
Storage Technologies and Pathways in Renewable-Energy Research on National Energy Independence: A Keyword Analysis

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Tomasz Wałek¹, Marek Szafraniec²

Abstract:

Purpose: The study investigates the evolution of energy-storage technologies within renewable-energy research and examines how technological priorities have changed in response to the growing importance of energy security and energy independence. Particular attention is devoted to identifying the dominant storage technologies, emerging technological pathways, and recent shifts in research focus associated with the post-2022 energy environment.

Design/Methodology/Approach: The study uses a bibliographic dataset comprising 472 Scopus-indexed publications related to renewable energy, energy storage, and energy independence/security at national and supranational scales. A technology-oriented analysis was conducted using author-keyword occurrence, co-occurrence network analysis, Average Publication Year (APY), and Total Link Strength (TLS). Storage-related keywords were identified, classified into technology families, and examined in terms of their frequency, network embeddedness, and temporal position within the literature.

Findings: The results indicate that battery-based technologies remain the dominant storage pathway, with battery energy storage systems representing the most visible and strongly connected technological keyword within the literature. At the same time, hydrogen-related technologies, including green hydrogen and Power-to-X pathways, occupy the most recent positions in the research landscape. Pumped hydro storage remains a well-established and highly integrated system-scale storage option. The findings suggest increasing diversification of storage technologies and a growing research focus on long-duration, hydrogen-based, and sector-coupling solutions.

Practical implications: The results provide insights for policymakers, energy planners, and investors by identifying technologies that are attracting growing scientific attention and are likely to play an important role in future energy systems. The findings may support strategic decisions concerning renewable-energy deployment, storage investments, energy-system flexibility, and energy-security planning.

Originality/value: The study contributes to the literature by examining the technological evolution of storage-supported renewable energy systems rather than focusing exclusively on energy-storage technologies or energy-security concepts separately. It provides a technology-oriented perspective on the changing priorities of renewable-energy research and identifies the storage pathways that increasingly support energy-security and energy-

¹Silesian University of Technology, Faculty of Organization and Management, Poland,
e-mail: tomasz.walek@polsl.pl;

²Silesian University of Technology, Faculty of Organization and Management, Poland,
e-mail: marek.szafraniec@polsl.pl;

independence objectives.

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1. Introduction

The transition towards low-carbon energy systems has become one of the defining challenges of the twenty-first century. Rising global energy demand, increasing electrification of transportation and industry, and ambitious climate-neutrality targets have accelerated the deployment of renewable energy sources (RES) across the world (Ellabban *et al.*, 2014; Haegel *et al.*, 2019).

Solar photovoltaic and wind-energy technologies now represent the fastest-growing sources of electricity generation, forming the foundation of national and regional decarbonization strategies (Geels *et al.*, 2017; Breyer *et al.*, 2022).

However, the widespread deployment of renewable energy creates new technical and operational challenges. Unlike conventional power plants, renewable sources are characterised by variability and weather dependency, resulting in significant mismatches between electricity production and consumption. Maintaining secure and reliable operation of power systems with high shares of renewable generation therefore requires additional flexibility resources capable of balancing supply and demand across different time scales (Denholm and Hand, 2011; Pfenninger and Staffell, 2016).

Energy storage technologies have emerged as one of the most important solutions addressing these challenges. Storage systems improve system flexibility, facilitate renewable-energy integration, reduce curtailment, support frequency regulation, and enhance the resilience of electricity networks (Luo *et al.*, 2015; Aneke and Wang, 2016). Their role has expanded substantially over recent decades, evolving from auxiliary balancing equipment into strategic infrastructure supporting the operation of increasingly renewable-based energy systems.

The technological landscape of energy storage has also become considerably more diverse. Battery energy storage systems, particularly those based on lithium-ion technology, currently dominate many renewable-energy applications due to their declining costs, high efficiency, and scalability (Zakeri and Syri, 2015; Albertus *et al.*, 2020). At the same time, alternative storage pathways such as pumped hydro

energy storage (PHES), hydrogen-based storage systems, vehicle-to-grid (V2G) technologies, thermal storage, and long-duration energy storage (LDES) are attracting growing attention because of their potential to provide flexibility services over longer time horizons and larger geographical scales (Blanco and Faaij, 2018; Dowling *et al.*, 2020).

Recent geopolitical developments have further increased the strategic relevance of energy storage. The disruptions in global energy markets observed after 2022 exposed vulnerabilities associated with energy import dependence and highlighted the importance of secure domestic energy infrastructures (Kuzemko *et al.*, 2022; Misik and Nosko, 2023).

As a result, energy storage technologies are increasingly being considered not only from the perspective of renewable-energy integration but also as instruments supporting energy security, energy independence, and long-term system resilience (Marhold, 2023; Vasylieva *et al.*, 2025).

Different storage technologies contribute to these objectives in different ways. While battery systems are generally associated with short-term balancing and distributed applications, pumped hydro storage, hydrogen storage, and Power-to-X technologies are increasingly linked with long-duration balancing, sector coupling, seasonal storage, and strategic energy-system flexibility (Blanco and Faaij, 2018; Glenk and Reichelstein, 2019). Consequently, understanding how attention toward individual storage technologies evolves over time may provide valuable insights into future energy-system development pathways.

Despite the increasing importance of storage technologies, relatively limited attention has been devoted to understanding how the technological structure of energy-storage research evolves and which technologies emerge as dominant directions of development. Existing studies frequently focus on individual technologies, specific applications, or particular dimensions of energy systems, while a broader perspective on the evolution of storage technologies remains underdeveloped.

The aim of this study is to investigate the evolution of renewable energy-storage technologies within the context of national and supranational energy independence and to identify changing technological priorities associated with contemporary energy-system transformation. Particular attention is devoted to the emergence of hydrogen-based technologies, long-duration storage solutions, and other technologies increasingly linked with energy-security objectives.

To achieve this objective, the study addresses the following research questions:

• **RQ1:** *Which energy-storage technologies are most prominently represented in renewable-energy research related to energy independence?*

- **RQ2:** *How has the technological structure of the energy-storage research evolved over time?*
- **RQ3:** *Which technologies and pathways are positioned most recently according to Average Publication Year (APY)?*
- **RQ4:** *Which technological pathways are emerging as priorities for future renewable-energy systems?*

The findings contribute to a better understanding of technological change within the renewable energy-storage domain related to energy independence and provide insights into the technologies that are likely to play a central role in future low-carbon and resilient energy systems.

2. Literature Review

Energy storage has become an essential component of modern energy systems because it enables greater integration of renewable energy sources while improving flexibility, reliability, and operational stability (Luo *et al.*, 2015; Aneke and Wang, 2016). As renewable-energy deployment has accelerated, energy-storage technologies have expanded from relatively specialised applications into a diverse portfolio of solutions supporting both local and system-wide energy objectives.

Early renewable-energy applications typically relied on small-scale storage systems designed to improve reliability and self-sufficiency in isolated or weak-grid environments. Research frequently focused on stand-alone photovoltaic systems, hybrid renewable configurations, distributed generation, and rural electrification projects, where energy storage served primarily as a supporting technology (Diab and O'Leary, 1989; O'Neill, 1991). During this stage, the primary objective was to ensure continuity of supply and improve the economic performance of decentralised renewable-energy systems.

As renewable-energy deployment intensified, battery-based storage technologies became increasingly important. Lithium-ion batteries and battery energy storage systems (BESS) emerged as the dominant storage technologies because of declining costs, technological maturity, and compatibility with solar and wind generation (Hoppmann *et al.*, 2014; Zakeri and Syri, 2015).

Research increasingly focused on battery sizing, management systems, optimization methods, renewable-energy integration, and microgrid applications (Hoppmann *et al.*, 2014; Zakeri and Syri, 2015).

Similar developments can be observed in studies addressing prosumer-oriented microgrids and smart-metering infrastructures supporting local energy management and distributed renewable-energy integration (Walek, 2024). Empirical evidence from Polish cities additionally indicates that the implementation of intelligent and environmentally friendly urban solutions may be constrained by high costs,

insufficient funding, and limited awareness of their potential benefits (Janik *et al.*, 2023).

At the same time, large-scale storage technologies continued to develop. Pumped hydro energy storage remains the most mature and widely deployed utility-scale storage technology worldwide, providing substantial storage capacity and long operational lifetimes (Blakers *et al.*, 2017; Stocks *et al.*, 2021). Numerous studies identify PHES as one of the most effective mechanisms for balancing renewable generation and supporting large-scale decarbonization pathways (Luo *et al.*, 2015; Child *et al.*, 2018).

Hydrogen-based energy-storage technologies constitute another rapidly expanding area of research. Hydrogen is increasingly considered a strategic energy carrier capable of linking electricity generation with transportation, industry, and heating sectors (Blanco and Faaij, 2018).

Hydrogen storage and Power-to-X pathways are particularly important because they provide opportunities for long-term and seasonal balancing, thereby extending the role of energy storage beyond conventional electricity applications (Glenk and Reichelstein, 2019).

Growing interest has also been observed in long-duration energy-storage technologies. Future electricity systems based largely on renewable energy are expected to require storage capabilities extending far beyond daily or weekly balancing cycles. Consequently, research increasingly focuses on technologies capable of storing energy for extended periods, including hydrogen systems, PHES, thermal storage solutions, and other forms of long-duration storage (Albertus *et al.*, 2020; Dowling *et al.*, 2020).

The strategic significance of energy storage has become even more evident in discussions concerning energy security and energy independence. Energy systems characterised by high levels of renewable generation and domestic storage capacity can reduce dependence on imported fuels while enhancing resilience against supply disruptions and external shocks (Goldthau and Sovacool, 2012; Cherp and Jewell, 2014).

Following the energy-market disruptions associated with the war in Ukraine, many studies emphasised the role of renewable energy and storage technologies in strengthening national and regional energy autonomy (Kuzemko *et al.*, 2022; Misik and Nosko, 2023). A particularly interesting illustration of this relationship can be observed in publications authored by researchers affiliated with Ukrainian institutions.

In these studies, renewable-energy deployment, distributed generation, battery energy storage, and power-grid modernization are frequently analysed in the context

of national energy independence, power-system resilience, grid reliability, and the reconstruction of Ukraine's energy sector following the damage caused by the war (Kurbatova *et al.*, 2024; Diachenko, 2025; Hrytsiuk *et al.*, 2025).

Unlike many studies focused on microgrids and local energy self-sufficiency, Ukrainian publications tend to conceptualize energy autonomy primarily as a strategic objective pursued at the national level and closely linked to energy security, protection against external disruptions, and the restoration of critical energy infrastructure.

Although substantial progress has been made in understanding renewable energy, storage technologies, energy security, and energy resilience, important research gaps remain. Existing studies frequently examine renewable energy, energy storage, and energy security as separate domains.

Research devoted to renewable energy often focuses on generation technologies and deployment pathways, whereas storage studies typically address technical performance, optimization, economics, or operational integration. Investigations of energy security and resilience, in turn, concentrate primarily on policy, governance, and conceptual dimensions (Zhou *et al.*, 2018; Yu *et al.*, 2023; Janta *et al.*, 2025).

Consequently, limited attention has been devoted to the combined perspective linking renewable energy systems (RES), energy-storage technologies (ESS), and energy independence objectives. While individual technologies such as batteries, hydrogen systems, or pumped hydro storage are frequently analysed separately, considerably less is known about their relative evolution and changing importance within the broader context of renewable-energy development and energy autonomy.

This gap is particularly relevant in the contemporary energy landscape. The increasing importance of energy independence and security creates a need to better understand which storage technologies are receiving growing attention and how technological priorities are evolving in response to changing economic, environmental, and geopolitical conditions. The present study addresses this need by examining the evolution of major energy-storage technologies and their role within the broader transformation of renewable-energy systems.

3. Research Methodology

The study employed a bibliometric design to identify and compare the energy-storage technologies, energy carriers, conversion-storage pathways, and deployment configurations represented in research concerning renewable-based energy independence and security at the country level. Bibliographic records were retrieved from the Scopus database in June 2026 using a multi-block Boolean search applied to publication titles, abstracts, and author keywords. The search strategy was expressed as the intersection of five complementary thematic blocks:

- renewable-energy sources defined as: ‘renewable energy’; ‘renewable electricity’; ‘renewable power’; ‘variable renewable energy’; ‘photovoltaic*’; ‘PV’; ‘solar power’; ‘wind power’; ‘wind turbine*’; ‘wind energy’; ‘renewable energy source*’;
- electricity generation and power systems, including: ‘electricity’; ‘power’; ‘electric* system*’; ‘power system*’; ‘grid’; ‘power sector’; ‘power generation’; ‘electricity generation’; ‘power production’; ‘electricity production’;
- energy-storage technologies and conversion-storage pathways operationalised as: ‘energy storage’; ‘power storage’; ‘electricity storage’; ‘electric energy storage’; ‘battery energy storage’; ‘BESS’; ‘battery storage’; ‘pumped hydroelectric energy storage’; ‘PHES’; ‘pumped storage hydropower’; ‘pumped storage hydroelectricity’; ‘PSH’; ‘pumped hydro storage’; ‘PHS’; ‘long duration energy storage’; ‘LDES’; ‘long term energy storage’; ‘LTES’; ‘seasonal energy storage’; ‘SES’; ‘V2B’; ‘vehicle to grid’; ‘V2G’; ‘vehicle to everything’; ‘V2X’; ‘P2G’; ‘P2X’;
- concepts associated with energy independence, security, autonomy, and resilience, including: ‘security’; ‘autonom*’; ‘resilien*’; ‘self sufficien*’; ‘self-reliance’; ‘independen*’; ‘dependen*’; ‘sovereign*’;
- restriction of these concepts to national, supranational, and cross-border contexts defined as: ‘countri*’; ‘nation*’; ‘internation*’; ‘state*’; ‘union*’; ‘cross border*’.

The five blocks were connected with the Boolean operator AND, whereas alternative terms within each block were connected using OR. The complete search was performed using the Scopus TITLE-ABS-KEY field. The database filters limited the results to English-language journal articles and reviews.

The database search returned 3,998 records. The records were subsequently assessed for thematic eligibility using their titles, abstracts, and author keywords. Publications were retained when they concerned renewable electricity or power systems, explicitly included an energy-storage component or storage-based flexibility mechanism, and addressed energy independence, security, autonomy, resilience, self-sufficiency, dependence, or sovereignty at the national, supranational, or cross-border level.

Full records were consulted whenever eligibility could not be determined from the bibliographic metadata alone. After database filtering and thematic eligibility screening, the final analytical corpus comprised 472 publications.

Author keywords were selected as the analytical unit because they represent the terminology deliberately chosen by authors to describe the main subject matter of their publications. A co-occurrence network was generated in VOSviewer version 1.6.20 using full counting and a minimum occurrence threshold of two.

This relatively inclusive threshold was adopted to capture both established storage

technologies and less frequently represented or potentially emerging approaches. The resulting network comprised 253 author-keyword nodes.

Three VOSviewer indicators were used in comparative analysis. Occurrences represented the number of publications in which a keyword appeared and were interpreted as a measure of its visibility in the analysed corpus. Total link strength (TLS) represented the cumulative strength of a keyword's co-occurrence relationships with all other nodes and was used to assess its network embeddedness and degree of integration with the wider research field.

APY indicated the mean publication year of documents containing a keyword and was used to compare the relative temporal position of the identified topics. APY was not interpreted as a direct measure of publication growth, and TLS was not treated as evidence of technological performance, practical superiority or causal contribution to energy independence. All TLS values were interpreted exclusively within the network constructed at the minimum occurrence threshold of two.

All 253 qualifying author keywords were then screened to identify terms referring to storage approaches represented in research on renewable-based national energy independence. The classification followed an independent dual-reviewer procedure. Two researchers independently assigned each of the 253 keywords to one of the energy storage families (Table 1) or excluded term. Disagreements were resolved through consensus.

After the independent assessment, the reviewers compared their classifications and resolved disagreements and borderline cases through consensus. The retained keywords were interpreted as storage approaches represented within this research context, however, their network position should not be understood as direct evidence that a particular technology causes or guarantees national energy independence.

As a final interpretative step, the content of selected publications directly addressing the identified storage technologies and pathways was examined in greater detail, and the resulting qualitative insights were used to contextualise the bibliometric indicators and support the discussion of the results.

4. Research Results and Discussion

At a minimum occurrence threshold of two, the author-keyword co-occurrence network contained 253 keywords. Following predefined dual-reviewer coding, 16 storage-relevant nodes were retained. General field labels, enabling processes, operational parameters, and non-storage flexibility options were excluded. The results are shown in Table 1.

The technology-focused screening showed that the storage landscape was dominated by battery-related terminology. 'Battery energy storage systems' was the most

visible and strongly connected technology-specific keyword, with 49 occurrences, a total link strength of 127, and an average publication year of 2023.00. Other battery-related terms included ‘batteries’ (11 occurrences; TLS = 34; APY = 2022.09), ‘battery energy storage’ (8; 23; 2022.00), and ‘Li-ion batteries’ (8; 25; 2023.50). ‘Second-life batteries’ had the most recent temporal position within this group (APY = 2024.67), although its occurrence count of three means that it should be interpreted as an exploratory signal.

Table 1. Energy-storage technologies and storage-related deployment pathways identified in renewable-energy research associated with national energy independence

Author keywords	Occurrences	TLS	APY	Energy storage family
battery energy storage systems	49	127	2023.00	Battery-based
electric vehicles	17	49	2021.59	Mobile
pumped hydro storage	16	50	2021.63	Mechanical
power-to-x	14	42	2024.07	Hydrogen/PtX
green hydrogen	12	43	2024.42	Hydrogen/PtX
batteries	11	34	2022.09	Battery-based
hydrogen	11	31	2021.91	Hydrogen/PtX
battery energy storage	8	23	2022.00	Battery-based
li-ion batteries	8	25	2023.50	Battery-based
vehicle-to-grid	6	16	2020.67	Mobile
long-duration energy storage	5	15	2022.20	Cross-cutting duration descriptor
hydrogen storage	3	11	2022.33	Hydrogen/PtX
second-life batteries	3	11	2024.67	Battery-based
grid storage	2	5	2020.50	Grid-based
hydrogen energy storage and economy	2	5	2021.00	Hydrogen/PtX
storage batteries	2	5	2020.00	Battery-based

Abbreviations: TLS - Total link strength; APY - Average publication year; PtX - Power-to-X (Power to everything).

Source: Authors’ calculations.

Among non-battery physical storage technologies, ‘pumped hydro storage’ had the strongest position, with 16 occurrences, TLS = 50, and APY = 2021.63. It can therefore be characterised as an established and broadly connected system-scale storage option within the analysed literature.

‘Second-life batteries’ had the highest APY (2024.67), although this result was based on only three occurrences. Among the more frequently represented pathways, ‘green hydrogen’ and ‘Power-to-X’ occupied the most recent temporal positions.

‘Hydrogen’ and Power-to-X-related terminology exhibited a more recent temporal position. ‘Power-to-X’ recorded 14 occurrences, TLS = 42, and APY = 2024.07,

whereas ‘green hydrogen’ recorded 12 occurrences, TLS = 43, and APY = 2024.42. The broader term ‘hydrogen’ had an earlier APY of 2021.91, suggesting that the more specific framing of green hydrogen is concentrated in more recent publications. These indicators describe temporal positioning rather than a statistically demonstrated growth rate and should not be interpreted as evidence of technological superiority.

‘Electric vehicles’ and ‘vehicle-to-grid’ recorded 17 and 6 occurrences, respectively. However, these terms were classified as mobile storage deployment configurations rather than independent physical storage technologies. Overall, the results identify battery-based storage as the dominant technological core, pumped hydro storage as the principal established non-battery option, and green hydrogen and Power-to-X as the most recent strongly connected storage pathways.

The results reveal a clear differentiation among energy-storage technologies in terms of their visibility, embeddedness within the research network, and temporal position in the literature. The most prominent storage-related keyword is battery energy storage systems.

This finding confirms the dominant role of battery-based technologies within contemporary renewable-energy systems and is consistent with previous studies emphasizing the rapid diffusion of battery storage driven by falling costs, modularity, and compatibility with photovoltaic and wind-energy installations (Hoppmann *et al.*, 2014; Zakeri and Syri, 2015; Albertus *et al.*, 2020).

The network structure also indicates that battery-related technologies form the technological core of research linking renewable energy and energy independence. The strong position of keywords such as battery energy storage systems, battery energy storage, and Li-ion batteries suggests that much of the literature continues to focus on short-duration balancing, distributed generation, microgrids, and local energy-system optimization.

This result supports the observation that battery systems remain the preferred technological solution for applications requiring operational flexibility and integration of variable renewable generation (Luo *et al.*, 2015; Aneke and Wang, 2016).

At the same time, the results reveal the growing importance of non-battery storage pathways. Pumped hydro storage occupies a particularly interesting position within the network. Although its APY (2021.63) indicates that it is not among the newest research themes, its relatively high occurrence frequency and high TLS demonstrate that it remains a well-established and highly integrated topic within the broader research field. This finding supports previous studies that identify PHES as the most mature large-scale storage technology and one of the most important mechanisms for balancing renewable electricity systems (Blakers *et al.*, 2017; Stocks *et al.*, 2021).

Perhaps the most significant observation concerns the emergence of hydrogen-related technologies. Keywords such as green hydrogen (APY = 2024.42), Power-to-X (APY = 2024.07), and hydrogen storage (APY = 2022.33) occupy some of the most recent positions in the dataset.

Although their absolute frequencies remain lower than those of battery-related technologies, their relatively high APY values indicate that these topics have attracted increasing scientific attention only in recent years.

This pattern suggests that hydrogen-based technologies are no longer treated as peripheral research themes but are becoming increasingly relevant within discussions concerning future renewable-energy systems.

The relationship between hydrogen-related concepts and energy independence is particularly noteworthy. Earlier studies viewed hydrogen primarily as an alternative energy carrier and decarbonization tool (Blanco and Faaij, 2018; Glenk and Reichelstein, 2019).

More recent literature increasingly links hydrogen to strategic flexibility, long-duration balancing, seasonal storage, and resilience against supply disruptions. These functions are especially important in the context of energy security concerns emerging after the disruptions observed in global energy markets following 2022 (Kuzemko *et al.*, 2022; Misik and Nosko, 2023).

A similar trend can be observed for Power-to-X technologies. The presence of Power-to-X among the most recent keywords in the network suggests an increasing interest in sector coupling and the conversion of renewable electricity into alternative energy carriers.

Unlike conventional storage technologies, Power-to-X systems extend the role of storage beyond electricity-sector balancing by creating links between electricity generation, transport, industry, and heating sectors. As a result, they are increasingly viewed as strategic technologies supporting both decarbonization and long-term energy-system flexibility (Blanco and Faaij, 2018; Glenk and Reichelstein, 2019).

The findings also reveal that energy-storage research related to energy independence is becoming increasingly diversified. While earlier studies predominantly focused on batteries, photovoltaic systems, and localised applications, recent contributions explore a broader portfolio of technologies and deployment pathways.

This diversification is reflected not only in the emergence of hydrogen-related technologies but also in the growing attention devoted to electric vehicles, vehicle-to-grid configurations, and long-duration storage solutions. The coexistence of these technologies within the same research domain suggests that future energy systems are likely to depend on combinations of complementary storage technologies rather

than on a single dominant solution.

Although the occurrence frequency of terms electric vehicles and vehicle-to-grid technologies remains moderate, their presence within the network demonstrates that mobility-related storage is becoming increasingly integrated into discussions concerning renewable-energy systems.

Vehicle batteries are gradually being examined not only as components of transportation systems but also as distributed storage assets capable of supporting local flexibility and grid balancing. Nevertheless, the relatively low frequency of vehicle-to-grid suggests that its practical deployment remains at an earlier stage compared with conventional battery-storage applications.

The results also provide indirect evidence of a changing perception of energy storage within the broader energy-transition discourse. Storage is no longer viewed exclusively as a technical balancing tool. Instead, it increasingly appears in the context of resilience, security of supply, strategic flexibility, and long-term adaptation of energy systems. This tendency is visible in both the emergence of hydrogen-related concepts and the growing prominence of technologies associated with long-duration balancing and sector integration.

The temporal structure of the identified storage technologies further suggests that renewable-energy storage research is currently undergoing a transition from a period dominated by battery deployment toward a more diversified technological landscape.

Batteries continue to occupy the central position in the literature; however, newer technologies such as green hydrogen and Power-to-X are gaining visibility at a faster pace. This does not imply that batteries are becoming less important. Rather, it indicates that researchers increasingly recognize the limitations of relying solely on short-duration storage solutions in energy systems characterised by high shares of renewable generation.

The observed technological evolution has important implications for future research and energy policy. Battery technologies will likely remain crucial for distributed and short-term flexibility applications. However, achieving high levels of renewable-energy penetration may require complementary technologies capable of providing long-duration and seasonal storage services.

The increasing visibility of hydrogen storage, Power-to-X pathways, and pumped hydro storage suggests that future research will increasingly focus on integrated storage portfolios capable of simultaneously supporting decarbonization, flexibility, resilience, and energy-security objectives.

Overall, the findings suggest that the technological structure of renewable-energy

storage research is becoming progressively more complex. While battery-based storage remains the dominant technological pathway, emerging technologies such as green hydrogen and Power-to-X are rapidly gaining prominence and may play a central role in the next generation of renewable-energy systems. The results therefore indicate not only continuing technological diversification but also a gradual shift toward storage solutions capable of addressing increasingly strategic energy-system challenges.

The study is subject to several limitations. First, the analysis was restricted to English-language journal articles and reviews indexed in Scopus; therefore, relevant publications available in other databases, languages, or document types may not have been included. Second, author keywords reflect the terminology selected by individual authors and may differ in specificity, contain lexical variants, or omit relevant technological information.

Although the independent dual-reviewer procedure reduced the subjectivity of keyword classification, the assignment of terms to storage technologies, pathways, and deployment configurations remained partly interpretative. The qualitative interpretation was additionally supported by a closer examination of selected publications rather than by a systematic content analysis of all records in the corpus; consequently, it was used only to contextualise the bibliometric findings.

Finally, Occurrences, TLS, and APY describe research visibility, network embeddedness, and relative temporal position, but do not measure publication growth, technological performance, actual deployment, or a causal contribution to energy independence. The inclusion of records retrieved in June 2026 also means that the final publication year was incomplete.

5. Conclusions, Proposals, Recommendations

This study investigated the technological evolution of energy-storage solutions within renewable-energy systems associated with national and supranational energy-independence objectives. Using a bibliometric approach based on 472 Scopus-indexed publications, the analysis identified the dominant storage technologies, assessed their relative position within the research network, and examined their temporal evolution using occurrences, TLS, and APY.

The results indicate that battery-based technologies constitute the dominant technological core of the analysed literature. BESS achieved the highest occurrence frequency and the highest level of network embeddedness, demonstrating their central role in contemporary renewable-energy systems. Battery-related solutions remain the primary technological pathway for supporting renewable-energy integration, distributed generation, microgrids, and local energy-management applications.

The findings further reveal that pumped hydro storage remains the most established large-scale non-battery storage technology. Its relatively high occurrence frequency and strong network integration indicate that it continues to play an important role in studies addressing large-scale renewable-energy deployment, system flexibility, and long-duration balancing.

A particularly important result concerns the emergence of hydrogen-based technologies and Power-to-X pathways. Green hydrogen and Power-to-X exhibited the most recent temporal positions among the analysed technologies, indicating rapidly growing scientific interest in their application.

These technologies increasingly appear in studies related to long-duration storage, sector coupling, seasonal balancing, and the enhancement of strategic flexibility in renewable-energy systems. Their recent prominence suggests that they are becoming central components of future energy-transition strategies.

The results also demonstrate that the technological structure of storage-related research is becoming progressively more diversified. While batteries continue to dominate in absolute terms, renewable-energy storage research is no longer limited to battery technologies alone.

The growing visibility of hydrogen storage, Power-to-X systems, pumped hydro storage, long-duration storage, vehicle-to-grid solutions, and second-life battery applications indicates a gradual expansion of technological options available for renewable-energy integration and energy-system management.

From the perspective of temporal evolution, the results suggest that renewable-energy storage research is entering a new phase characterised by increasing attention to strategic storage technologies. Rather than focusing exclusively on short-term operational balancing, the literature increasingly addresses technologies capable of supporting long-term system flexibility, large-scale renewable integration, and improved resilience against energy-market disruptions and supply shocks.

The findings have several implications for researchers, policymakers, and energy-system planners:

- Battery energy storage systems are likely to remain the dominant technology for distributed renewable-energy applications, particularly in microgrids, local energy communities, and decentralised energy systems.
- Pumped hydro storage should continue to be considered a critical component of large-scale renewable-energy transitions due to its maturity, scalability, and long operational lifetime.
- Hydrogen-based storage and Power-to-X technologies deserve increasing policy and research attention because of their potential role in seasonal balancing, sector coupling, and long-term energy-system flexibility.

- Future energy systems are unlikely to rely on a single storage technology. Instead, they will require hybrid storage portfolios combining multiple storage technologies operating at different temporal and spatial scales.
- The growing strategic importance of storage suggests that energy-storage policy should be integrated more closely with broader objectives related to energy security, resilience, and long-term system transformation. Several research directions emerge from the present analysis:
 - Future studies should investigate the relationships between specific storage technologies and measurable indicators of energy security, resilience, and energy independence.
 - Greater attention should be devoted to comparative assessments of storage technologies operating over different storage durations, ranging from short-term battery balancing to seasonal hydrogen storage.
 - Additional research is needed on the integration of hydrogen systems, Power-to-X pathways, and long-duration storage technologies into national and regional renewable-energy systems.
 - Future bibliometric studies could combine technological analysis with quantitative energy-system indicators in order to assess how research trends correspond to actual deployment patterns and policy developments.
 - The growing visibility of second-life batteries and vehicle-to-grid systems suggests promising opportunities for future investigations into circular-economy approaches and distributed storage architectures.

Overall, the study shows that renewable-energy storage research is undergoing a transition from a technology landscape dominated by conventional battery applications toward a more diverse storage ecosystem in which hydrogen, Power-to-X, pumped hydro storage, and other long-duration storage solutions are becoming increasingly important. These technologies are expected to play a crucial role in supporting future low-carbon, flexible, and resilient energy systems.

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