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The Role of Energy Storage in Climate Change Mitigation: Pathways Toward Sustainable Energy Systems

S Mehmood Ullah Shah[1] Shaoor Ahmed[2] Dr. Imran Khan[3] Sughra Bibi[4]

[1] MS Student, Department of U.S Pakistan Center for Advanced Studies in Energy, University of Engineering and Technology Peshawar, Pakistan.

[2] Telecommunication Engineer, Department of Engineering, Iqra University, Karachi, Sindh, Pakistan.

[3] Assistant Professor, Department of Artificial Intelligence, Dawood University of Engineering and Technology, Pakistan.

[4] PhD Physics Scholar, SST, Physics in Punjab Education Department, University of Education, Lahore, Punjab, Pakistan.

Corresponding Author: S Mehmood Ullah Shah, **Correspondence through:** 16pwele4990@uetpeshawar.edu.pk

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ABSTRACT

This study aimed to review existing literature and evaluate recent evidence related to technological innovation, environmental benefits, policy support and deployment challenges, with a focus on the role of energy storage in decarbonization. A qualitative systematic literature review design was used with secondary data collection approach from peer-reviewed journal articles and international energy reports. A total of 120 publications (from 2020-26) were screened, and 80 articles met the inclusion criteria and were used in the final sample for thematic analysis. The results revealed that 35.0% of the analysed studies were on lithium-ion battery storage, 22.5% of the studies were on pumped hydro storage, 17.5% of the studies were on hydrogen storage, 13.8% of the studies were on thermal energy storage, and 11.2% of the studies were on compressed air energy storage. In addition, 31.3 per cent of the studies cited the integration of renewable energy as the main advantage of energy storage, followed by grid stability (23.7 per cent), carbon emission reduction (20 per cent), energy security (15 per cent), and economic efficiency (10 per cent). The review also found that significant capital investment, reliance on critical minerals, recycling issues, and regulatory uncertainty are significant issues for broad-scale implementation. The study found that by increasing grid reliability, improving the use of renewables, and contributing to global climate change mitigation, energy storage was one of the most important enablers for low-carbon energy transitions. Further technological innovation, policy support, and sustainable investment were still key to meeting resilient and sustainable energy systems.

Keywords: *Battery Energy Storage, Climate Change Mitigation, Decarbonization, Hydrogen Storage, Renewable Energy Integration, Sustainable Energy Systems.*

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Introduction

Climate change issues remain one of the top concerns impacting global environmental sustainability, economic growth, and energy security in developing and developed countries, respectively. Fossil fuel emissions increase the concentration of GHGs, intensifying global warming, increasing the frequency of extreme weather events, SLR, biodiversity loss, and disruption of agricultural production systems. To scale up renewable energy technologies like solar, wind and hydropower, governments and international organizations increased their efforts to achieve carbon neutrality. The production and wind setting of renewable energy was increasingly significant, and the challenges of integrating these resources into the power grid were significant due to their intermittent production. The most immediate near-term solution that emerged to help alleviate the electricity supply vs demand imbalance was energy storage technology for storing excess electricity produced during periods of high production to reduce electricity demand during periods of low production. Energy storage contributed to cleaner electricity generation systems and facilitated the shift towards low-carbon development (International Energy Agency [IEA], 2024; Deng et al., 2023).

The role of rising energy storage was increasingly highlighted on the global stage in the energy transition, especially for connecting variable renewable energy (VRE) technologies into the modern electricity network. By the late 1990s, advanced energy storage (AES) was being seen as playing a critical role in the future of electricity systems to incorporate variable renewable energy (VREs). The implementation of BESS and other forms of energy storage, like pumped hydro storage, compressed air energy storage, thermal storage, and hydrogen storage, received a lot of attention, as they can enhance the flexibility and operational efficiency of the grid. These technologies helped reduce renewable energy curtailment, enhance electricity frequency stability and power quality, and make energy infrastructure more resilient against climatic effects. The cost of batteries, technology and favorable government policies drove down the prices and accelerated the commercialization of energy storage applications from residential and industrial to utility. Energy storage commercialization for residential, industrial, and utility applications was fuelled by the cost reduction of batteries, the development of new technology, and policy support. Large-scale storage technologies were identified as a crucial part of sustainable energy access, which overcame technical challenges associated with renewable electricity generation and mitigated the dependency on fossil fuel-based power generation platforms (Zakeri & Syri, 2023; Luo et al., 2022).

How energy storage contributed to economic and environmental sustainability was also linked to the increased possibilities for electrifying mobility, industry and households. Micro grids and efficient storage technologies became an increasingly large part of the electric vehicles, smart grid, and distributed energy systems puzzle. Energy storage technologies became more critical to the successful electric vehicles, smart grid and distributed energy systems and to micro grids too. Circular economy also stimulated innovation in battery recycling and in the recovery of materials, as well as in the more sustainable use of battery storage systems, thereby reducing environmental impacts. R&D in next-generation batteries, green hydrogen, and long-duration storage technologies helped broaden pathways toward net-zero emission goals and provide enhanced energy cost effectiveness and resilience. More intelligent and adaptive energy systems (IEA, 2024) were also complemented by the ability of digital technologies, Artificial Intelligence and predictive energy management systems to optimize and provide intelligence to energy storage systems (Koohi-Fayegh & Rosen, 2020).

Although tremendous technological advancements have been made, there remain several obstacles to the widespread use of energy storage technologies. The investment required for deployment, critical minerals supply chain issues, critical minerals recycling issues, regulatory uncertainty and infrastructure issues were influencing the deployment in many countries. There were also other technical, financing and policy challenges in the developing economies which hindered financing of sustainable infrastructure for energy, reducing investments. Explicit policy support, international cooperation, technological developments, and market changes were still crucial to unlocking the climate mitigation potential of energy storage, researchers said. Focusing on the contribution of energy storage in the fight against climate change was a valuable exercise that informed policymakers, energy planners, scientists, and industry interested in accelerating the transition to sustainable and resilient energy systems (Tarascon, 2023; Ritchie & Roser, 2024).

Background of the Study

Traditionally, Global energy systems have relied on fossil fuels (coal, oil, natural gas) and escalating needs for electricity associated with the industrialization. These energy sources have led to economic expansion, but have also resulted in considerable GHG emissions that have contributed to climate change. Countries were encouraged to ramp up the production of renewables and reduce carbon emissions using 'cleaner technologies' and under an international accord, such as the Paris Agreement. The increase in the number of solar power and wind power installations was not only rapid, but it was also motivated by the declining cost of the installations and technological development. However, renewables have encountered reliability issues due to their intermittent and weather-reliant nature in ensuring stable electricity supplies. These operational issues were thought to be solvable by energy storage, which was recognized as a necessary enabler to balance renewable energy generation and electricity demand (Deng et al., 2023; Zakeri & Syri, 2023).

In the last ten years, the energy storage industry has seen amazing progress in battery efficiency, battery storage capacity, battery safety and battery stock-life testing. Lithium-ion batteries were selected as the storage technology because they possess high energy density, low cost, and are used in a wide variety of applications ranging from electric vehicles to residential energy storage systems to Utility-Scale Power generation. At the same time, new technologies like PHE, hydrogen storage, compressed air energy storage and thermal energy storage entered the market for storing and integrating low-carbon electricity generation at large scales and integrating VGEs. New energy systems introduced continuous solutions based on new battery chemistry, online monitoring and control of systems and smart grid technologies that enhanced the energy systems' operation efficiency by reducing carbon emissions in power generation (Koohi-Fayegh & Rosen, 2020; Luo et al., 2022).

Shifting to energy storage was a sign of the increased awareness of this technology's economic, environmental and strategic value in enabling global climate policy. To encourage implementation and development of storage, governments used measures ranging from subsidies and financial incentives to carbon pricing, renewable energy policies, and investment initiatives to strengthen national energy security. Energy storage provides a platform for electricity market flexibility, reduced peak demand, risk to the electricity grid, renewable curtailment, and decentralized electricity generation. These advances proved that the capabilities of the energy storage technology were more than just a support technology: it was now an integral part of the new low-carbon energy systems (International Energy Agency [IEA], 2024; Tarascon, 2023). Researchers began exploring technological innovation, policy effectiveness and readiness, and environmental performance to identify ways to make energy storage a stronger contributor to mitigating climate change. This study builds on these developments by examining the strategic elements of energy storage in facilitating sustainable energy systems and supporting global efforts to decarbonize energy use (Ritchie & Roser, 2024; Zakeri & Syri, 2023).

Research Objectives

1. To explore the mitigation of climate change by integrating renewable energy systems with the help of energy storage technologies.
2. To assess the role of energy storage in supporting sustainable, reliable and resilient energy infrastructure.
3. To uncover the technological, economic and policy channels that enabled the widespread adoption of energy storage for realizing a low-carbon energy transition.

Research Questions

Q1. How did energy storage technologies help to support the integration of renewables for climate change mitigation?

Q2. How were energy storage systems employed to improve the sustainability, reliability, and resilience of modern energy systems?

Q3. Which technology, economic and policy paths were most conducive to the widespread deployment of energy storage technology for sustainable energy transitions?

Significance of the Study

This study built an extensive knowledge of energy storage's strategic deployment in enabling climate change mitigation and moving towards more sustainable energy systems. The results built upon the literature and aggregated the state of knowledge on new technologies, integration with renewables and policy that affected energy storage investment. The study was useful for policy debates on ways to enhance energy security, abate GHGs, and build resilience in electricity networks. The recognition of storage technology that can increase the use of renewable energy and system reliability provided substantial benefits to energy planners and utility operators. The results also helped investors and industry players identify new potential market opportunities and challenges in energy storage. In addition, the study provided a valuable reference for researchers and academics to help pave the way for further research into innovation, sustainable development, circular economy and low-carbon energy, thereby contributing to achieving climate neutrality and SDGs globally.

Literature Review

Energy Storage Technologies and Renewable Energy Integration

As the amount of RE generated increased rapidly, solar and wind resource variability and intermittency increased, requiring technologies to address both. In contrast to conventional fossil fuel plants, renewables are also not immune to the weather, which makes electricity production volatile, and so does the grid. This led to the appearance of energy storage technologies – able to store energy when there is more available than is needed, and release it when there is less energy available than is needed. Use of lithium-ion batteries, pumped hydro storage, compressed air energy storage, flow batteries, hydrogen storage and thermal storage could significantly speed up the ability to integrate RE energy and reduce curtailment of electricity, the scientists said. However, the scientists said the use of lithium-ion batteries, pumped hydro storage, compressed air energy storage, flow batteries, hydrogen storage and thermal storage could significantly speed up the ability to integrate RE energy and reduce curtailment of electricity. These technologies also help enhance electricity network flexibility and frequency control, as well as the quality of electricity (Koohi-Fayegh & Rosen, 2020; Zhang et al., 2023), which is necessary for increasing the share of renewables in electricity generation sectors.

Technological innovations continually enhance the efficiency, lifespan and cost-effectiveness of energy storage systems, such as those used in modern energy systems. Increased energy density, faster charging speeds and safety features during the manufacture of batteries have enabled electrochemical storage to be considered in residential, commercial and utility applications. On a seasonal level, however, problems with the ups and downs in renewable electricity provision and demand were addressed by the introduction of hydrogen storage (HD) and pumped hydro storage (PH) (LDS). Connecting multiple energy storage technologies, in addition to a smart grid, with hybrid renewable energy systems provided extra energy system flexibility. It enabled optimization of energy dispatch through digital monitoring and predictive control. These initiatives enhanced systems' ability to provide uninterrupted electricity service even with the variability of renewables (Olabi et al., 2021; Duggan, 2025).

An integrated energy storage system was also called out as an essential part of decentralized energy systems, micro grids and VPPs in recent studies. Distributed storage installations have the potential to engage consumers in electricity markets and optimize energy resilience while reducing dependence on centralized fossil-fuel generation. The automatic / optimization of charging and discharging (via AI, IoT, smart models) also helped to lower the costs of operation and accelerate the use of renewable energy. Hence, energy storage is now regarded as a facilitator which could lend a hand to the integration of renewables and to modernizing the electricity networks and achieving long-term energy sustainability (George-Andrei Beşchea et al., 2026; Integrated Energy Storage Systems Review, 2025).

Climate Change Mitigation Technology

Energy storage was widely recognized as a potential solution to greenhouse gas emissions, and the pace of transition to a low-carbon energy system and the momentum for addressing it through climate change mitigation grew. The understanding that energy storage is an important element in tackling greenhouse gas emissions and accelerating the transition to low-carbon energy systems grew, making it more common to address it as part of climate change mitigation. Electricity generation through renewable fuels had the greatest negative impact on carbon emissions; however, this was reduced by the lack of backing from storage solutions, as well as intermittent energy generation. One solution to the difficulty of balancing electricity supply and demand was to use energy storage to alleviate the negative impacts of wind and solar power sources, typically by enabling backup power generation from non-renewable sources and a greater inflow of renewable power. The promotion of supply-side measures such as raising and conservation for reduced electricity generation and reduced transport and industrial emissions, as well as the encouragement of energy efficiency, reduced emissions, and net zero on a national level (Koohi-Fayegh & Rosen, 2020; Zhang et al., 2023).

Not only was energy storage an integral part of renewables integration; it also played a role in green electricity use in the specific context of renewables. The EES improved electric vehicle performance and facilitated vehicle-to-grid applications, which helped electric vehicle batteries meet demand spikes on the electricity network. Hydrogen's applications for energy storage became increasingly interesting for decarbonizing heavy industries, long-distance transportation systems, and off-peak periods. The researchers suggested that this could be a key opportunity for the deep decarburization of energy, given that hydrogen generation also has the potential to significantly lower the dependence on fossil fuels in Australia, alongside renewable electricity generation. The researchers said that this could be a major opportunity for the deep decarburization of energy, as hydrogen generation will also lower or eliminate dependence on fossil fuels in Australia while generating renewable electricity.

The researchers also pointed to some sustainability issues that need to be addressed in the future, such as the development of new technologies for collecting and storing energy. Battery manufacturing was highly technology-dependent, and minerals such as lithium, cobalt, and nickel were difficult to come by; other batteries were environmentally polluting and also geopolitically risky. The reduction of environmental impacts in batteries' life cycles thus evolved to become a crucial research axis in the field of battery recycling, strategies for the circular economy and sustainable material innovation. Based on current literature, if the goal of climate mitigation is to be achieved in the future, the performance level of the storage technology, the sustainability of the stored materials and their responsible use must be optimized to achieve the greatest benefit to the environment in the long term.

Managing Energy Systems in a Sustainable Way

The shift to an energy system that utilizes sustainable elements requires not only advances in technology, but also the emergence of favorable policy frameworks and institutional innovations. Global governments established renewable energy targets, carbon pricing schemes, investment subsidies and policy changes to promote energy storage and speed up the decarburization process. Researchers emphasized the issue of policy certainty to reduce the risk of investments from the private sector, as well as consideration of investments/development and research on advanced storage technologies. Good governance systems were also in place for the practices identified for electricity market reforms, which recognized the benefits of electric storage solutions like frequency regulation, peak shifting, reserve capacity and balancing the grid (Duggan, 2025; Oliver et al., 2026).

New technologies continued to be a critical factor in the progress of sustainable development with steady advancements in battery chemistry, digital energy management, smart grid and artificial intelligence applications. The application of new technologies resulted in more precise predictions, more efficient dispatch of electricity, greater efficiency in electricity storage and reduced energy system operation costs. Further improvements to the flexibility and beneficial usage of renewable energy have been made through the introduction of sector coupling, the introduction of DERs, and demand response programmes into the system, as well as with the introduction of intelligent energy management systems. A convergence of storage technologies, performance and digitalization technologies, and advanced grid infrastructure was recognized as one of the pathways to attain resilient and carbon-neutral electricity systems (Pastore, 2026).

Although a lot of progress has been made, there are still definite challenges that must be overcome for widespread adoption of energy storage technologies. Investment costs, regulatory issues, infrastructure restrictions, and market design problems, as well as a lack of international cooperation, all had a significant effect on the adoption of storage, especially in developing economies. The researchers recommended coordinated policymaking, increased public and private capital related to clean fuel technologies, knowledge sharing and technology transfer across the nations and sustainable financing approaches to accelerate the commercialization process and equity of the access to clean fuel technologies. The successful integration of the technological transformation, the good governance and a climate policy comprehensive enough to enable long-term energy transformation and decarburization in the future depended on that.

Research Methodology

Research Design

This study is a qualitative research with a systematic literature review. This design allowed for a detailed assessment of the state-of-the-art scientific understanding about the role of energy storage technologies in sustainable energy systems and climate change mitigation. A structured systematic review method was used to gather, analyses, and synthesize evidence from peer-reviewed journal articles, international publications, and conference materials. The emphasis of the research was on the recurrent themes, technological innovations and advancements, policy trends, environmental threats, and prospects for energy storage.

Data Sources

The study used exclusively secondary sources of information—such as peer-reviewed academic and institutional publications—that were reliable and reputable. Most of the information came from peer-reviewed journal articles relevant to the topic and cited in Google Scholar, Scopus, or the Web of Science index. Further data were gathered from reports issued by international organizations such as the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), the Intergovernmental Panel on Climate Change (IPCC), and the World Bank. The chosen publications covered the following areas: renewable energy integration, battery energy storage systems, hydrogen storage, thermal storage, pumped hydro storage, climate policy, and sustainable energy transitions.

Sample and Sampling Technique

The selection of relevant publications was done through purposive sampling to include publications that directly addressed the objectives of the study. The literature search involved screening of a total of 120 peer-reviewed research articles, review papers, and international policy reports published in the last seven years (2020-26). Following defined inclusion and exclusion criteria, 80 publications met these quality criteria and were included in the final analytical sample. The studies chosen were cross-disciplinary, geographical, technological and policy in scope, ensuring a broad and full picture of ongoing energy storage and climate change mitigation developments.

Inclusion and Exclusion Criteria

The criteria for selection were peer-reviewed journal articles published in English during the specified timeframe (2020-2026) and related to energy storage technologies, renewable energy integration, sustainable energy systems, climate change mitigation, and energy policy. Preference was given to studies with empirical results, systematic reviews and meta-analyses, and policy evaluations. Any non-peer-reviewed publications, duplicate studies, opinion pieces, editorials, or any research that was not related to the Sustainable Energy and Climate Mitigation (SEC) was removed from the review.

Data Collection Procedure

A systematic and transparent literature search process was used. Electronic databases such as

Google Scholar, Scopus, Science Direct, Springer Link, IEEE Explore, Wiley Online Library and Taylor & Francis Online were used to identify relevant publications. Energy storage and battery energy storage were the keywords, along with renewable energy integration, climate change mitigation, hydrogen storage, smart grids, low carbon energy systems, and sustainable energy systems. Titles and abstracts were scanned for relevance before reading the articles. After selecting articles, a thorough review of the full-text articles was undertaken.

Data Analysis Technique

Thematic content analysis, one of the qualitative data analysis techniques, was used to analyses the selected literature. Information extracted was classified under main themes: integration of renewables, climate change mitigation, technological innovations, policy development, economic challenges, environmental sustainability, and future research directions. This synthesis aimed to characterize common patterns and relationships across studies, while contrasting patterns were examined for balanced interpretations. The thematic analysis enabled a thorough assessment of the role of energy storage technologies for sustainable energy and decarburization at the global level.

Results and Analysis

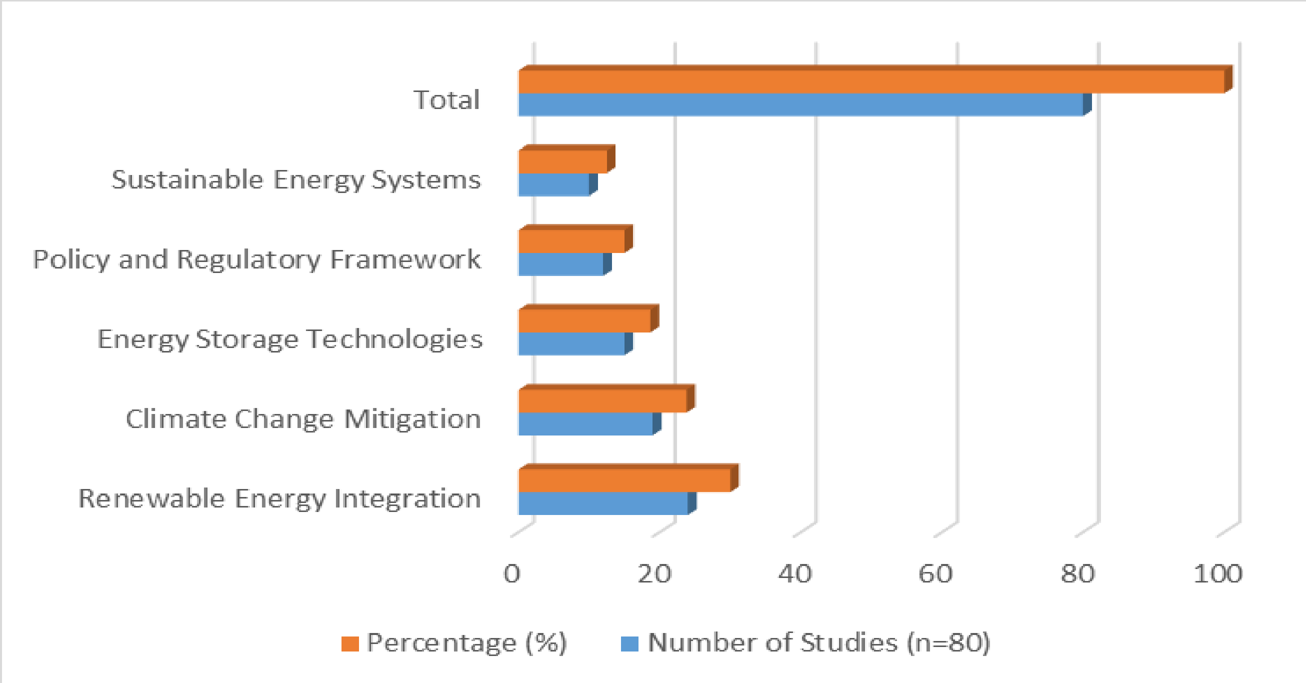
Distribution of Selected Literature by Research Theme

Table 1: *Distribution of Reviewed Studies According to Major Research Themes*

Research Theme	Number of Studies (n=80)	Percentage (%)
Renewable Energy Integration	24	30.0
Climate Change Mitigation	19	23.8
Energy Storage Technologies	15	18.7
Policy and Regulatory Framework	12	15.0
Sustainable Energy Systems	10	12.5
Total	**80**	**100.0**

The research demonstrated in Table 1 showed that Renewable Energy Integration was the topic of the highest number of research studies (30.0%), suggesting that researchers heavily concentrated on the need for energy storage to manage the volatility of renewable energy sources like solar and wind. The second largest group number was Climate Change Mitigation (19 studies, 23.8%), indicating the increasing relevance of energy storage in the fight against greenhouse gas emissions, as a contributor to decarburization and towards meeting the target net zero status. Energy Storage Technologies (18.7%) included 15 studies, reflecting ongoing research on energy storage technologies such as batteries, hydrogen storage, and thermal storage, and the development of new energy-efficient and smart grid technologies. In comparison to other categories, there were 12 studies (15.0%) in Policy and Regulatory Framework, underlining the central role of government incentives, market reforms and regulation to stimulate energy storage deployment. Sustainable Energy Systems had the smallest portion (12.5%), showing that while sustainable energy continued to be an important research topic, more research was focusing on technological advancements and integration of renewable energy.

Figure 1*: Distribution of Reviewed Studies According to Major Research Themes*



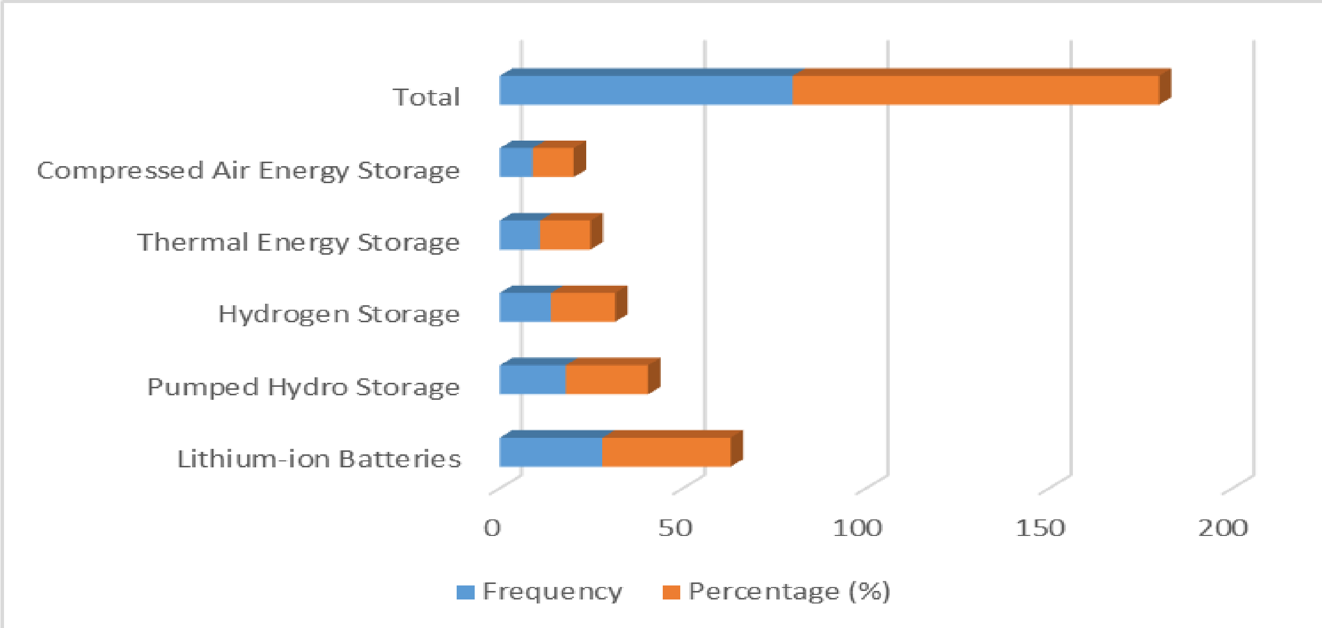
Energy Storage Technologies Examined in the Literature

Table 2: *Types of Energy Storage Technologies Discussed in the Reviewed Studies*

Energy Storage Technology	Frequency	Percentage (%)
Lithium-ion Batteries	28	35.0
Pumped Hydro Storage	18	22.5
Hydrogen Storage	14	17.5
Thermal Energy Storage	11	13.8
Compressed Air Energy Storage	9	11.2
Total	**80**	**100.0**

As per the results shown in Table 2, Lithium-ion Batteries were the most discussed energy storage technology, with 28 studies (35.0%) accounting for the complete literature reviewed. The significant percentage was the result of the expansion of lithium-ion batteries by their relatively high energy density, rapid charging capacity, declining production costs and a wide range of applications for residential, commercial, and utility-type energy storage applications. Pumped Hydro Storage was the second largest technology group, accounting for 18 studies (22.5%), showing that it remains an important and established large-scale storage technology to balance the supply and demand of electricity. 14 studies (17.5%) were found for Hydrogen Storage, showing a growing importance in the field of providing long-duration energy storage, decarbonizing industries and generating green hydrogen for low-carbon energy systems of the future. Increased interest in improving the energy efficiency through better utilization of energy stored in thermal form was found in 11 studies (13.8%) of Thermal Energy Storage. Compressed Air Energy Storage was the least represented technology in these studies, with a total of 9 studies (11.2%), indicating that Compressed Air Energy Storage is still comparatively less commercialized and has not been much researched for large-scale electricity storage, but still has considerable potential.

Figure 2: *Types of Energy Storage Technologies Discussed in the Reviewed Studies*



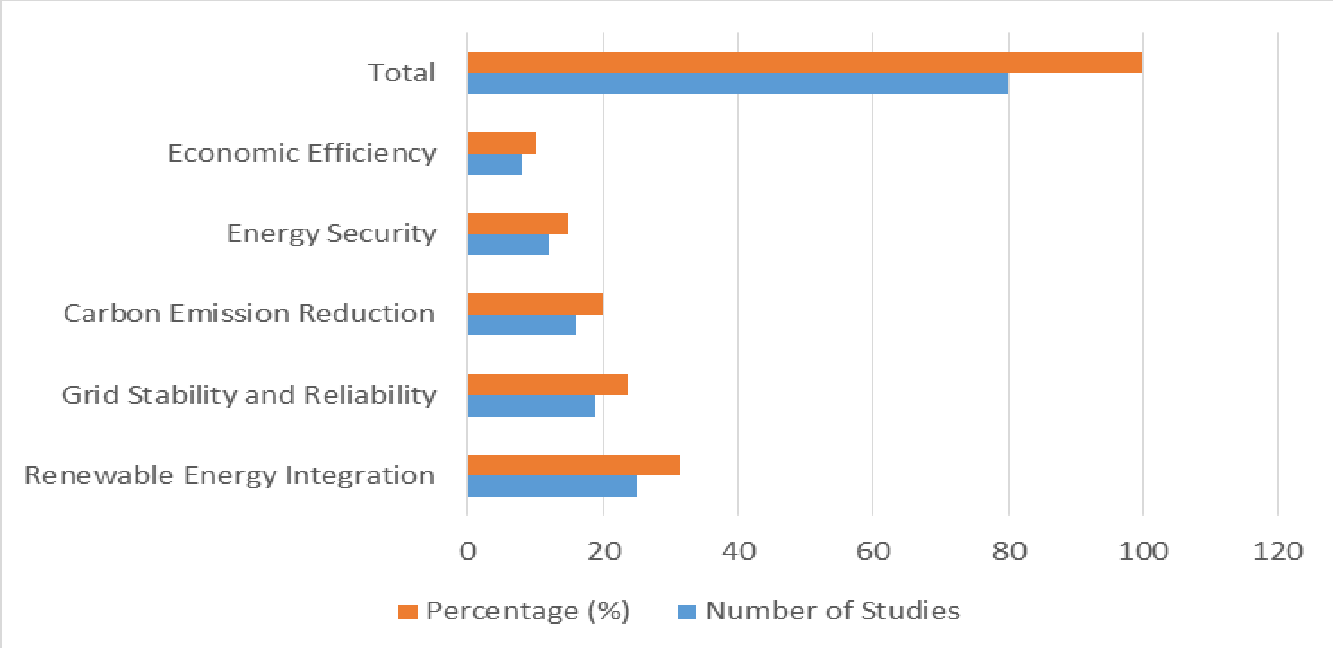
Major Contributions of Energy Storage to Sustainable Energy Systems

Table 3: *Identified Benefits of Energy Storage Systems*

Identified Benefit	Number of Studies	Percentage (%)
Renewable Energy Integration	25	31.3
Grid Stability and Reliability	19	23.7
Carbon Emission Reduction	16	20.0
Energy Security	12	15.0
Economic Efficiency	8	10.0
Total	**80**	**100.0**

Table 3 shows that the highest number of studies (25 studies; 31.3%) identified REI as the benefit of energy storage systems. This outcome showed that researchers mostly expressed awareness that energy storage would play a vital role in controlling the volatility of Renewables (RE), minimizing electricity curtailment, and maximizing solar and wind energy usage. With 19 studies (23.7%), Grid Stability and Reliability was the second most common technology feature, demonstrating the potential energy storage technology has to support frequency regulation, voltage stability, load balancing, and a continuous supply of electricity when energy supplies fluctuate. The studies on Carbon Emission Reduction (16 studies, 20.0%) acknowledge that energy storage plays an important role in reducing fossil fuel electricity generation dependency and contributing to achieving the decarburization target for countries and globally. With respect to Energy Security, 12 studies (15.0%) highlighted the importance of the use of storage technologies to reinforce energy security, increase levels of electricity resilience, and ensure energy supply in situations of peak demand and emergency. In economic efficiency, the lowest proportion was with 8 studies (10.0%) and in the reviewed literature it was found that the energy storage systems could have enhanced the efficiency of the electricity market and reduced long-term operational costs; however, economic factors were less significant when compared to the environmental and technical factors.

Figure 3: *Identified Benefits of Energy Storage Systems*



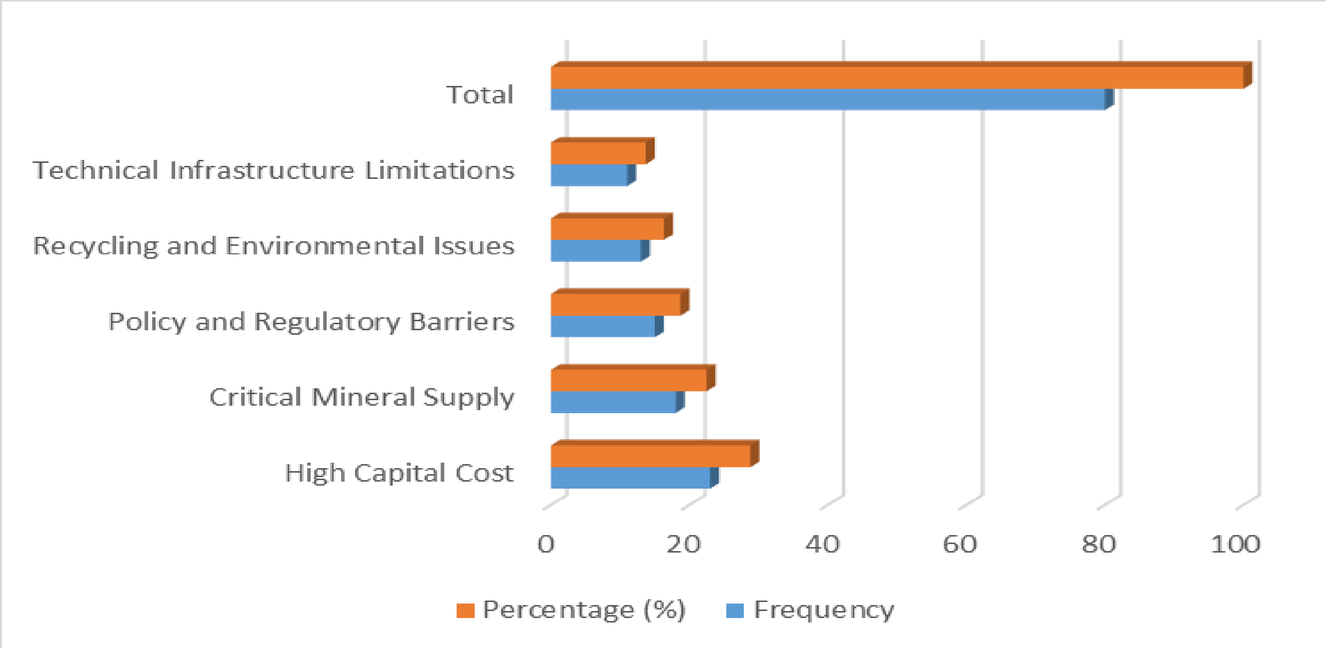
Challenges Affecting Energy Storage Deployment

Table 4: *Major Challenges Identified in the Literature*

Challenge	Frequency	Percentage (%)
High Capital Cost	23	28.8
Critical Mineral Supply	18	22.5
Policy and Regulatory Barriers	15	18.7
Recycling and Environmental Issues	13	16.3
Technical Infrastructure Limitations	11	13.7
Total	**80**	**100.0**

Table 4 shows that the issue of High Capital Cost (23 studies, 28.8%) is the biggest challenge for energy storage technologies deployment. Based on this finding, the high investment that energy storage units require remains a major constraint, especially for developing countries and emerging energy markets. Critical Mineral Supply came in second with 18 studies (22.5%), highlighting the increasing concerns regarding the availability and sustainability of critical materials, including lithium, cobalt and nickel, which are commonly used in battery production. Policy and Regulatory Barriers represented 18.7% of the studies, with noted delays to investment and large-scale implementation of energy storage projects due to inconsistent regulations, fewer financial incentives, and policy uncertainty. Eight of these studies (16.3%) fell under the category of Recycling and Environmental Issues, indicating the need for efficient and sustainable battery recycling methods, waste management strategies, and environmental considerations for reducing the environmental impact of battery production. Technical Infrastructure Limitations included 11 studies (13.7 per cent), indicating that poor technical grid infrastructure, transmission line limitations, and poor technological preparedness continue to hinder effective incorporation of advanced energy storage technologies.

Figure 4: *Major Challenges Identified in the Literature*



Discussion

Therefore, the findings of this research revealed that energy storage has a catalytic effect on carbon emission reduction, supporting the energy sector in integrating renewable energy into electric power systems. The evidence gathered and analyzed indicated that battery energy storage systems, pumped hydro storage and hydrogen storage & thermal energy storage systems all enhanced the grid flexibility and grid reliability in their role in reducing the variability of PV and wind energy. These findings were in line with the recent studies that found energy storage is an integral component of a decarbonized electricity system, which is important given the ability to match demand and supply as well as mitigate fossil-fuel reliance by electricity generation (Levin et al., 2023; Rana et al., 2023; Adeyinka et al., 2024).

Furthermore, the state-of-the-art energy storage methods revealed a significant impact on their effectiveness and scalability due to technological advancements. Industrial developments, such as lithium-ion batteries and hybrid energy storage, are enhancing the energy efficiency, capacity and resilience of electricity networks via compressed carbon dioxide storage and long-duration energy storage. In general, it was found that the synergy of AI, digital energy management, and smart grids was consistently suggested as a solution to help optimize charging/discharging and improve the performance of the power grid. The reduction of renewable energy curtailment and strengthening of electricity security during variability in renewable energy generation were other technical benefits obtained (condensed from recent International research (Ma et al., 2024; Yi et al., 2024; Adeyinka et al., 2024)).

Another important result, directly linked to the reduction of greenhouse gas emissions and, in general, environmental sustainability, was the role of energy storage. Unavoidably, all cited studies have concluded that energy storage and the connection of RES to peak hours mean a shift away from carbon-intensive peaking power plants in general. This was a capacity-building effort for decarburization of the electricity sector, for transport and industry and for long-term climate mitigation measures. Energy storage technologies that would enable more flexible penetration of renewable electricity sources and reduce system vulnerabilities were discussed, including long-duration storage technologies (such as hydrogen storage, thermal storage, and advanced battery systems), which play an important role in achieving the net zero emissions target. The results aligned with the recent reviews, which highlight the importance of storage technologies as essential technologies to support climate-resilient low-carbon energy systems (Levin et al., 2023; Arévalo et al., 2024).

While energy storage technology has advanced to a remarkable degree, the study found that several factors still apply and are affecting the broader roll-out of these technologies. Major interests in the surveyed literature were also the costs of anticipated capital investments, dependence on critical minerals supply chains, recycling restrictions, infrastructure problems, and regulatory uncertainties. The researchers pointed out that coordinated market reforms, policy frameworks and financial incentives were needed for the technology's adoption if it was to be a general solution. The hybridization of these with various technologies, along with the development of international collaborations, was frequently mentioned as a means to improve economic viability and accelerate commercialization (Yi et al., 2024; Ma et al., 2024; Shamsi et al., 2024).

The results indicated that energy storage is a crucial element for sustainable energy transitions, as it can facilitate the increased integration of renewable energy into the electricity supply increase the reliability of the electricity supply, make the electricity supply more climate-resilient, and reduce GHG emissions. The technology, investment, governance and international cooperation needed to be further developed, they wrote. Scaled-up installations of long-duration storage solutions, development of smart tools for energy management and continued research into sustainable battery materials, and introduction of adaptive policy frameworks would support efforts to achieve climate neutrality (Levin et al., 2023; Adeyinka et al., 2024; Rana et al., 2023; Yi et al., 2024; Arévalo et al., 2024).

Conclusion

The study was a literature review (LR) that reviewed relevant literature and emphasized the role of energy storage in climate change mitigation and sustainable energy systems. The results indicated that energy storage technologies have enabled energy integration from renewables and ensured energy stability of the electrical grid, which has helped ensure reliability and flexibility in energy. Battery energy storage, pumped hydro storage, hydrogen storage, and thermal energy storage were the most common technologies identified as having the potential for being integrated to address intermittency challenges of renewable energy sources and low-carbon electricity generation. Furthermore, the review included evidence of the effectiveness of energy storage in reducing GHGs, which was concluded as the more thorough use of renewables and the decreased reliance on power generation using fossil fuels. The innovation of technology, digital energy management and policy behind the scenes further drove the diffusion and implementation of storage technologies.

Recommendations

Governments need more comprehensive policy frameworks to support investments in energy storage through financial instruments, tax incentives, and policies. Energy storage is imperative to include with renewable energy (RE) projects for their role in supplementing electricity reliability and reducing carbon emissions, as part of a country's energy strategies. There should also be greater interaction between the public and private sector for the rapid commercialization of new storage devices. Scientific and industry efforts will need to be stepped up for investment in innovative battery technologies, hydrogen storage, and long-duration energy storage technologies. In this context, however, it would make sense to increase efforts in the field of the environment, especially in the area of battery recycling, creation of sustainable materials, and circular economy activities. The system could also be improved by putting in place smart grid infrastructure and digital energy management systems that improve the efficiency and reliability of the energy system. Smart grid infrastructure and digital energy management systems could further optimize and strengthen the system by improving the efficiency and reliability of modern electrical systems.

Future Directions

Future research should consider the energy market profile and future value of emerging energy storage systems like gravity-based batteries, advanced hydrogen storage system technologies, and solid-state batteries. The comparison of different policy models and investment strategies for successful energy storage applications in developed and developing countries would benefit in understanding effective policy models to enable successful energy storage applications on a large scale. The potential of AI, machine learning and digital technologies for improving energy storage infrastructure and the management of renewable energy sources should be explored further. Long-term sustainability evaluations in terms of economic performance, environmental impacts, resource utilization efficiency and battery lifecycle assessment could also offer useful guidance to any policymakers, researchers and energy planners aiming at the carbon-neutral and sustainable energy systems.

Conflict of Interest

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