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Research Article

Establishing robust low-carbon power networks: A structured bibliometric-informed review of energy storage solutions and regulations (2023–2025)

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Abstract. The accelerating penetration of solar photovoltaic and wind generation has increased the need for energy storage systems capable of supporting grid stability, flexibility, adequacy, and resilience. This study presents a structured bibliometric-informed review of energy-storage research and deployment developments during 2023–2025, with attention to short-, medium-, and long-duration technologies, policy, digitalization, and the Middle East and North Africa (MENA). Literature was identified through Scopus, Web of Science, and IEEE Xplore and complemented by authoritative institutional and government reports. The analytical corpus contains 41 dated sources from 2023–2025, supplemented by a small number of earlier or undated contextual sources. Publication-year trends, recurrent citation patterns within the reviewed corpus, thematic concentration, technology performance, cost, discharge duration, and technology readiness were synthesized. The corpus increased from 11 publications in 2023 to 13 in 2024 and 17 in 2025, indicating rising research attention. The evidence shows that lithium-ion/LFP remains dominant for short-duration services, while sodium-ion, flow batteries, LAES, A-CAES, hydrogen, thermal storage, and pumped hydro address increasingly diverse duration and sectoral requirements. The literature is also shifting from technology-specific studies toward hybrid storage, grid-forming capability, circularity, AI-enabled operation, and market design. For MENA systems, portfolio-based solutions appear more appropriate than reliance on a single technology. Robust low-carbon grids therefore require coordinated technological, economic, regulatory, and digital strategies.

Keywords: Renewable energy, Energy storage, Lithium-ion, Flow batteries, Hydrogen, Long-duration storage, Grid integration

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1. Introduction

The global power sector is undergoing a structural transition as solar photovoltaic (PV) and wind generation account for an increasing share of new electricity capacity. Their low operating emissions and declining costs make them central to decarbonization(Khaleel et al., 2024), yet their weather-dependent output creates rapid ramps, surplus generation, curtailment, congestion, and temporal mismatches between electricity production and demand. These consequences are relevant when renewable penetration is higher and conventional synchronous generation plays a reduced role in providing system inertia and balancing capacity (Firoozi et al., 2025; Khalid, 2024). Energy storage evolved from a niche technology providing some advantages in particular uses to an indispensable feature for future low-carbon electricity systems. Storage can decouple electricity consumption and generation, and perform a multiplicity of functions: shifting load, peak shaving, frequency containment/support, stand-by capacity, relieving congestion, managing variability of renewable electricity sources, and resilience (De Carne et al., 2024). Energy storage technologies, however, vary considerably in their physical principle of operation, duration of discharge, round-trip efficiency, CAPEX and OPEX, lifetime, technological maturity, and ancillary hardware required to provide their intended service. While lithium-ion batteries are well suited to fast-response and short-duration balancing, flow batteries, LAES, A-CAES, TES, PHS, and hydrogen systems are more suitable for longer-duration and sector-coupled applications. It has become timely to summarize the topic due to the pace of deployments. Worldwide storage capacity is growing at high speed, with some 200GWhofnew battery energy-storage capacity reported in 2024, while battery prices continued to fall and lithium-iron phosphate is increasing adoption in stationary applications (Bloomberg NEF, 2024; Berbatović, 2025; Ngoy et al., 2025). Yet deployment growth is uneven: short-duration electrochemical storage is commercially mature, while many medium- and long-duration options remain constrained by capital cost, conversion losses, site requirements, supply chains, market design, and uncertain revenue mechanisms.

Recent scholarship further shows that technology performance alone is insufficient to explain storage adoption. Policy support, market rules, grid-forming power electronics, digital control, forecasting, artificial intelligence (AI), and hybrid system design

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increasingly determine the value that storage can deliver. These factors are especially important for long-duration energy storage, whose contributions to adequacy, resilience, seasonal balancing, and avoided network expansion are not always fully remunerated in electricity markets.

Abundant solar resources, rapidly growing electricity demand, expanding grid infrastructure, ambitious industrial decarbonization targets, and emerging hydrogen strategies create a distinctive combination of opportunities and challenges, and burgeoning strategies toward hydrogen production result in a unique configuration of opportunities and limitations. Regional trajectories will probably not be based on the use of a single storage technology: batteries for intra-daily balance; thermal storage to complement concentrating solar power and industrial process heat; pumped storage for long-duration balancing where geography and topology allow it; and hydrogen to link the power system with the energy needs of industry and storage seasonally (Yang et al. 2024). Particular attention has been given to storage performance, grid stability and resilience, ancillary-service pricing, investment incentives, and the technical, financial, and regulatory barriers to large-scale deployment. Recent research has also increasingly sought to identify the principal constraints to storage integration and to provide evidence-based recommendations for grid planners, operators, policymakers, and investors. Such an integrated perspective is essential for developing effective storage policies, facilitating renewable-energy integration, and maintaining reliable and resilient low-carbon electricity systems.

Despite the expanding literature, recent studies are dispersed across battery chemistry, mechanical and thermal storage, hydrogen, grid integration, economics, and policy. This study therefore aims to (1) map publication trends and recurrent citation patterns in the selected 2023–2025 literature; (2) compare major technologies using discharge duration, efficiency, cost, readiness, advantages, and limitations; and (3) interpret policy, digitalization, hybridization, and regional implications for robust low-carbon networks, particularly in MENA. Combining descriptive bibliometric indicators with structured thematic synthesis provides both a map of recent research activity and an engineering interpretation of its practical significance.

3. Literature Review

Energy storage has become an essential component of modern low-carbon electricity systems because of its ability to mitigate the variability of renewable energy sources, improve grid flexibility, and support reliable power system operation. Recent research has expanded beyond conventional battery technologies to include electrochemical, mechanical, thermal, and chemical storage systems with different discharge durations, efficiencies, costs, and levels of technological maturity. At the same time, increasing attention has been directed toward grid integration, hybrid storage configurations, digital control, artificial intelligence, sustainability, and policy frameworks. This section first introduces the principal energy-storage concepts relevant to the present review and subsequently provides a critical synthesis of recent studies published primarily between 2023 and 2025.

2.1 Key Concepts

2.1.1 Short-Duration Electrochemical Energy Storage

LIBs, especially LFP batteries, are still among the most advanced technologies for relatively short-term stationary storage applications. These applications are mainly for discharge durations of 1 to 4 hours and have very high round-trip efficiencies (85% to 95%). The fast response time, versatility, scalability, and manufacturing readiness of the batteries make them potentially suitable for wide application for frequency regulation, smoothing of renewable energy, peak shaving, and short-duration load shifting (Hasan et al., 2025; Ngoy et al., 2025). However, a substantial number of deployed energy storage systems have drawn increasing attention to their supply chain and environmental issues, as resource constraints (Li, Ni, Co, and other critical materials) and end-of-life and battery degradation have become significant considerations for the feasibility of such grid-scale deployment. Besides economic and efficiency aspects (Cui et al., 2025; Lundahl et al., 2023; Rezaei et al., 2025), battery performance has been addressed in recent literature in relation to life cycle assessment, recycling, material recovery, thermal performance, and circular economy. Consequently, although LIBs and LFP batteries currently represent highly mature short-duration storage solutions, their long-term role in sustainable electricity systems must be assessed together with raw-material security, recycling capability, environmental performance, and the availability of complementary storage technologies.

2.1.2 Sodium-Ion Batteries and Emerging Electrochemical Technologies

Sodium-ion batteries (SIBs) have received increasing attention as an alternative or complementary electrochemical storage technology. Their principal advantage is the widespread geographical availability and relatively low cost of sodium compared with some of the critical materials required for conventional lithium-ion systems. In response to these problems, there have been a number of studies which aim to introduce sodium-ion batteries as alternatives to those that depend on lithium, nickel and cobalt, and this therefore allows supply chains to be much more diversified (Zhao et al., 2023; Garcia et al., 2024; Pilali et al., 2025). The low energy density of the battery compared to that of Li-ion batteries makes sodium-ion batteries unattractive in applications in which it is important However, these limitations are less constraining for stationary electricity storage, since weight constraints are less of an issue for storage installations than for electric vehicles or portable electronics. Therefore, their potentially favorable safety features, plentiful raw materials and anticipated cost decreases may make sodium-ion technology more and more competitive for stationary applications. Nevertheless, sodium-ion batteries remain less commercially mature than conventional lithium-ion systems. Their future contribution is therefore more likely to complement rather than completely replace lithium-ion batteries. This diversification could become particularly valuable as stationary-storage deployment expands and pressure on critical-material supply chains increases.

2.1.3 Flow Batteries for Medium-Duration Storage

Redox flow batteries represent an important class of electrochemical storage technologies for medium-duration applications, particularly over approximately 4–12 hours. Vanadium redox flow batteries (VRFBs) currently have the best technology readiness level; however, other electro chemistries made out of iron, zinc, and so on are becoming a field of increasing research interest (Khaki

& Das, 2023; Huang et al., 2024; Issa et al., 2025). Among many strengths of flow batteries, power output and energy output can be separately scaled up.

The power output is mainly determined by the electrochemical stack, and the stored energy is largely determined by the volume of the electrolyte. This separation provides considerable flexibility in the design of systems for long-duration operation.(Sumitomo Electric, n.d.) Flow batteries are also suitable for deep discharge and repeated cycling and may achieve considerably longer cycle lives than conventional lithium-ion batteries. However, their broader deployment is constrained by relatively high capital costs, system complexity, electrolyte costs, and material-related limitations. In particular, vanadium availability and cost remain significant concerns for VRFBs. These limitations have encouraged research into alternative flow-battery chemistries and lower-cost system configurations. Flow batteries therefore occupy an important intermediate position between short-duration batteries and longer-duration mechanical, thermal, and chemical storage systems.

2.1.4 Liquid-Air and Compressed-Air Energy Storage

Mechanical and thermodynamic energy-storage systems have gained increasing attention for medium- and long-duration applications. Liquid-air energy storage (LAES) stores electricity indirectly by liquefying air during charging and recovering electrical energy through expansion during discharge. The main advantages include the abundance of the materials, the possibility of scalability, and the lower dependence on geographically constrained reservoirs compared to conventional pumped-hydro systems (Rabi et al., 2023; Burian & Dančová, 2023; She et al., 2025). LAES could offer hours of energy storage and could be applicable for large-scale electricity systems. Nevertheless, its round-trip efficiency is generally lower than that of lithium-ion batteries, and high initial capital costs remain a significant challenge. (Cetegen et al., 2024) System performance can also depend strongly on the integration and recovery of thermal energy during liquefaction and expansion. (Yu et al., 2025)

Advanced adiabatic compressed-air energy storage (A-CAES) provides another medium- to long-duration alternative. A-CAES stores compressed air while capturing thermal energy generated during the compression process and subsequently reusing that heat during expansion. Technology potential is increased by enhanced compressibility systems, storing thermal energy, caverns, and integration systems. (X. Zhang et al., 2024; Dupin & Teixeira, 2025). Despite these improvements, A-CAES remains subject to geological constraints, relatively high infrastructure costs, and lower round-trip efficiency than electrochemical batteries. Its value is therefore highly dependent on storage duration, site availability, system scale, and the services required by the electricity network.

2.1.5 Hydrogen, Thermal Energy Storage, and Pumped Hydro

Hydrogen storage is increasingly considered for long-duration and seasonal energy storage, particularly where very large quantities of energy must be stored over periods extending from days to months. Renewable electricity can be converted to hydrogen via electrolysis, stored in appropriate facilities such as salt caverns, and used for producing electricity or for industrial use (Khakimov et al., 2024; Liu et al., 2025; Kumar et al., 2025). The principal advantage of hydrogen is its ability to provide very large storage capacities and to connect the electricity sector with industrial, transport, and fuel applications. However, its electricity-to-electricity round-trip efficiency is substantially lower than that of battery systems because of energy losses during electrolysis, compression or storage, and reconversion to electricity. (de Moura Altea & Yanagihara, 2024) .Key barriers are also high costs of electrolyzers and infrastructure requirements. Thermal energy storage (TES), including molten-salt and other high-temperature storage systems, is another option for hours-to-days energy storage. TES can support concentrating solar power plants, industrial heat applications and sector coupling. Its comparatively low storage cost and compatibility with thermal processes also make it particularly relevant for industrial decarbonization. (EASE, 2023)

However, its application for direct electricity-to-electricity storage is typically less widespread than for electrochemical storage systems. In contrast, pumped hydro storage (PHS) is one of the most mature forms of large-scale electricity storage. It can potentially offer long operational lives, high energy capacity, and discharge times of several hours. However, whether these projects become reality hinges heavily on geography, availability of water, environmental constraints, land use, planning, and the lengthy time required to obtain permission. (Hunt et al., 2023; Nikolaos et al., 2023). These technologies illustrate an important characteristic of modern energy-storage systems: increasing storage duration generally requires consideration of technologies beyond conventional batteries. Therefore, hydrogen, TES, PHS, LAES, A-CAES, and flow batteries should not necessarily be regarded as direct substitutes for lithium-ion storage but as complementary technologies addressing different timescales and system requirements.

2.1.6 Grid Integration, Hybrid Storage, and Digitalization

The usefulness of energy storage is not measured by the amount of energy that can be stored in installed capacity. The storage systems provide a variety of grid services such as frequency regulation, system balancing, congestion management, peak-load reduction, renewable energy integration, reserve capacity, and system resilience. Therefore, De Carne et al. (2024) claimed that storage assessment should focus beyond capacity to the service that it provides to the electricity system. VREs present challenges when it comes to intermittency, frequency stability, frequency control and stability, power quality, and balancing loads. With a growing percentage of renewables, the influence of interactions between storage technologies and operating the grid has grown in importance for the electric system (Khalid, 2024). Therefore, Hybrid Storage Systems are a significant area of research. Hybrid configurations are not only another type of storage system; they actually consist of more than one storage system, and each system has different response times and discharge durations. (Areola et al., 2025) pointed out the advantages of integrating short-term and long-term energy storage solutions into PV generation. Short-duration storage can react to short-term variations in the duration of less than a day, and long-duration storage can mitigate long durations of low renewable generation. With the increasing digitization and artificial intelligence, the operational value of storage is also slowly changing over and over again. The use of AI-based forecasting, predictive maintenance, degradation prediction, digital twins, and optimized real-time asset coordination can enhance asset utilization, reliability, and system coordination (Bello et al., 2024; Belkhode, 2025; Singh et al., 2025). Digital platforms can also enable integrated operations of heterogeneous storage technologies by assigning each technology to the services and time scales that the technology is best suited for. These developments demonstrate that future energy-storage systems must increasingly be evaluated as integrated elements of electricity networks rather than isolated physical devices.

2.2. Previous Studies

Recent research on energy-storage systems can be broadly classified into several interconnected domains: short-duration electrochemical storage, medium- and long-duration mechanical or electrochemical storage, seasonal hydrogen storage, grid integration, economic optimization, sustainability, hybrid systems, and policy. Although substantial progress has been achieved within each of these areas, many studies continue to focus on individual technologies or specific dimensions of performance. Thus, an integrated analytical framework taking into account technical performance, cost, storage duration, grid function, environmental implications, digitalization, and policy simultaneously is still needed. Khaki and Das (2023). This research examined operational optimization of vanadium redox flow batteries (VRFBs) and lithium-ion batteries across multiple objectives. Their analysis included the influence of energy storage levelized cost, as well as factors like rate of charge and charge time, charge rate and power, and charge duration, power capacity and energy capacity, charge-depth of charge and energy charge efficiency. They found that the ideal storage solution will depend on operational profile and the demand length of a store. Lithium-ion batteries were more advantageous for applications requiring rapid charging and shorter-duration response, whereas flow batteries offered important advantages for longer-duration operation because of their long cycle life and ability to scale power and energy capacity independently.

This comparison illustrates an important limitation of attempts to identify a universally superior storage technology. Performance depends not only on efficiency or capital cost but also on the service that the system is expected to provide. A technology suitable for frequency regulation may not necessarily be optimal for multi-hour load shifting or long-duration grid resilience. Rabi et al. (2023) reviewed liquid-air energy-storage technology in great detail and pointed out its prospects for large-scale and long-duration electricity storage. LAES has the advantage that it does not have some of the geographical constraints of pumped-hydro storage and can potentially be deployed at large scale using abundant working materials. But the technology is still limited by moderate round-trip efficiency and relatively high upfront capital needs. Their results point to future competitiveness of LAES being highly dependent on improvements in thermal integration, system design and the economics of deployment.

Alongside increasing concern regarding raw-material availability and the sustainability of battery supply chains, research on sodium-ion batteries has surged. Zhao et al. (2023) discuss the development and engineering of sodium-ion batteries in a review, and the authors debate the development status and future perspective. The benefits it gives are plenty, as sodium is relatively abundant and geographically available everywhere; therefore, it's useful for grid storage and static energy storage, since capacity fade, although it can be a disadvantage, is not a key feature in this application. Ongoing work attempts to characterize sodium-ion materials, their performance and safety, and the potential for their commercialization. Electrodes were reviewed for emerging materials in sodium-ion in Garcia et al. (2024), and comparing the technology transition Li-ion-Na-ion with the SWAT framework in Pilali et al. (2025). Although the figures show that Na-ion is starting to be competitive with Li-ion batteries, especially for grid applications requiring capacity only for a few tens of hours, it shows that technologies are going to diversify and Na-ion cannot replace the Li-ion battery. On the system level. De Carne et al. (2024) enlarged the concept of storage applications so that it could even accommodate the notion of storage services, which can be, for example, frequency regulation, grid support, balancing and management of load. A service-based appraisal of storage is then required to evaluate the relevance for the grid: Storage usability for the grid is quantified not just by energy storage capacity, but also by the number and time of services a storage can provide at once to the grid. Related to it, Khalid (2024) investigates storage technology for smart grid applications with regard to renewable energy generation and finds that issues regarding the high renewable power penetration, i.e fluctuation issues, frequency stability, power quality, control systems for these sources, and additional demand for services like flexible energy storage are addressed. Therefore, a storage technology is to be considered in the system, i.e as a whole design

One possibility to address this concern is with hybrid storage configurations. In a storage dispatch study considering the cost of firm renewables (Yang et al. 2024), the authors examined the role of short-, Medium-, and long-duration storage, showing the cheapest systems have an optimal combination of technologies. Short-duration storage has a role in harvesting diurnal variability. Long-duration storage involves more days when renewable generation is low and can firm the renewables. Their analysis suggests that a holistic mix of storage technologies providing portfolio value is more beneficial than selecting just a single technology (even within a certain duration range, see Table 2 of the main text of their study). Interest has also been in mechanical energy storage. In a comprehensive review of the status of compressed air energy storage (CAES), Zhang et al. (2024) focused on aspects from the basic principle to engineering to the possible implementation of ACAES technologies. They noted that the optimal design of these three application areas of ACAES (compression, thermal storage, and heat reconversion) and the installation relevance (location and infrastructure concerns and expensive capital costs) have been hindered for these authors, and that thermal storage often plays a significant role in ACAES feasibility in design. Most hydrogen research has been on long duration and seasonal storage. The potential of hydrogen technology in long-duration and seasonal storage, access to renewable energy resources, and industrial applications was explored by (Khakimov et al 2024).

Large storage capacities are possible with underground storage in geological formations, particularly salt cavern geology. It is not as competitive as other applications that can be met with greater efficiency in electricity-to-electricity terms because of low efficiencies, high capital cost of electrolyzers, and the requirements of new infrastructure. In 2025, a new article of this nature reminds readers of the difference between storing it short-term or long-term. Hasan et al. (2025) surveyed future trends of lithium-ion battery technology, concentrating on problems like the availability of resources, environmental issues, cost reduction, and sustainability. But, over the long term, such problems will make single-chemistry battery technology impossible to maintain and may leave it possible for “it” to only exist for a long time based on this battery technology. Ngoy et al. (2025) also looked at the lithium-ion battery in the context of a sustainable electricity system and noted that they are highly suitable for short-duration stationary energy storage applications and showed how complementary technologies are needed to achieve longer duration storage. Thus, the emphasis is shifting towards positioning Li-ion batteries and longer duration storage as a portfolio, not a replacement.

Complement Aries. In line with an emerging conceptual understanding of complementaries in technologies for power systems, this topic includes research on storage complements, which includes exploring the viability of multiple technologies for use within the grid: as an example of longer-duration, grid-scale, and cost-effective applications of flow battery based on the work by Issa et al. (2025) where the benefits over Li-ion applications include longer battery lifetime, flexibility to use the cell deeply and capacity being a independent factor to discharge, where there are still identified challenges to broader adoption. Future technological advancements of storage complements, which increasingly become competitive at longer discharge times and deeper depth of charge, include flow batteries, along with pumped hydro storage and Compressed Air Energy Storage (CAES).

Sustainability. The topic has additionally integrated environmental concern for the new area of storage as a significant focus of current Research; "recycled and circular economy will play roles for lithium-ion" Cui et al., (2025) and "material challenges and end-of - the - lifecycle of secondary battery production" Rezaei et al., (2025). The wider array of applications means that environmental factors now need to be taken into account with technologies; environmental factors will have to consider the material sourcing, the disposal at end - of-lifecycle, recycling, as well as supply chain viability for these resources, in addition to technology efficiency and cost. The area of sustainable operation is becoming more established. Digital operations & management: A notable increase in interest and applications of data-driven techniques has appeared in the domain of digital operations and management of storage systems – including artificial intelligence (AI)- based prediction forremaininguseful life (RUL) to support preventative maintenance practices (Belkhode, 2025; Singh et al., 2025) as well as in optimising battery applications in renewable energy systems(Bello et al., 2024), which shows there is a growing understanding of reliance on the forecasting, monitoring, control, optimisation of, and integration of managerial functions of energy storage.

Table1 highlights recent trends and technological advances in several areas. Generally speaking, we note a shift in recent literature from a focus on efficiency towards a more holistic approach to technology development where policy, long duration or short durations, and sustainable application are more prominently featured over a timeframe of between 2 and 3 years. An important point arises in that 'nowhere can we see that any singular technique can supply the totality needs to support a highly integrated renewable grid'. Key gap in literature: Much of the current literature investigates the performance of technologies under given parameters, addresses specific points of either technical performance, a certain set of conditions, an economic dimension, an issue of sustainability, a given structure related to policy or even a particular geographic location. Very few researchers tackle several technological points in tandem; i.e., several technological performances, overall economic viability, multiple needed services, Sustainability factors, applicable regulations, and digital system components combined together with geographical parameters for a specific energy storage technology, or compare the effectiveness of different types. Study aim: the present research thus intends to address this key information deficit by providing a bibliometric profile and comprehensive analysis, utilizing themes identified, for recent publications (2023 - 2025) to describe and analyse new technologies and/or combinations of the technologies, to guide future technology design and deployment by evaluating multiple points beyond solely technology performance and assessing different duration of technologies' suitability for the designing of an robust energy supply system for a low-carbon electric network..

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4. Methodology

A comprehensive, bibliometrically-informed review was carried out to explore the current status of stationary energy storage and its contribution to enabling a strong, low carbon electricity network. Literature reviewed was mainly within the year range 2023-2025. Studies were identified using the peer-reviewed resources (Scopus, Web of Science and IEEE Xplore) and selectively supplemented by relevant institutional and governmental reports, when required. After the process of relevance and quality analysis, an analytical body consisting of 41 sources published from 2023 to 2025 was formed.

The information was gathered and sorted by storage technology, discharge duration, round trip efficiency, cost, technology readiness level (TRL), deployment status, policy and regulatory aspects and artificial-intelligence and digital applications. Thematic and comparative analysis were used to identify recent trends, technological challenges, and emerging opportunities, which were then combined with descriptive bibliometric indicators to identify trends in resilient low-carbon electricity systems.

3.1 Design and scope of the review

This review has used a structured, bibliometric guided-review design. For the core review, data published between 2023 and 2025 was included due to this being a period in which innovative stationary E.S technologies, deployment mechanisms, policy approaches and digital solutions are emerging. Undated/earlier documents were only sourced where it was vital to include any essential technology, institutions or the historical context to explain and inform the review.

3.2 Information sources and search strategy

Relevant literature was retrieved from the academic databases, namely Scopus, Web of Science and IEEE Xplore. Phrases used in the search were energy storage, battery energy storage, long duration energy storage, lithium ion, LFP, sodium ion, flow battery, liquid-air, compressed-air, hydrogen storage, thermal energy storage, pumped hydro, grid integration, grid forming inverter, artificial intelligence, digitalization, policy, and MENA. Where further deployment or policy or regional evidence was needed, relevant peer-reviewed literature was complemented by reports from IEA, IRENA, the World Bank, the U.S. Department of Energy, selected European institutions and other authoritative sources.

3.3. Eligibility and screening process

Studies were considered if they focused on stationary or grid-scale energy-storage systems and offered relevant information on technology type, discharge duration, characteristics, cost, technology readiness, deployment status, environmental/supply-chain considerations, policy, digital applications and/or regional applicability. Peer-reviewed studies and authoritative institutional reports which directly assisted the goals of the review were given priority. Studies that were not related to stationary energy storage, did not contain relevant information on stationary energy storage, or significantly duplicated information previously represented in other studies were not included.

3.4 Data extraction and coding

For each of the sources included, details were gathered regarding the year of publication, storage technology and storage subtype, discharge duration, round-trip efficiency, estimated cost, technology readiness level (TRL), deployment status, geographic scope, policy dimensions, artificial-intelligence and digital-operation aspects, and the main advantages and limitations reported. The analytical corpus was composed of these 41 sources, with 11 sources from 2023, 13 from 2024, and 17 from 2025. Other institutional and project-specific and contextual sources to support the general discussion were not included in the analysis of number of publications.

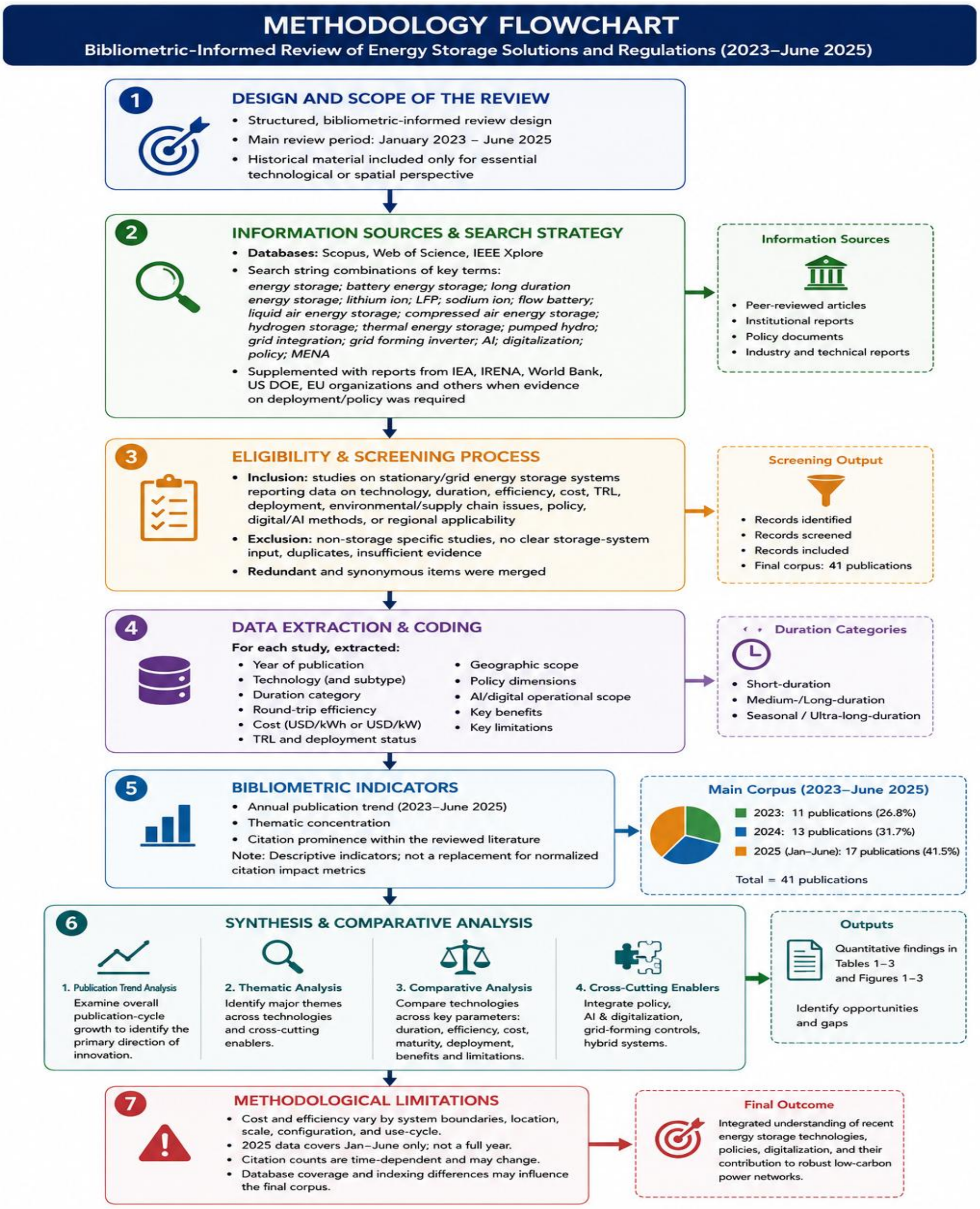

Figure 1. shows the methodology of the study

3.5 Bibliometric Indicators

The bibliometric part of this review was descriptive, i.e., non-network. It was based on the distribution of publications according to year and thematic concentration, and the recurrence of important references in the selected corpus. No citation-impact analysis, co-citation analysis, bibliographic coupling or bibliometric network mapping was undertaken. These indicators are used to illustrate patterns in the literature that has been examined—and not necessarily to capture the entire scientific research output or the impact of the energy-storage field. The ability to identify similarities and differences.

3.6 Identification of similarities and differences.

The selected literature was first analysed by publication trend to get an idea about the temporal distribution of the selected literature. These studies were then thematically and comparatively synthesized across short, medium, long-duration and seasonal storage technologies. Comparisons included deployment status, technology readiness, advantages and limitations, grid applications, and cross cutting themes of policy, artificial intelligence, grid forming control, digitalization, and hybrid storage systems, as well as discharge duration and efficiency, and cost. Cautious interpretation of quantitative values was required as the estimates of cost and efficiency reported may be subject to different interpretations depending on system boundaries, system configuration, geographic sources.

4.. Results and Bibliometric Trends

4.1 Publication trend (2023–2025)

Within the chosen core corpus of the reviews, publications ranged between 11 (in 2023) and 17 (in 2025), corresponding to an increase of 18.2% (2023 to 2024) and 30.8% (2024 to 2025) – indicating that the chosen material between 2023 and 2025 saw an increase of 54.5%. In addition to this temporal increase, the relative share of publications on relevant subject matter topics -such as the design and recycling of the mentioned two -is also increasing, in addition to those on sodium-ion related systems, as well as those on flow-batteries, LAES and A-CAES as well as those on combined salt and cavern storage concepts, as well as energy and sustainability-related concepts in strategic energy planning, grew between the given years. But the herein given developments describe the composition of the reviews in its chronological and thematical makeup, and not the global production volume for the specific fields.

Table 1. Publication-year distribution of the core review corpus.

Year	Publications	Share	Year-on-year change
2023	11	26.8%	—
2024	13	31.7%	+18.2%
2025	17	41.5%	+30.8%

4.2 Citation and thematic concentration

A number of relevant studies were cited in the various analytical parts of the review. Rabi et al. (2023) made several contributions to the discussion of LAES, while Angelico et al. (2025), Khaki and Das (2023), Liu et al. (2025), Mohseni and Brent (2025), and Ngoy et al. (2025) made multiple technological or system-level contributions. These patterns of recurrence are due to the references used in the present review and do not provide a measure of the overall citation impact.

The literature was analyzed to identify five main thematic areas: lithium-ion performance, cost, and recycling; sodium-ion and alternative electrochemical technologies; medium- and long-duration storage systems such as flow batteries, LAES, and A-CAES; hydrogen, TES, and PHS for medium- and long-duration and/or seasonal storage; and system-level integration including grid security, economics, policy, artificial intelligence, and regional pathways. These themes together suggest a greater focus on integrated and hybrid storage solutions than on technology assessment.

4.3 Integrated Analysis of Quantitative Data

Table 2 and Figures 2–4 are not to be read as stand-alone technology scores. The high round-trip efficiency of lithium-ion/LFP systems is shown in Figure 2, and the primary suitability for short-duration applications is reflected in Figure 4. Hydrogen has a significant power-to-power inefficiency but can be stored over days to seasons, thus offering a system function different from that of electricity. The ranges of estimated costs in Figure 3 are not necessarily directly comparable because reported costs may refer to various system boundaries such as storage capacity, installed-system costs, or conversion-related components. There is an intermediate class of flow batteries, LAES and A-CAES that either have lower efficiency than lithium-ion batteries or can be used for longer discharge periods, Asset life or repeated multi-hour energy shifting.

In general, there is quantitative evidence for a portfolio approach to energy storage. Flow, cryogenic, and compressed-air systems are becoming more applicable the longer the duration of storage, while the more the duration is shorter, the more relevant are high-efficiency batteries. There are other options such as PHS, TES, and hydrogen for longer-term seasonal and/or sector-coupled applications. As such, they should not be evaluated individually and ranked overall in terms of storage technologies; efficiency, cost, discharge time, readiness of the technology, and local infrastructure should be evaluated together.

Table 2. Comparative Assessment of Energy Storage Technologies (2023–2025)

Technology	Typical Discharge Duration	Round-trip Efficiency (%)	Estimated Cost ($/kWh)	Technology Readiness Level (TRL)	Advantages	Challenges
Lithium-ion Batteries (Li-ion, LFP)	1–4 hours	85–95%	120–200	9 (Fully commercial)	High efficiency, fast response, wide deployment	Dependence on lithium/nickel supply chains, recycling challenges (Hasan et al., 2025)
Sodium-ion Batteries (Na-ion)	1–4 hours	80–90%	80–150 (expected)	7–8 (Emerging commercial)	Abundant low-cost materials, improved safety	Lower energy density, limited commercial availability (Yu et al., 2023)
Flow Batteries (Vanadium/Iron)	4–12 hours	70–85%	200–400	7–8 (Commercial projects)	Very long cycle life (>20,000 cycles), decoupled energy and power	High capital cost, vanadium supply dependence (Liang et al., 2023)
Liquid-Air Energy Storage (LAES)	6–12 hours	55–70%	100–150	6–7 (Pilot/Early commercial)	Uses abundant materials, scalable for large systems	Lower efficiency requires supportive policy frameworks (Liang et al., 2023)
Advanced Compressed Air Energy Storage (A-CAES)	8–24 hours	60–70%	50–100	6–7 (Pilot/Developing projects)	Large-scale potential, relatively low cost	Geological site constraints, lower efficiency than batteries (Liang et al., 2023)
Hydrogen (Salt Caverns)	Days – Seasons	30–45% (power-to-power)	10–50 (storage) + conversion costs	5–7 (Demonstration projects)	Seasonal storage, versatile for power and industry	Low round-trip efficiency, high electrolyzer costs (Liang et al., 2023)
Thermal Energy Storage (TES – molten salts/carbon)	Hours – Days	60–80%	20–50	7–8 (Commercial)	Low cost, supports industrial decarbonization	Limited electricity applications, moderate efficiency (U.S. Department of Energy, 2023)
Pumped Hydro Storage (PHS)	8–20 hours	70–85%	30–80	9 (Most mature)	Largest global capacity (>90%), long operational life	Environmental and geographical constraints, long permitting times (Alnaqbi et al., 2022)

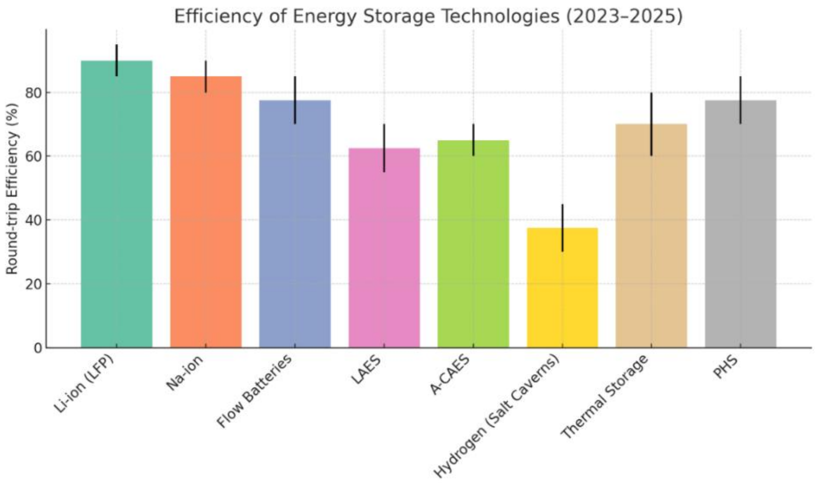

Figure 2. Round-trip Efficiency of Energy Storage Technologies (2023–2025).

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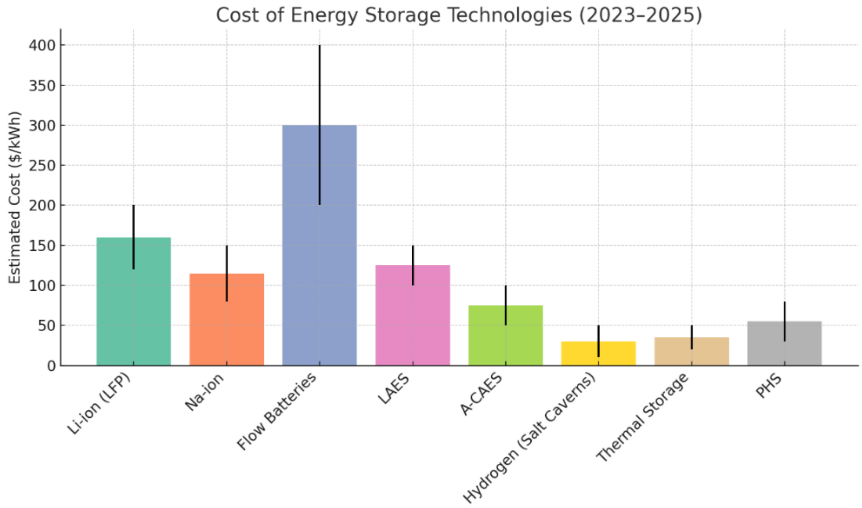

Figure 3. Estimated Cost of Energy Storage Technologies (2023–2025).

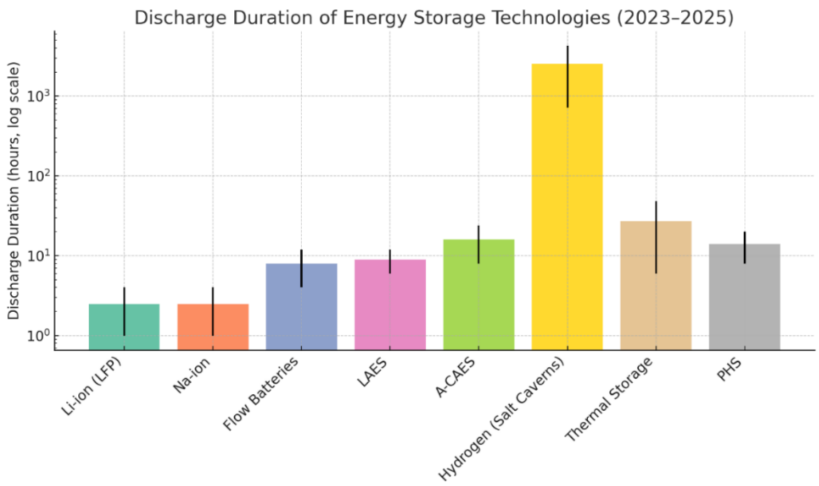

Figure 4. Discharge Duration Ranges of Energy Storage Technologies (2023–2025).

5. Discussion

5.1 Comparative Assessment of Technologies

Energy storage technologies vary significantly in terms of discharge duration. Discharge duration, round-trip efficiency, economic feasibility, cycle life, and technological maturity vary widely across energy storage technologies. Among lithium-ion chemistries, LFP has gained significant traction in stationary, short-duration applications, with round-trip efficiencies ranging from 85% to 95%. LFP is relatively affordable and has a long cycle life of around 4,000–10,000 cycles. Its cost was approximately $115/kWh in 2024 (Bloomberg NEF, 2024). For sodium-ion systems, energy density is typically lower than that of a Li-ion battery. But based on predicted cost prices, the Na-ion batteries could approach the cost range of LFP technology ($80-150 / kWh). The high safety of a given LFP would make the technology interesting for the future in providing a cheap solution for the stored energy needs (Liu et al., 2025; Rezaei et al., 2025). The discharge duration of flow batteries can be between 4–12 hours, and the cycle life is very high (>20,000 cycles), while the cost of the battery is relatively high ($200-400/kWh) (Zhang et al., 2024). In medium systems, LAES and A-CAES have achieved efficiencies of 55-70% and 60-70%, respectively, in hundreds of MWh-scale long-duration and seasonal systems. (Ding et al., 2025)

The price of storage is $10–50/kWh, and the caveats are low power-to-power round trip efficiency, and the high cost of the electrolyzer. The round-trip efficiency for such processes is in the range of 30-45% while the main challenge is the high cost of the electrolyzer. Liu et al. (2025) state that the cost of thermal energy storage is around $20-$50/kWh and can enable flexibility in the industrial heat sector and multi-day flexibility. Pumped hydro storage represents over 90% of the world's installed storage capacity and has a very long lifetime, typically of more than 40 years (Pompei et al., 2023). Therefore, no single energy storage device can cover all the power-system related services and a system-level view of it is required (Nikolaos et al., 2023) Such a perspective also implies a portfolio approach to energy storage, in which short-duration batteries are combined with medium- and long-duration systems. However, neither the advantages of resilience nor those of seasonal balancing have yet been incorporated sufficiently into existing policies and market signals. (Mohseni & Brent, 2025) Similar issues are presented through current market conditions and policy. (Mohseni & Brent, 2025) No single technology for storage can meet all demands placed on the system, as shown in Table 2, and each one can contribute both advantages and disadvantages; a hybrid strategy of short-duration batteries with medium/long duration storage is necessary for a stable grid. System integration, however, is hampered by both technical and market barriers Long-duration energy storage technologies such as liquid-air storage, flow-battery, and hydrogen-based storage systems are currently 2-4 times more expensive per kW per kWh than batteries; the cost burden remains a major obstacle for large-scale deployment without supporting policies and market design. Technically, from a technological standpoint, flow batteries undergo deterioration, whereas LAES and CAES incur conversion losses. Hydrogen storage exhibits a comparatively low round-trip efficiency of about 30–45%.

Environmental and social implications also need to be addressed. The exploitation of cobalt and lithium causes environmental damage, whereas the recycling rate of these products is currently low. PHS have significant implications on environments and land-use issues. Limited policy frameworks and inadequate market design represent another barrier to large-scale deployment, as many electricity markets provide clearer incentives for short-duration arbitrage and frequency services than for resilience and seasonal balancing. Mean round-trip efficiency with bars indicating minimal and maximal intervals for each technology. The Li-ion (LFP) presents the best figures (85-95%), whereas the H2 in salt caverns presents the lowest (30-45%). Estimated cost per kWh for major storage technologies. The Li-ion and Na-ion have a continuously decreasing price, whereas flow batteries present a large capital investment. Hydrogen and thermal storage have the cheapest storage costs. The stored durations that can be discharged among energy storage technologies, for instance, Li-ion and Na-ion batteries, belong to the short-term discharge category that can last for 1- 4 h; whereas flow batteries, LAES, and A-CAES belong to the 4- 24 h category. TES and Hydrogen have capacities for storing energy for days or even seasons; however, pumped hydro (PHS) has 8- 20 h and is still globally the biggest LDES system. It is also the anchor to the LDES capability.

Multiple instances of resource- and grid-specific storage technologies being localized within the MENA region were evidenced. Egypt expected 2.4 GW pumped storage plant planned for Ataqa Mountain in the area west of Suez; this will be the largest LDES proposal in the region. Re-tenders for the project in January 2025 because the original financing had not yet been finalized (Africa Energy Portal, 2025). Secondly, Concentrated Solar Power combined with storage of Molten Salt in Morocco's NOOR Ouarzazate solar project also presents evidence of local implementation of CSP with thermal energy storage technologies, besides environmental considerations connected with the deployment of large-scale CSP plants (Laaroussi et al., 2023). Lastly, the project NEOM Green Hydrogen is one of the major investments made in the area of renewable hydrogen production. It is planned to produce some 600 tons/day of carbon-free hydrogen in Saudi Arabia with an estimated investment cost of USD 8.4 billion, utilizing electricity produced from renewable energy, likely to be used for the production of green ammonia for export (Oxford Business Group, 2023). The UAE Masdar and the Emirates Water and Electricity Company concluded an agreement in 2025 for a gigawatt-level project in Abu Dhabi with both solar PV and BESS. The project consists of 5.2 GW of solar PV and 19 GWh of Battery-Energy Storage (BESS), the system can serve up to 1 GW of Renewable Baseload around the clock (and could support dispatchability of solar generation) (Masdar, 2025). The regional examples above show how various storage technologies are aligned with specific resources and system needs: hydro in Egypt, Thermal in Morocco, Hydrogen in Saudi Arabia, and Battery-digital in the UAE. Generally, the role of artificial intelligence and other digital technologies in optimizing the systems for using storage technology is expanding rapidly. AI algorithms process and consolidate various data sets to perform predictive analyses to truncate and enable the assurance of current installation validity. In the context of batteries, machine learning algorithms are projected to reduce the maintenance cost and extend the lifetime of batteries with improved predictions about its eventual aging and the stability of its thermal cycling and electrolyte (Belkhode, 2025)

5.2. Economic Benefits and Strategies for Transitioning to Sustainable Low-Carbon Grids

Economic and job creation opportunities in new grid construction, installation and maintenance and attracting international companies with a low-carbon supply chain will also come with the development of resilient low-carbon energy grids. Economic benefits in the new technologies, particularly solar and wind systems will include, reduction of dependency on expensive backup diesel systems, household energy consumption as well as avoiding the losses that may occur in the future due to unstable grids and climate changes that may run into billions. The focus on the transition should involve economic structures of the public-private partnership, strategic and focused incentives, diversified economies, and construction of innovative and research and development ecosystems, strategically. Current policies on energy storage technologies such as the construction of resilient low-carbon grids, hybrid systems and AI-focused integration of renewables are Active 2023-2025 policies. The policy regimes change towards stability and predictable economic incentives, e.g., carbon taxation. As there is a possibility of economic opportunity and robustness, the economic change is there, though funding and geopolitics, and considering costs as a whole (not only capital) are still major obstacles. Particular applications like the heliostat solar field with CAES provides good economic returns and payback period of up to 2 years and can be used as an example that will help steer opportunities in economics.

The implementation of the smart grids could be promising in terms of employment opportunities in the engineering and construction sectors and making renewable energy-based green areas more competitive, which is a favorable change to socio-economic climate change resiliency activities. The listed regions still have an investment in the low-carbon supply chain industry globally. Smart grids reduce the expense involved in using the costly diesel generators in houses and enterprises by streamlining and reducing the expenses on using renewables. Smart grids have been appreciated and recognized to help economies of any magnitude to conserve the worth of the economic activities and prevent losses during economic change and even weather changes.

The economic contribution of the low-carbon energy transition to the regions is that it compensates for the loss of jobs in the high-carbon sectors through the introduction of new industries and the creation of new sustainable jobs. Investment in R&D and innovative public-private partnerships can result in diversification of the economy by using innovative grid technologies. The transition is facilitated by government coordination of the technical and regulatory frameworks of low-carbon grids. Smart grids can easily connect and integrate the collaboration strategies of cross-border collaboration by the people. The use of sustainable technologies was spurred by the facilitation of cooperation with the strategies of the public cross-border collaboration and supply side public procurement with the low-carbon technology.

In order to make the transition economically in, the economic cooperation of the private sector should be achieved through healthy strategies and policy options in innovation, research providing large-scale incentives and public-private relationships. The combination of these strategies will ensure the shift to low-carbon technologies to a significant extent and development of a consistent framework of their adoption. The implementation and incorporation of the approaches will help in the retrogressive and progressive sustainable economic development. In addition, it will also offer long-lasting economic growth, sustainability, and competitiveness among the low-carbon economic environment.

6. Conclusion

No single technology can satisfy all grid requirements related to efficiency, discharge duration, cost, technological maturity, environmental performance, and operational flexibility. The literature of 2023-2025 suggests that LFP systems, which operate on a short-duration basis, remain the best technology for short-time applications where high round-trip efficiency, long cycle life, and rapid transient response. On the contrary, other options, such as flow batteries, liquid-air energy storage, high-efficiency compressed-air energy storage, pumped hydro storage, thermal energy storage, and hydrogen storage, have complementary properties that can be applied to medium- and long-term applications or for seasonal storage.

Consequently, low-carbon electricity system resilience will be better achieved through a technology portfolio-based solution than relying on the optimal characteristics of a single energy storage technology. Selecting the right technology depends on the grid requirement, resource availability, infrastructural conditions, duration of energy storage needed, and cost considerations. For a more flexible electricity grid and an efficient integration of variable renewables, a combination of short-duration batteries with medium- and long-duration technologies would likely be beneficial.

The results demonstrate that improving technologies would not be enough to deploy electricity storage on the required scale. The successful implementation of storage technologies relies on the development of efficient regulations, markets, investments and digital technologies such as AI for forecasts, optimization and controls. Therefore, technological, financial, regulatory and digital strategies should be designed jointly, aiming for reliable, resilient, flexible and sustainable low-carbon electricity grid systems.

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