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A Review of Innovative Approaches in Renewable Energy Storage

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Abstract

The transition to renewable energy sources such as solar and wind has presented significant intermittency and grid stability challenges. Energy storage technologies have emerged as crucial solutions to address these issues, enabling renewable energy's efficient and reliable integration into power systems. This review explores the diverse technological landscape of renewable energy storage, including electrochemical, mechanical, thermal, chemical, and emerging hybrid systems. It highlights the advances in battery technologies such as lithium-ion, solid-state, and flow batteries, as well as the potential of pumped hydro, compressed air, and flywheel systems. The paper also discusses the role of AI and data-driven optimization in enhancing storage efficiency, the importance of novel materials science in developing next-generation storage solutions, and the growing trend of decentralized and distributed storage systems. However, several challenges remain, including energy density, economic competitiveness, and environmental sustainability. The paper concludes with recommendations for accelerating the innovation and deployment of energy storage technologies, emphasizing the need for research funding, policy support, and market innovations. Addressing these barriers and deploying efficient, cost-effective, and scalable storage solutions will facilitate the transition to a renewable energy future.

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1. Introduction

1.1 Background and Significance of Renewable Energy Storage

The increasing global reliance on renewable energy sources has intensified the demand for efficient storage solutions. Renewable energy, derived from solar, wind, hydro, and other sustainable sources, has demonstrated immense potential to reduce dependency on fossil fuels, mitigate climate change, and enhance energy security (Jafarizadeh *et al.*, 2024). However, one of the primary limitations of these sources is their inherent intermittency, which creates challenges for maintaining a stable and reliable energy supply. Unlike conventional power plants that operate on demand, solar and wind energy production fluctuates based on weather conditions, time of day, and seasonal variations (Ren, Liu, Wan, Guo, & Yu, 2017). This variability underscores the necessity of advanced storage technologies to bridge the gap between energy generation and consumption, ensuring a consistent power supply for residential, commercial, and industrial applications (Ellabban, Abu-Rub, & Blaabjerg, 2014).

Energy storage has emerged as a critical enabler of the renewable energy transition by facilitating load balancing, peak shaving, and frequency regulation (Razif, Ab Aziz, Ab Kadir, & Kamil, 2024). By storing excess energy produced during periods of high generation and deploying it when demand surpasses supply, storage systems enhance grid resilience and operational efficiency. The ability to store energy also reduces the reliance on backup fossil-fuel-based power plants, further lowering greenhouse gas emissions and contributing to decarbonization goals. Additionally, energy storage enables greater penetration of distributed energy resources, fostering decentralized power generation models such as microgrids and peer-to-peer energy trading systems (Fernandez, Go, Wong, & Früh, 2024).

The significance of renewable energy storage extends beyond grid stability to economic and policy dimensions. The falling costs of renewable energy technologies have accelerated their deployment globally, but the economic viability of large-scale adoption

remains contingent on effective storage solutions (Adeyinka, Esan, Ijaola, & Farayibi, 2024). Without storage, curtailment of excess energy generated during peak production hours leads to inefficiencies and financial losses for energy producers. Moreover, governments and regulatory bodies recognize the importance of storage in achieving energy independence and are increasingly implementing incentives, subsidies, and mandates to accelerate research, development, and deployment of storage technologies (Luthander, Lingfors, & Widén, 2017).

In addition to large-scale grid applications, energy storage plays a crucial role in off-grid and remote electrification efforts. In many regions, particularly in developing economies, access to reliable electricity remains a challenge due to infrastructural limitations (Zebra, van der Windt, Nhumaio, & Faaij, 2021). Standalone storage systems, often coupled with solar or wind installations, provide a sustainable alternative to diesel generators, reducing both costs and environmental impact. Similarly, energy storage enhances resilience in disaster-prone areas by ensuring an uninterrupted power supply during grid failures, supporting emergency response operations and critical infrastructure (Ko *et al.*, 2019).

The energy storage landscape is evolving rapidly, driven by materials science, artificial intelligence, and power electronics advancements. Innovations in battery chemistry, such as solid-state and lithium-sulfur technologies, improve energy density, lifespan, and safety. At the same time, alternative storage solutions, including hydrogen-based systems and thermal storage, are expanding the range of applications beyond conventional battery storage. These technological advancements are complemented by integrating smart grid technologies and energy management systems, which optimize storage operations and enable real-time grid balancing (X. Liu *et al.*, 2024).

1.2 The Role of Storage Technologies in Addressing Intermittency and Grid Stability

One of the most pressing challenges associated with renewable energy sources is their intermittency, which can cause fluctuations in power supply and create instability in electrical grids. Unlike conventional energy generation methods that provide a consistent output, renewable energy production varies based on environmental conditions (Impram, Nese, & Oral, 2020). Solar power generation depends on sunlight availability, making it inconsistent during cloudy days and entirely absent at night (Ewim, Abolarin, Scott, & Anyanwu, 2023). Similarly, wind power is influenced by atmospheric conditions, sometimes generating surplus energy and at other times producing little to no electricity. This variability poses a fundamental challenge to grid operators, who must always balance electricity supply and demand (Sengupta, Habte, Wilbert, Gueymard, & Remund, 2021).

Energy storage technologies offer a viable solution to address this issue by capturing excess energy during periods of high generation and discharging it when supply is insufficient. Batteries, pumped hydro, compressed air, and other storage methods can store surplus energy, effectively smoothing out fluctuations and ensuring continuous power availability. This function, known as load leveling, helps mitigate the impact of intermittency by ensuring a consistent energy supply (Gür, 2018).

Beyond simple energy storage and release, storage

technologies also play a crucial role in frequency regulation. The stability of an electrical grid depends on maintaining a constant frequency, typically 50 or 60 Hz, depending on the region. Power supply and demand fluctuations can cause frequency deviations, potentially leading to system instability or blackouts. Fast-responding storage solutions, such as lithium-ion and supercapacitors, provide near-instantaneous frequency regulation by absorbing excess energy or injecting stored power into the grid when needed (Nadeem, Hussain, Tiwari, Goswami, & Ustun, 2018).

Another essential function of storage technologies is peak shaving, which involves reducing the demand on the grid during peak usage periods. Many electricity grids experience peak demand in the early evening when households and businesses simultaneously consume high amounts of electricity (Rizvi, Chaturvedi, & Kolhe, 2023). Without storage, utilities may need to rely on fossil-fuel-powered peaker plants to meet this demand, increasing both costs and carbon emissions. By storing energy during off-peak periods and discharging it during peak hours, energy storage systems reduce the strain on the grid and minimize the need for additional power generation (Uddin, Romlie, Abdullah, Abd Halim, & Kwang, 2018).

Energy storage also enables greater integration of decentralized and distributed energy resources. Traditional power grids operate on a centralized model, where large power plants generate electricity and transmit it to consumers. However, the rise of rooftop solar panels, wind turbines, and community microgrids has introduced a decentralized approach to energy generation. Storage technologies facilitate this transition by allowing individual consumers and businesses to store excess renewable energy for later use or for sale back to the grid. This capability fosters energy independence, reduces reliance on utility companies, and enhances grid resilience (Ahmadi *et al.*, 2021).

Moreover, storage technologies contribute to grid stability by providing backup power during outages and emergencies. In extreme weather events, cyberattacks, or equipment failures, stored energy can safeguard against blackouts. Microgrids with energy storage can operate independently of the main grid, ensuring continued power supply to critical infrastructure such as hospitals, emergency response centers, and communication networks (Abdelkader *et al.*, 2024).

The growing deployment of smart grids and digital energy management systems further enhances the role of storage technologies in grid stability. Through artificial intelligence and machine learning algorithms, storage systems can predict fluctuations in supply and demand, optimizing energy distribution in real time. These innovations improve grid efficiency, lower operational costs, and maximize the utilization of renewable energy resources (Arévalo & Jurado, 2024).

1.3 Emerging Trends in Energy Storage and Their Impact on the Energy Transition

The rapid advancement of renewable energy has necessitated continuous innovation in energy storage technologies to support grid stability, improve efficiency, and facilitate widespread adoption. As global energy markets transition away from fossil fuels, emerging trends in energy storage are shaping the future of power generation, distribution, and consumption (Qahtan, Alade, Rahaman, & Saleh, 2024). These trends encompass novel battery chemistries, alternative storage solutions, artificial intelligence-driven

energy management, decentralized storage networks, and regulatory advancements to accelerate deployment. Lithium-ion batteries have dominated the energy storage landscape due to their high energy density, efficiency, and declining costs. However, concerns regarding resource availability, environmental impact, and performance limitations have spurred research into next-generation battery chemistries. Solid-state batteries, for example, replace traditional liquid electrolytes with solid alternatives, enhancing safety, energy density, and lifespan. These batteries are expected to revolutionize storage applications by reducing the risk of thermal runaway, a significant concern in conventional lithium-ion systems (Zhao, Stalin, Zhao, & Archer, 2020).

Another promising innovation is lithium-sulfur batteries, which offer higher energy capacity and lower production costs than lithium-ion counterparts. By utilizing sulfur, an abundant and low-cost material, these batteries present an economically viable alternative with significant potential for long-duration storage (Manthiram, Chung, & Zu, 2015). However, challenges related to cycle stability and sulfur dissolution remain key areas of research. Beyond lithium-based chemistries, alternative materials such as sodium-ion and zinc-air batteries are gaining attention. Sodium-ion batteries provide a sustainable and cost-effective alternative by leveraging more abundant raw materials, making them particularly attractive for large-scale grid storage. Zinc-air batteries, on the other hand, harness oxygen from the air as a reactant, enabling high energy density and low production costs, though efficiency improvements are still required for widespread adoption (Ikeuba *et al.*, 2024).

While batteries are the most widely used storage technology, alternative solutions are emerging to complement and, in some cases, surpass battery performance in specific applications. Hydrogen storage has gained traction as a versatile and long-term energy storage and sector coupling solution. By using electrolysis to produce hydrogen from excess renewable electricity, energy can be stored in gaseous or liquid form and later converted back into electricity using fuel cells or turbines. This approach provides large-scale storage capacity and enables decarbonization in transportation, manufacturing, and heating industries (Kamran & Turzyński, 2024). Another alternative, thermal energy storage, leverages heat retention in materials such as molten salts, phase change materials, and underground reservoirs. These systems store excess energy in the form of heat and later convert it back into electricity or use it directly for heating applications. This technology is particularly beneficial in concentrated solar power plants, where molten salt storage enables continuous energy generation even when sunlight is unavailable (Ali *et al.*, 2024).

Gravity-based storage systems are also emerging as a promising alternative to traditional battery solutions. These systems store energy by lifting heavy weights during periods of excess electricity generation and releasing the stored energy by lowering them when needed. Companies developing this technology aim to provide cost-effective, long-duration storage without the environmental and resource extraction concerns associated with batteries.

Artificial intelligence and machine learning are increasingly vital in optimizing energy storage operations. AI-driven predictive analytics enable better forecasting of energy generation and demand patterns, improving decision-making for when to store or discharge energy. By integrating AI with real-time data from weather patterns, grid conditions, and

consumer behavior, energy storage systems can dynamically adapt to maximize efficiency and cost savings (Ahmad *et al.*, 2021). Smart energy management platforms are also enhancing the coordination of distributed energy resources. Virtual power plants aggregate multiple decentralized storage units—such as residential batteries, commercial energy systems, and electric vehicle fleets—into a single network that can respond flexibly to grid conditions. This approach improves grid resilience, reduces strain during peak demand, and increases the participation of prosumers (consumers who also produce energy) (Yang *et al.*, 2021).

The rise of decentralized energy generation drives demand for modular storage solutions that can be deployed at various scales. Unlike traditional centralized power plants, distributed storage enables localized energy generation and consumption, reducing transmission losses and enhancing energy security. Residential and community battery systems are gaining popularity, allowing homeowners and businesses to store solar energy and reduce dependence on the grid (Parra *et al.*, 2017). Microgrid-integrated storage is another emerging trend, particularly in regions with unreliable grid infrastructure. By combining renewable energy sources with storage, microgrids provide stable and self-sufficient power solutions for rural communities, disaster-prone areas, and remote industrial sites. Advances in blockchain technology further enhance decentralized energy trading, enabling peer-to-peer electricity exchanges and improving the efficiency of distributed storage networks (Zakeri, Gisse, Dodds, & Subkhankulova, 2021).

Governments and regulatory bodies are increasingly recognizing the critical role of energy storage in the clean energy transition. Policies promoting investment in storage infrastructure, incentives for research and development, and mandates for grid integration are accelerating deployment. In several regions, energy storage is classified as a standalone asset eligible for subsidies, tax credits, and market participation.

Energy storage markets are also evolving, with new business models emerging to make storage more economically viable. Time-of-use pricing structures encourage consumers to use stored energy during peak periods, reducing grid congestion and improving cost efficiency. Meanwhile, energy-as-a-service models allow businesses and municipalities to lease storage capacity rather than making large upfront investments (J. Liu, Hu, Kimber, & Wang, 2020). The expansion of carbon pricing mechanisms is further incentivizing energy storage adoption. By placing a cost on carbon emissions, these policies make renewable energy storage more financially attractive than fossil-fuel-based power generation. As more regions implement ambitious decarbonization targets, storage is poised to play a central role in meeting renewable energy goals (Kök, Shang, & Yücel, 2018).

These emerging trends' convergence accelerates the global shift towards a cleaner and more resilient energy system. As energy storage technologies become more advanced, cost-effective, and widely accessible, they facilitate the integration of renewable energy at an unprecedented scale. This, in turn, reduces reliance on fossil fuels, lowers greenhouse gas emissions, and enhances energy security. Furthermore, the combination of innovative storage solutions, AI-driven optimization, decentralized networks, and supportive policy frameworks is reshaping the energy landscape. The ability to store and dispatch renewable energy efficiently breaks down barriers to clean energy adoption, enabling countries to

achieve their sustainability targets while ensuring economic stability (Kiasari, Ghaffari, & Aly, 2024).

In conclusion, emerging trends in energy storage are paving the way for a transformative energy transition. Innovations in battery chemistry, alternative storage technologies, AI-driven energy management, decentralized systems, and evolving regulatory frameworks are collectively enhancing the viability of renewable energy. As these advancements mature, they will play an instrumental role in building a future where clean, affordable, and reliable energy is accessible to all.

1.4 Research Objectives and Scope of the Review

The growing imperative for sustainable energy solutions has intensified global efforts to enhance energy storage technologies, essential for enabling a transition to renewable energy. As the intermittency of wind and solar power poses challenges to grid stability and energy reliability, advancements in storage solutions have become a focal point of energy research and policy development. This review aims to provide a comprehensive analysis of innovative approaches in energy storage, examining key technological developments, market trends, regulatory frameworks, and the broader implications of storage for the clean energy transition.

The scope of this review encompasses an interdisciplinary exploration of the latest breakthroughs in energy storage, assessing their technical feasibility, economic viability, and environmental impact. By integrating insights from engineering, economics, environmental science, and policy studies, this research seeks to present a holistic understanding of the evolving energy storage landscape. The review also explores how these technologies align with global sustainability goals, addressing key barriers to widespread adoption while identifying potential pathways for future research and investment.

2. Technological Landscape of Renewable Energy Storage

2.1 Electrochemical Energy Storage

Electrochemical storage has become a cornerstone of the energy transition, offering efficient, scalable, and high-performance solutions. Lithium-ion has dominated the market among the various battery technologies available due to its high energy density, long cycle life, and declining costs. However, new battery chemistries, including solid-state batteries and alternative metal-ion technologies, are emerging to address material availability, safety, and sustainability limitations (Ogunsola, Adebayo, Dienagha, Ninduwezuor-Ehiobu, & Nwokediegwu, 2024b).

Lithium-ion batteries have seen rapid performance and cost reduction improvements, making them the preferred choice for grid storage, electric vehicles, and consumer electronics. Their high energy density and efficiency make them well-suited for short- to medium-duration applications. However, concerns regarding the availability of raw materials such as lithium, cobalt, and nickel and safety risks associated with thermal runaway have prompted research into alternative chemistries.

Solid-state batteries represent a promising advancement, replacing conventional liquid electrolytes with solid materials, enhancing safety, and increasing energy density. These batteries exhibit greater thermal stability, reducing the fire risk and degradation. While facing challenges in

scalability and manufacturing costs, ongoing research in solid-state technology aims to make them commercially viable in the coming decade (Dienagha, Onyeke, Digitemie, & Adekunle, 2021; Ogunsola, Adebayo, Dienagha, Ninduwezuor-Ehiobu, & Nwokediegwu, 2024c).

Beyond lithium-based storage, sodium-ion and potassium-ion batteries are gaining attention due to their reliance on more abundant and cost-effective materials. While these alternatives offer lower energy density than lithium-ion, they present advantages regarding resource availability and environmental impact. Additionally, innovations in lithium-sulfur and metal-air batteries are being explored to achieve higher energy densities and longer lifespans, which could further revolutionize electrochemical storage (Oladosu *et al.*, 2022).

Performance improvements in battery storage also rely on advancements in electrode materials, electrolytes, and battery management systems. The development of silicon anodes, high-nickel cathodes, and solid-state electrolytes is pushing the boundaries of energy storage efficiency. Recycling and second-life battery applications are also gaining traction, enabling more sustainable use of battery materials and reducing environmental impact. Electrochemical energy storage remains a driving force in the renewable energy landscape, with continuous innovations poised to enhance efficiency, scalability, and sustainability (Digitemie & Ekemezie, 2024).

2.2 Mechanical Energy Storage

Mechanical energy storage systems have been widely utilized for decades, offering highly efficient and long-duration energy storage solutions. These technologies leverage gravitational and kinetic forces to store and release energy on demand. Among the most prominent mechanical storage methods are pumped hydro storage, compressed air energy storage (CAES), and flywheel energy storage.

Pumped hydro storage is the most established and widely deployed large-scale energy storage solution. It operates by pumping water from a lower reservoir to a higher one during periods of excess electricity generation and releasing it through turbines to generate power when demand increases. With efficiency rates exceeding 80% and the capability to store energy for extended periods, pumped hydro remains a critical component of global energy storage infrastructure. However, its deployment is constrained by geographical requirements, environmental concerns, and high capital costs (Myllynen, Kamau, Mustapha, Babatunde, & Collins, 2024). CAES utilizes excess electricity to compress air into underground caverns or storage tanks. The pressurized air is released and expanded through turbines to generate electricity when energy is needed. CAES offers high storage capacity and long discharge durations, making it suitable for grid-scale applications. However, its efficiency is lower than pumped hydro's, primarily due to heat losses during compression and expansion. Innovations in thermal management and adiabatic CAES are addressing these inefficiencies, improving overall system performance.

Flywheel energy storage utilizes the rotational inertia of a spinning rotor to store energy. When energy input is applied, the rotor accelerates, and when energy is needed, the kinetic energy is converted back into electricity. Flywheels offer high power density, rapid response times, and long operational lifespans, making them well-suited for grid stabilization and short-duration storage applications.

Advances in high-speed carbon fiber flywheels and superconducting magnetic bearings are improving efficiency and reducing frictional losses (Ozowe, Ikevuje, Ogbu, & Esiri, 2023b).

Emerging mechanical storage innovations include gravity-based energy storage systems, which operate on principles similar to pumped hydro but without water. These systems raise and lower heavy masses to store and release energy, offering a scalable and geographically flexible alternative. Companies are developing modular gravity storage solutions for deployment in urban and industrial settings. Mechanical storage technologies continue to evolve, offering robust, long-duration energy storage solutions essential for balancing renewable energy supply and demand (Onukwulu, Dienagha, Digitemie, & Ifechukwude, 2024c).

2.3 Thermal Energy Storage

Thermal energy storage (TES) plays a vital role in renewable energy integration by enabling thermal energy capture, retention, and controlled release for various applications. Unlike electrochemical or mechanical storage systems, TES stores energy in heat or cold, making it particularly valuable for industrial processes, grid stability, and district heating and cooling systems. The primary categories of TES include sensible heat storage, latent heat storage using phase-change materials (PCMs), and thermochemical energy storage, each offering unique advantages and challenges in energy management.

Sensible heat storage is the most established form of TES, relying on the thermal capacity of water, rocks, concrete, and molten salts to store and release energy. The technology operates by heating a storage medium during surplus energy generation and extracting the stored heat when needed. Water-based thermal storage is widely utilized in district heating systems and solar thermal plants due to its cost-effectiveness and high heat capacity (Collins, Hamza, Eweje, & Babatunde, 2024b). However, it requires significant space, and heat losses over time can reduce efficiency. Molten salt storage has gained prominence in concentrated solar power (CSP) plants, where excess heat is stored in high-temperature salts, such as a sodium nitrate–potassium nitrate mixture. This approach allows CSP systems to generate electricity even after sunset, significantly improving dispatchability. With temperature stability exceeding 500°C, molten salt TES offers high energy density and long-duration storage. However, challenges include corrosive effects on containment materials and the need for precise thermal insulation to prevent energy losses (P. A. Adepoju *et al.*, 2022; Ogunsola, Adebayo, Dienagha, Ninduwezuo-Ehiobu, & Nwokediegwu, 2024a).

PCMs enhance thermal storage by utilizing the latent heat released or absorbed during phase transitions, such as solid-to-liquid or liquid-to-gas transformations. These materials, including paraffin waxes, salt hydrates, and organic compounds, enable high energy densities and stable thermal performance. Unlike sensible heat storage, PCMs maintain a nearly constant temperature during energy exchange, making them ideal for applications requiring precise temperature control, such as building-integrated energy systems and industrial heating processes (Ozowe, Ikevuje, Ogbu, & Esiri, 2023a). Despite their advantages, PCM-based storage systems face challenges such as thermal degradation, low thermal conductivity, and phase separation issues. Recent advancements focus on nanocomposite PCMs and

encapsulation techniques to enhance heat transfer rates and durability. Additionally, hybrid storage approaches integrating PCMs with traditional TES mediums are being explored to improve efficiency and cost-effectiveness (Oladosu *et al.*, 2024).

Thermochemical energy storage (TCES) represents the next frontier in thermal storage, offering significantly higher energy densities than conventional methods. TCES relies on reversible chemical reactions to store and release heat, enabling near-lossless energy retention over extended periods. Examples include metal oxides, zeolites, and salt hydrates, which undergo endothermic and exothermic reactions during charging and discharging cycles. A key advantage of TCES is its ability to store heat for indefinite durations without losses, making it well-suited for seasonal energy storage and industrial applications. However, widespread adoption is hindered by reaction kinetics, material stability, and cost-effectiveness challenges. Ongoing research explores catalysts and composite materials to enhance reaction efficiencies and scale up TCES deployment (Oladosu *et al.*, 2024).

TES offers various applications beyond power generation, including waste heat recovery, industrial process heating, and district heating and cooling systems. Industries such as steel, cement, and chemical manufacturing generate substantial excess heat that can be captured and reused, significantly improving energy efficiency and reducing greenhouse gas emissions. Moreover, TES integration with heat pumps and combined heat and power (CHP) systems enhances grid flexibility by enabling demand-side energy management. TES is increasingly being explored in the power sector to stabilize renewable energy generation by storing surplus electricity as heat and later converting it back into power. This is particularly relevant for grid-scale applications, where hybrid systems combining TES with mechanical and electrochemical storage can optimize energy dispatch and load balancing (A. H. Adepoju, Eweje, Collins, & Austin-Gabriel, 2024b).

While TES technologies have demonstrated substantial potential, further advancements in material science, system integration, and cost reduction are required to expand their adoption. Improving thermal conductivity, enhancing energy density, and developing advanced insulation techniques remain critical areas of research. Policy support and economic incentives will also play a crucial role in scaling up deployment, particularly in industries with high thermal energy demands. With ongoing innovations, TES is set to become an integral component of the renewable energy landscape, offering efficient, scalable, and long-duration storage solutions for various applications (Onukwulu, Dienagha, Digitemie, & Ifechukwude, 2024b).

2.4 Chemical and Hydrogen-Based Storage

Chemical and hydrogen-based energy storage systems offer long-duration storage solutions with high energy densities, making them vital for grid stabilization, industrial applications, and the decarbonization of hard-to-electrify sectors. These storage mechanisms convert surplus electricity into chemical energy, which can be stored for extended periods and later reconverted into electricity or used directly in industrial processes. Unlike electrochemical and mechanical storage, chemical solutions enable cross-sector energy integration by facilitating energy transport, fuel production, and industrial heat applications. The primary

technologies in this category include green hydrogen production and storage, ammonia synthesis, liquid organic hydrogen carriers (LOHCs), and fuel cells. Each approach presents unique advantages and challenges in achieving scalable and cost-effective renewable energy storage (Ozowe, Ikevuje, Ogbu, & Esiri, 2022).

Hydrogen is a versatile energy carrier with applications spanning electricity generation, transportation, and industrial processes. When produced using renewable electricity through water electrolysis, green hydrogen offers a zero-carbon alternative to fossil fuels. Electrolyzers split water molecules into hydrogen and oxygen, storing the resulting hydrogen in gaseous or liquid form for later use.

Despite its potential, green hydrogen production faces significant challenges, including high electricity consumption, electrolyzer costs, and storage inefficiencies. Electrolysis currently exhibits an energy efficiency of 60%–80%, with losses incurred during hydrogen compression, liquefaction, and reconversion. Innovations in solid oxide electrolyzers (SOECs) and proton exchange membrane (PEM) electrolyzers are improving efficiency and durability, yet cost reductions are required for widespread adoption (Erhueh, Nwakile, Akano, Esiri, & Hanson, 2024).

Storage remains a critical bottleneck due to hydrogen's low volumetric energy density and high diffusivity, which necessitate advanced containment solutions. Common storage methods include compressed hydrogen tanks, cryogenic liquid hydrogen, and underground caverns. While compression to 700 bar is widely used in mobility applications, it demands significant energy input. Cryogenic storage (-253°C) improves energy density but requires substantial cooling infrastructure. Underground storage in salt caverns and depleted gas fields presents a promising large-scale solution, yet its feasibility depends on geological conditions. Researchers are developing metal hydrides and porous materials such as carbon nanotubes and metal-organic frameworks (MOFs) that enable safer, high-density hydrogen absorption to enhance hydrogen storage. These innovations aim to reduce storage costs and enhance energy efficiency (Ozowe *et al.*, 2022).

Ammonia is gaining traction as a promising hydrogen carrier and alternative fuel due to its high hydrogen content, ease of storage, and established production infrastructure. Unlike hydrogen, which requires compression or liquefaction, ammonia can be stored in liquid form at -33°C or ambient temperatures under moderate pressure, making it more practical for transport and long-term storage.

Green ammonia is produced through electrolytic hydrogen and nitrogen fixation via the Haber-Bosch process and powered by renewable electricity. This process enables ammonia to function as both an energy storage medium and a direct combustion fuel in power generation and shipping. Ammonia-fueled gas turbines and internal combustion engines are being developed to facilitate direct ammonia utilization. However, combustion-related challenges, including NO_x emissions and combustion efficiency, require further research to optimize performance and environmental impact. One of the most promising applications of ammonia lies in co-firing with natural gas and coal to reduce carbon emissions in existing power plants. Utilities can transition toward lower-carbon energy generation without extensive infrastructure overhauls by integrating ammonia into fuel mixes (A. H. Adepoju, Eweje, Collins, & Hamza, 2023).

LOHCs provide an innovative hydrogen storage and transport

method by chemically bonding hydrogen to liquid carrier molecules, such as toluene and dibenzyl toluene. These carriers allow hydrogen to be stored and transported at ambient temperature and pressure, eliminating the need for high-pressure tanks or cryogenic cooling. Hydrotic dehydrogenation can release hydrogen on demand, making LOHCs suitable for large-scale hydrogen distribution. The primary advantage of LOHCs is their compatibility with existing fuel infrastructure, enabling seamless integration into supply chains without significant retrofitting. However, LOHC technologies currently face high energy penalties in the hydrogen release process, necessitating catalyst efficiency and thermal management advancements (Myllynen, Kamau, Mustapha, Babatunde, & Adeleye, 2023).

Fuel cells are essential for reconverting stored chemical energy into electricity, playing a key role in hydrogen-based storage systems. They operate through electrochemical reactions that convert hydrogen or ammonia into electricity, heat, and water, offering high efficiency and minimal environmental impact. Various fuel cell technologies cater to different applications, including proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), and alkaline fuel cells (AFCs). PEMFCs are widely used in transportation and stationary power generation due to their high efficiency, fast response time, and compact size. However, they rely on expensive platinum-based catalysts, increasing costs and limiting scalability. Research into non-precious metal catalysts is underway to reduce dependency on rare materials and enhance commercial viability (A. H. Adepoju, Austin-Gabriel, Eweje, & Hamza, 2023).

SOFCs operate at high temperatures (600°C – 1000°C), making them well-suited for industrial combined heat and power (CHP) systems. Their ability to utilize a variety of fuels, including hydrogen, ammonia, and syngas, offers flexibility in energy generation. However, SOFCs require long startup times and expensive ceramic materials, necessitating further technological advancements.

Chemical storage technologies extend beyond grid applications, critical in industrial decarbonization, heavy-duty transport, and energy-intensive manufacturing. The integration of hydrogen storage with steel production, chemical synthesis, and fertilizer manufacturing enables carbon-neutral industrial processes. In aviation and maritime transport, ammonia and hydrogen-based fuels are emerging as viable alternatives to fossil fuels, with ongoing research into hydrogen-powered aircraft, ships, and fuel-cell heavy trucks. Furthermore, hydrogen storage facilitates sector coupling, linking power generation with heating, transportation, and industry. Energy resilience and sustainability can be enhanced by integrating renewable hydrogen into gas grids and industrial energy systems. Hybrid approaches combining battery storage with hydrogen-based backup power are being explored to provide long-duration energy security (Kamau, Myllynen, Mustapha, Babatunde, & Alabi, 2024).

Despite rapid advancements, several barriers must be addressed for chemical and hydrogen-based storage to reach full-scale deployment:

- Electrolysis, fuel cells, and storage infrastructure remain expensive compared to conventional energy carriers. Policy incentives, technological breakthroughs, and economies of scale are crucial for cost reduction.
- Hydrogen production, storage, and reconversion involve

multiple energy conversion steps, leading to overall efficiency losses. Improvements in electrolyzer efficiency, fuel cell performance, and direct hydrogen utilization strategies are needed.

- Large-scale hydrogen deployment requires significant pipeline investments, refueling stations, and industrial integration. Governments and industries must collaborate to build the necessary infrastructure.
- Hydrogen's flammability, embrittlement effects on metals, and leakage risks necessitate rigorous safety measures. Advanced materials and storage technologies must be developed to enhance safety and durability.

Chemical and hydrogen-based storage will play an increasingly pivotal role in achieving carbon neutrality and energy independence. With continued innovations in electrolysis, storage media, and fuel cell technologies, these storage solutions will become integral components of future energy systems, complementing batteries, mechanical storage, and thermal storage (Akinade, Adepoju, Ige, Afolabi, & Amoo, 2021; Uchendu, Omomo, & Esiri).

2.5 Emerging and Hybrid Storage Technologies

As the global energy landscape shifts toward cleaner and more sustainable systems, traditional energy storage solutions like batteries, pumped hydro, and compressed air are being supplemented—and in some cases, replaced—by emerging and hybrid storage technologies. These newer technologies offer the potential for greater scalability, longer-duration storage, and improved efficiency, which are critical for balancing the intermittent nature of renewable energy sources like solar and wind. These innovations span supercapacitors, flow batteries, hybrid energy storage systems, and other next-generation solutions, each contributing unique characteristics to enhance energy storage capabilities.

Supercapacitors, also known as ultracapacitors, are energy storage devices that excel in high power density and rapid charge/discharge cycles. Unlike conventional batteries that store energy chemically, supercapacitors store energy electrostatically in an electric field, leading to much faster response times. This makes them ideal for applications requiring quick bursts of energy, such as frequency regulation in power grids and regenerative braking in electric vehicles. The core advantage of supercapacitors lies in their long cycle life, which can extend to over a million cycles, far surpassing traditional batteries that typically last a few thousand cycles. This durability significantly reduces the need for replacement and associated environmental impact. Additionally, supercapacitors are capable of operating in a wide temperature range and can charge and discharge efficiently in extreme conditions, making them suitable for various industrial, transportation, and grid stabilization applications (A. H. Adepoju, Eweje, Collins, & Austin-Gabriel, 2024a). However, their energy density—the amount of energy stored per unit of mass or volume—is much lower than that of batteries, which limits their use in long-duration energy storage. To address this challenge, researchers are working on hybridizing supercapacitors with other storage technologies, such as batteries, to combine the high power density of supercapacitors with the higher energy density of batteries. This combination is expected to enhance their performance in applications requiring both quick power delivery and longer storage times (Collins, Hamza, Eweje, & Babatunde, 2024a).

Flow batteries are an emerging electrochemical storage device class that stores energy in liquid electrolyte solutions in external tanks, rather than in the solid electrodes used in conventional batteries. The most common types of flow batteries include vanadium redox flow batteries (VRFBs) and all-vanadium flow batteries (AVFBs), which allow for decoupled energy storage and power generation. This means that the amount of energy stored in a flow battery is independent of the size of the battery's power output, providing scalability that is particularly suited for large-scale grid storage (Hamza, Collins, Eweje, & Babatunde, 2024).

The primary advantage of flow batteries lies in their long-duration energy storage capabilities. Unlike lithium-ion batteries, which are typically effective for short-to-medium duration storage (a few hours to a day), flow batteries can deliver energy for days to weeks depending on the size of the electrolyte storage tanks. This feature makes them highly suitable for storing excess renewable energy generated during periods of high production (such as sunny or windy days) for later use during times of high demand or low generation. However, while flow batteries offer significant advantages in terms of scalability and longevity, their development is still hindered by high initial capital costs, complexity in system integration, and relatively low energy density compared to other storage solutions like lithium-ion batteries. Nonetheless, the potential for modular design and ease of scaling up energy storage capacity could make flow batteries an attractive option for large-scale renewable energy projects, particularly in regions with significant seasonal variations in energy generation (Attah, Ogunsola, & Garba, 2023).

Hybrid energy storage systems (HESS) combine two or more types of energy storage technologies to optimize overall system performance by leveraging the strengths of each individual technology. The primary aim of HESS is to mitigate the weaknesses of individual technologies and achieve greater efficiency, cost-effectiveness, and extended storage duration. One of the most common combinations is the hybridization of batteries and supercapacitors.

In a battery-supercapacitor hybrid system, supercapacitors handle short bursts of power, such as when grid stability is threatened or during peak load times, while batteries provide longer-duration storage to ensure that excess energy is available over longer periods. This combination allows the system to perform more effectively in a wider range of applications, improving both power density (through the supercapacitors) and energy density (through the batteries) (Kamau, Myllynen, Collins, Babatunde, & Alabi, 2023).

Another promising approach to hybrid storage systems is combining lithium-ion batteries with flow batteries. Lithium-ion batteries are known for their high energy density and fast response times, making them ideal for applications requiring quick energy delivery, such as electric vehicles and small-scale grid storage. On the other hand, flow batteries provide scalability and long-duration storage. Integrating these two technologies makes it possible to create a hybrid system that balances short-term energy needs with long-term storage. Furthermore, researchers are exploring integrating thermal storage systems with electrical energy storage technologies. For example, a hybrid thermal-electric storage system could store renewable energy in the form of heat (using molten salts or phase-change materials) and then use that stored heat to generate electricity when required. This hybrid approach can provide additional flexibility in the grid and improve overall energy efficiency by utilizing both heat and electrical storage.

The future of hybrid storage systems is increasingly tied to developing advanced control systems and integrating artificial intelligence (AI) for real-time optimization. AI algorithms can enhance the performance of hybrid systems by predicting energy demand, optimizing storage charge/discharge cycles, and ensuring the most efficient use of stored energy. These algorithms can also assist in determining the optimal mix of storage technologies based on weather patterns, energy demand forecasts, and grid stability. For example, in a hybrid system that combines batteries, supercapacitors, and flow batteries, AI can monitor the grid's performance and decide in real time which storage technology should be used for a specific task, ensuring maximum efficiency. Additionally, AI can assist in predictive maintenance, identifying potential issues before they arise, and reducing downtime and maintenance costs (Onukwulu, Dienagha, Digitemie, & Ifechukwude, 2024a).

As renewable energy systems become more decentralized and the demand for storage solutions grows, the importance of AI-enabled hybrid energy storage systems will likely increase. These systems will improve energy storage efficiency and play a critical role in facilitating the integration of renewable energy into national and international grids. Despite their potential, emerging and hybrid energy storage technologies face several challenges. Many of these systems, such as flow batteries and hybrid solutions, are still expensive to deploy at scale. Continued research and development are needed to reduce costs and improve manufacturability (Ogunyemi, Ahmed, & Ajibola, 2024).

Integrating new storage systems with existing energy infrastructure poses technical challenges, particularly in terms of compatibility with traditional power grids. While many emerging technologies show promise, most are still in the development or pilot stages. Significant investment and long-term commitment are required to bring them to commercial maturity. The next generation of hybrid and emerging storage technologies will likely integrate multiple storage systems within smart grids that can provide adaptive, real-time responses to energy demand and supply changes. By improving the efficiency and cost-effectiveness of these technologies, they will become central to achieving energy resilience and facilitating the transition to a carbon-neutral future (Ramu, Subramani, Palaniyappan, & Pitchai).

3. Challenges and Limitations in Renewable Energy Storage

3.1 Technical Barriers

One of the most pressing technical challenges in renewable energy storage is the energy density of current storage technologies. Energy density refers to the amount of energy that can be stored per unit of mass or volume. While lithium-ion batteries have made substantial progress in energy density, they still fall short when compared to conventional fuels like gasoline, which have significantly higher energy densities. This limitation constrains the range and efficiency of energy storage systems, especially for long-duration storage required to balance renewable energy supply and demand. For example, lithium-ion batteries, despite their widespread use, may only provide several hours of energy storage, whereas longer-duration storage (lasting days or even weeks) remains a challenge, particularly for seasonal fluctuations in renewable energy generation (Jafarizadeh *et al.*, 2024).

Furthermore, energy storage systems face ongoing concerns

related to efficiency—the percentage of energy that can be recovered from storage. In many cases, energy losses during charging and discharging cycles can significantly reduce the overall efficiency of storage technologies. For example, while pumped hydro storage systems can achieve high round-trip efficiency (up to 80-90%), other technologies such as batteries typically experience greater energy losses, with round-trip efficiencies ranging from 70-85%. Flow batteries, while offering the advantage of scalability, still face efficiency challenges due to the complex nature of electrolyte solutions and energy conversion processes (Elalfy, Gouda, Kotb, Bureš, & Sedhom, 2024).

Another significant technical barrier is the degradation of storage systems over time. Many energy storage technologies suffer from capacity degradation after repeated charge/discharge cycles, reducing their effectiveness and lifespan. Lithium-ion batteries, for instance, experience gradual loss of capacity, typically after around 500-2,000 cycles depending on usage and operating conditions. This cycle life limitation poses challenges for the long-term deployment of large-scale storage systems, as frequent replacements could add substantial costs and environmental impacts. Additionally, thermal degradation (due to high temperatures) and mechanical wear can contribute to the decline in performance, making it essential to improve the durability and lifetime of energy storage technologies through advanced materials and better thermal management (Bokopane, Kusakana, Vermaak, & Hohne, 2024).

To overcome these technical barriers, there is a growing focus on innovating new materials and designs that can improve energy density and efficiency. Emerging technologies like solid-state batteries and supercapacitors hold promise, but much work remains to be done to enhance their performance and overcome their limitations.

3.2 Economic and Market Constraints

The economic viability of renewable energy storage technologies is one of the primary barriers to their widespread adoption. Despite significant advancements, many of these systems remain expensive, particularly for large-scale applications such as grid storage. Lithium-ion batteries, while being among the most commercially viable storage technologies, are still costly, with prices ranging from \$150 to \$200 per kWh for large-scale applications. While costs have fallen dramatically over the past decade, they remain high relative to the energy storage demands required for grid-scale applications and for storing seasonal energy surpluses from renewables like wind and solar power (Jafarizadeh *et al.*, 2024).

Capital expenditures (CAPEX) associated with building infrastructure for energy storage—such as battery storage systems, pumped hydro facilities, or flow battery plants—also remain a significant challenge. The upfront investment for large-scale systems can run into hundreds of millions of dollars, making it difficult for many energy producers to justify the cost, especially in regions where renewable energy prices are still volatile, or grid infrastructure is underdeveloped (Shan, 2024).

Moreover, scalability is another critical economic constraint. While many storage technologies work well on a small scale or in pilot projects, scaling up these systems to handle the increasing demand for renewable energy requires substantial technological advancements and new business models. For example, battery energy storage systems (BESS) are often

more suitable for short-duration applications and smaller-scale deployment, but expanding these systems to meet the needs of entire regions or national grids presents significant logistical and cost challenges. Similarly, the energy density limitations of many technologies (e.g., compressed air energy storage and flywheel systems) make them less effective in applications where longer-duration storage is needed, further complicating cost-benefit analysis at larger scales (Johnson, Seyi-Lande, Adeleke, Amajuoyi, & Simpson, 2024).

The levelized cost of storage (LCOS) is a key metric that reflects the cost-effectiveness of a given storage technology over its lifetime, including both capital and operating costs. Achieving competitive LCOS compared to other forms of energy generation, such as natural gas or nuclear power, is essential to drive the adoption of renewable energy storage technologies. However, the current LCOS for some storage systems is still too high for large-scale deployment, although cost reductions and market incentives (such as subsidies or tax credits) are helping to lower these costs over time (Klar, 2024).

3.3 Infrastructure and Grid Integration

The successful integration of renewable energy storage technologies into existing grid infrastructure poses substantial technical and regulatory challenges. One of the major hurdles is the grid integration of intermittent renewable energy sources, such as wind and solar power, which require storage systems to balance supply and demand in real-time.

A key solution to this issue is the development of smart grids—intelligent, flexible networks that incorporate advanced sensor technologies, communication systems, and control algorithms to optimize electricity generation, distribution, and storage. Smart grids enable dynamic load management, allowing for real-time communication between power producers, storage systems, and consumers. This enables more efficient use of stored energy during periods of high demand and ensures that excess renewable energy is stored when generation is high, preventing curtailment and improving grid resilience (Velasquez, Moreira-Moreira, & Alvarez-Alvarado, 2024).

However, smart grid implementation is still in its early stages in many regions, and regulatory frameworks often do not support the rapid deployment of new technologies. Grid operators must address complex questions around grid stability, ancillary services (such as voltage control and frequency regulation), and market mechanisms to support widespread integration of renewable energy storage systems. In addition, demand-response mechanisms—programs that incentivize consumers to shift their electricity use to off-peak periods—will play a crucial role in facilitating storage integration. These programs help to smooth out load profiles and make it easier for storage systems to handle variations in renewable energy supply (Khalid, 2024b).

While the potential of smart grids and demand-response mechanisms is clear, the transition to these systems requires substantial infrastructure investment and the development of new regulatory frameworks that encourage cooperation between utilities, storage providers, and consumers. The complexity of integrating multiple storage technologies with diverse energy sources makes grid modernization daunting and requires coordinated efforts from policymakers, utilities, and private industry (Moreno Escobar, Morales Matamoros, Tejeida Padilla, Lina Reyes, & Quintana Espinosa, 2021).

3.4 Environmental and Sustainability Considerations

As renewable energy storage systems become more widespread, addressing the environmental impact of these technologies is essential to ensure that they contribute to the overall goal of a sustainable energy future. One of the major environmental concerns is sourcing and mining materials used in energy storage devices, particularly for technologies like lithium-ion and flow batteries, which rely on raw materials such as lithium, cobalt, and nickel. These materials are often sourced from regions with limited environmental oversight, and their extraction can result in habitat destruction, water contamination, and human rights violations (Hannan *et al.*, 2021).

The challenge lies in finding sustainable alternatives to these materials and reducing the environmental footprint associated with their production. Research is underway to identify alternative materials, such as sodium-ion or solid-state batteries, which could reduce the need for rare and environmentally problematic materials. Additionally, developing recycling systems to recover valuable materials from used batteries is critical to reducing the environmental impact of energy storage. Battery recycling rates remain low, and the process is energy-intensive. However, advances in recycling technology and circular economy models offer promising solutions to address these issues.

The lifecycle impact of energy storage technologies is another important consideration. While storage systems can significantly reduce emissions from renewable energy generation, their manufacture, transportation, and end-of-life disposal still have environmental consequences. Therefore, it is essential to adopt cradle-to-cradle principles, where the materials used in energy storage systems can be reused or safely disposed of at the end of their useful life (Al-Shetwi, 2022).

Ultimately, the sustainability of energy storage technologies depends on a holistic approach that considers the full lifecycle impact, from material sourcing and manufacturing to operation and disposal. Governments, industries, and researchers must work together to develop policies and technologies that promote the circularity of materials and reduce the overall environmental burden of energy storage systems.

4. Innovations and Future Directions

4.1 AI and Data-Driven Optimization in Energy Storage

Artificial intelligence (AI) and machine learning (ML) transform the energy storage landscape by enabling predictive maintenance, energy management, and operational optimization. AI's ability to process vast amounts of real-time data and generate insights can vastly improve the efficiency and longevity of energy storage systems, while also making renewable energy more reliable (Khalid, 2024a). One of the most prominent applications of AI in energy storage is in predictive maintenance. By utilizing machine learning algorithms, storage systems can be constantly monitored for signs of wear and tear, battery degradation, or potential failures. Predictive models can analyze patterns in data such as temperature, voltage, and current fluctuations, providing early warnings of when a battery might need servicing or replacement. This can reduce downtime, optimize performance, and prolong the lifespan of energy storage devices. For instance, AI can predict the optimal time for recharging or discharging a system, ensuring the storage device operates at peak efficiency, avoiding unnecessary

wear, and reducing the need for costly repairs or replacements (Ahmad *et al.*, 2021).

Beyond maintenance, AI-driven optimization also plays a crucial role in energy management. Renewable energy sources, such as solar and wind, are inherently intermittent, meaning the energy they generate fluctuates throughout the day and season. AI-based systems can analyze weather patterns, historical generation data, and grid demands in real time to predict fluctuations in energy supply. This allows energy storage systems to charge when excess energy is available (e.g., during peak solar hours) and discharge when there is a demand on the grid or a reduction in generation. Through AI-driven optimization, energy dispatch becomes more efficient, ensuring that stored energy is used most effectively and reducing reliance on fossil fuels (Ukoba, Olatunji, Adeoye, Jen, & Madyira, 2024).

Furthermore, AI algorithms can improve the energy storage efficiency of large-scale systems, such as grid storage solutions. Machine learning models can continually assess factors such as energy loss during charge/discharge cycles, optimizing the processes to reduce inefficiencies. The integration of AI can also enable better coordination between different energy storage assets, improving load balancing and contributing to the grid stability in the face of fluctuating renewable generation.

AI is also at the forefront of the development of digital twins, virtual models of physical storage systems, which simulate their performance. This can be used to test different scenarios, optimize design features, and anticipate how new technologies will perform under various conditions, thus accelerating the development of next-generation storage solutions (Lv & Xie, 2022).

4.2 Advances in Materials Science for Next-Generation Storage

The development of new and advanced materials is one of the key drivers of progress in energy storage technology. Innovations in nanotechnology, sustainable materials, and bio-inspired designs hold the potential to significantly enhance the energy density, efficiency, and scalability of storage systems. Materials science is at the heart of overcoming the limitations posed by traditional storage technologies, and recent breakthroughs are paving the way for next-generation storage solutions (Bertaglia, Costa, Lanceros-Méndez, & Crespilho, 2024).

Nanotechnology is playing an increasingly important role in improving energy storage materials. By manipulating materials at the nanoscale, researchers are developing battery electrodes that are more efficient and have higher energy densities. For example, using graphene and other nanomaterials in battery electrodes can significantly enhance batteries' conductivity and energy storage capacity, leading to faster charge times and higher energy densities. Nanostructured electrodes are also being explored for solid-state batteries, which offer higher energy densities and greater safety than conventional lithium-ion batteries. Solid-state batteries use a solid electrolyte instead of a liquid one, improving their efficiency and reducing the risks of leakage or combustion (Kumar *et al.*, 2024).

In addition to nanotechnology, there is significant interest in bio-inspired materials for energy storage. Bio-mimetic materials, which mimic natural processes, are being explored for their potential to create more efficient and sustainable storage solutions. For example, bio-derived carbon materials

are being investigated in supercapacitors, where high surface area and conductivity are essential. These materials, sourced from natural and renewable substances, could improve energy storage efficiency and help reduce the environmental impact of mining raw materials like lithium and cobalt. Research is also focused on developing materials that can be sustainably recycled, ensuring a closed-loop system for energy storage technologies (Parameswaran *et al.*, 2023).

Additionally, solid-state batteries are poised to be a game-changer in performance and safety. These batteries use solid electrolytes instead of the traditional liquid ones used in lithium-ion systems, which increases energy density and eliminates the fire risk associated with liquid electrolytes. Furthermore, sodium-ion batteries are emerging as a low-cost and sustainable alternative to lithium-ion technology. These batteries use sodium, which is more abundant and less environmentally impactful to mine than lithium. Furthermore, research into phase-change materials (PCMs) is advancing. When heated or cooled, PCMs store energy in latent heat by changing phases (from solid to liquid or vice versa). These materials can be used for thermal energy storage, capturing excess energy from renewable sources like solar power and releasing it when demand is high (Pérez Mendoza, Schmidt, Zarbin, & Winnischofer, 2024).

4.3 Decentralized and Distributed Storage Systems

As the energy landscape evolves, there is a growing shift towards decentralized energy systems where energy production and storage are not confined to large, centralized power plants. Instead, energy is generated, stored, and consumed locally, creating more flexible and resilient energy grids. This shift is facilitated by developing distributed storage systems, peer-to-peer energy trading, and microgrid integration, aiming to decentralize energy control and empower consumers (Di Silvestre, Favuzza, Sanseverino, & Zizzo, 2018).

Peer-to-peer (P2P) energy trading is one of the most promising innovations in the renewable energy space. Individuals and businesses with solar panels or other renewable energy sources can use blockchain technology to sell excess power to their neighbors or local communities. This approach helps reduce energy costs and promotes the widespread adoption of renewable energy by making it more accessible. The blockchain enables secure, transparent transactions without intermediaries, providing greater efficiency and security in energy trading.

Microgrids are another innovation in decentralized energy storage. A microgrid is a localized energy system operating independently or in conjunction with the main grid. It typically incorporates renewable energy generation (such as solar or wind), energy storage, and load management systems to provide energy to a specific community or area. Microgrids offer enhanced resilience during grid failures, as they can disconnect from the central grid and function autonomously. They also allow for greater control over energy use, allowing consumers to manage their demand more effectively (Ajaz & Bernell, 2021).

Community-based energy storage systems are also gaining traction, where multiple households or businesses pool resources to share energy storage capacity. This approach reduces the cost per participant and makes distributed storage solutions more financially viable. Community energy storage systems can also serve as a buffer for excess energy produced by local renewable energy systems, ensuring it is available

when needed most. As more communities embrace distributed energy solutions, the potential for localized energy markets and the democratization of energy increases.

4.4 Policy and Market Innovations

The development and deployment of renewable energy storage technologies are closely tied to government policies, incentives, and the creation of favorable market conditions. Governments worldwide recognize the importance of energy storage in achieving their renewable energy and carbon reduction goals. As a result, policy innovations and regulations aimed at supporting storage adoption are evolving rapidly.

One of the most significant policy innovations is the introduction of subsidies, tax credits, and incentives designed to make energy storage more affordable and attractive. These incentives can help offset the high initial capital costs of installing energy storage systems, which are one of the main barriers to their widespread adoption. For example, the Investment Tax Credit (ITC) offers a 30% tax credit for solar-plus-storage systems in the United States, incentivizing residential and commercial users to invest in energy storage solutions.

Regulatory frameworks are also evolving to enable better integration of energy storage systems into the grid. In many countries, market rules are being updated to allow storage systems to participate in ancillary services markets, such as frequency regulation, where energy storage can help stabilize grid voltage and frequency. In addition, energy storage as a service is emerging as a new business model, where storage providers offer their services to grid operators, utilities, or individual customers on a subscription or pay-per-use basis. This model can help make energy storage more accessible to a wider range of consumers while reducing upfront costs.

New business models are emerging at the market level to facilitate cost-effective and scalable storage deployment. As storage costs continue to decrease, new market entrants, including utilities, tech companies, and startups, are exploring innovative ways to scale up energy storage deployments. For example, virtual power plants (VPPs), which aggregate and optimize the operation of multiple distributed energy resources (including storage), are becoming increasingly popular. VPPs can act as a single dispatchable asset in the market, enabling better grid management and energy efficiency.

The future of energy storage is inextricably linked to developing comprehensive policy frameworks that encourage innovation, investment, and scaling of storage technologies. Policymakers and market stakeholders must work together to create an environment conducive to the rapid adoption and integration of storage solutions, ensuring that renewable energy can achieve its full potential.

5. Conclusion and Recommendations

This review has explored the critical role of energy storage in supporting the integration and scaling of renewable energy technologies, which are pivotal to achieving global sustainability goals. The primary findings indicate that while energy storage systems have made substantial progress, significant challenges still exist. Various storage technologies, including electrochemical, mechanical, thermal, chemical, and emerging hybrid systems, offer promising solutions with advantages and limitations. Lithium-ion batteries continue to dominate the market, but

new materials such as solid-state batteries, sodium-ion, and flow batteries are expected to drive the next wave of innovation.

Furthermore, AI and machine learning are poised to revolutionize energy storage by optimizing energy management, predictive maintenance, and overall efficiency. However, despite these technological advancements, challenges persist in energy density, scalability, and economic competitiveness. Additionally, there is a pressing need for greater policy support and market incentives to accelerate the adoption of energy storage solutions and greater focus on sustainability, particularly regarding material sourcing and recycling.

The findings from this review carry significant implications for various stakeholders, including researchers, industry leaders, and policymakers. For researchers, there is a clear need for further studies focused on the materials science aspect of energy storage technologies. More specifically, research should focus on developing high-density materials that are both sustainable and cost-effective. Nanotechnology and bio-inspired innovations represent promising fields for breakthrough discoveries, which could contribute to better performance and lower production costs for batteries and other storage systems. Moreover, interdisciplinary collaboration between materials scientists, engineers, and AI experts will be essential in advancing energy storage technologies.

For the industry, the focus should shift toward scalable and cost-effective storage solutions. While large-scale solutions such as pumped hydro storage and compressed air storage are important for grid-level storage, distributed storage systems—including microgrids and peer-to-peer trading—present promising opportunities to decentralize energy distribution and increase resilience. Businesses should adopt and integrate smart grid technologies with energy storage systems to enhance grid flexibility and demand-response capabilities. Industries need to engage in sustainability initiatives, addressing the environmental impact of energy storage, particularly concerning battery recycling and material sourcing.

For policymakers, the role in driving the transition toward widespread energy storage adoption is critical. Governments must introduce and maintain supportive policy frameworks, including financial incentives, tax credits, and regulations that foster innovation in the energy storage market. This includes facilitating the creation of integrated energy storage networks, ensuring that energy storage can seamlessly connect with grid infrastructure. Policymakers should also consider the long-term sustainability of energy storage systems, with policies promoting recycling and using eco-friendly materials in energy storage systems.

Several strategic actions are recommended across the technological, economic, and policy domains to accelerate the innovation and deployment of energy storage solutions. From a technological standpoint, research funding should be prioritized to support the development of next-generation storage materials, especially those that focus on energy density and cost-effectiveness. Investment in AI-driven optimization systems is essential to improve the overall performance of storage solutions, as these systems can maximize the efficiency and lifespan of energy storage devices. Collaborative efforts between industry players and academic researchers should be strengthened to accelerate the commercialization of promising storage technologies.

Economically, developing business models that can make energy storage more affordable and scalable is important. Energy storage as a service should be explored as a way to lower initial investment costs for end-users, while virtual power plants can facilitate the aggregation of distributed storage assets, increasing their value in the marketplace. In addition, economies of scale should be pursued, particularly for technologies still in early stages of deployment, such as solid-state and flow batteries, to reduce production costs and make them competitive with established technologies.

At the policy level, governments should implement a comprehensive set of regulations that encourage the adoption of energy storage systems and ensure their integration into the existing energy infrastructure. This includes updating grid codes to accommodate energy storage solutions, promoting demand-response programs, and ensuring that storage systems are compensated for their role in ancillary services such as frequency regulation and voltage control. Additionally, policymakers must advocate for global standards that ensure the interoperability of storage systems, allowing them to work seamlessly with smart grids and renewable energy technologies. Finally, the importance of sustainability cannot be overstated. Efforts must be made to develop recycling and reuse strategies for energy storage devices, especially batteries, to minimize environmental impact and reduce the demand for raw materials. Research into sustainable materials for energy storage is of utmost importance in creating long-lasting, eco-friendly solutions.

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