar and wind. Innovations such as solid-state batteries, molten salt storage, and hydrogen-based solutions illustrate the transformative potential of these technologies in enhancing energy efficiency, grid stability, and scalability. As global energy systems continue to evolve, these developments position energy storage as a pivotal enabler of decarbonization goals. Energy storage will be indispensable in advancing the transition to renewable energy. Its role extends beyond technical integration to include the promotion of decentralized energy systems, enabling the development of microgrids and supporting electrification in underserved regions. The convergence of storage technologies with digital tools, such as artificial intelligence and big data analytics, presents unprecedented opportunities for optimizing energy distribution and consumption patterns. Moreover, advancements in hybrid systems and recycling technologies offer promising solutions to current limitations, particularly in improving affordability and minimizing environmental impact.

Despite these positive developments, current energy storage technologies remain beset by some significant limitations that call for continued research and innovation. From a technical perspective, the utilization of critical materials such as lithium, cobalt, and rare earth metals exposes supply chains to vulnerability and geopolitical risks, potentially limiting large-scale deployment. Most technologies remain below their theoretical maximum energy densities, which limits their application. In addition, a limited understanding of degradation mechanisms in batteries and other storage technologies hinders the development of more resilient and long-lasting solutions. The technical integration of heterogeneous storage technologies with existing, often aging, grid infrastructure is also a complex task. Economic and practical issues also complicate widespread adoption. Advanced storage technologies generally demand high initial capital outlay, which, despite decreasing lifecycle costs, can deter uptake. Scaling laboratory innovation to industrial-scale production remains a tall order, often plagued by engineering and logistical challenges. Regulatory fragmentation across geographies creates market inconsistencies and deters investment, while variability in real-world operating conditions invites questions of reliability and predictability for grid operators and consumers.

There are also important environmental concerns. End-of-life management is a concern due to the underdevelopment of recycling infrastructure for most storage technologies, which can contribute to growing waste streams. Some storage systems such as pumped hydro and certain thermal technologies, are water-intensive, which is a sustainability concern in water-stressed areas. Deployment at scale could also require large areas of land, which could lead to competition with agriculture, nature reserves, or urban development. To overcome these limitations, some promising future research avenues are being pursued. Interface engineering is gaining attention as researchers attempt to resolve stability issues in solid-electrolyte interfaces, especially in next-generation battery architectures. Multi-scale modeling efforts are improving the understanding of energy storage behaviour at the atomic levels, and thereby accelerating material discovery and optimization. The search for standard testing protocols, interconnect standards, and metrics for performance is essential to facilitate apples-to-apples technology comparisons as well as to attain system interoperability. Long-duration energy storage is the second key research priority, with the focus being on systems capable of delivering power over extended periods of days or even weeks, which is essential to account for seasonal variability in renewable energy output. Furthermore, bio-inspired storage technologies that mimic natural energy storage mechanisms hold the potential to create more effective and sustainable systems. Thermal management advances, particularly those aimed at optimizing system performance across a range of climatic conditions, are also central to extending the operational lifespan and reliability of storage technologies.

Integration of energy storage into the global energy sector is more than a technical necessity, it is a shared responsibility. Academic, industry, and government stakeholders must collaborate to render renewable energy not only more pervasive but also more accessible, stable, and sustainable. The narrowing timeframe to prevent the worst impacts of climate change reveals the urgent need to develop more sustainable energy systems.

Data availability statement

The data compiled and analyzed in this review are derived from previously published studies, all of which are cited in the text and available from the respective sources.

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Conflicts of interest

The authors declare no conflict of interest, as all sources used have been duly acknowledged.

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