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Review

Progress in Energy Storage Technologies and Methods for Renewable Energy Systems Application

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Abstract: This paper provides a comprehensive review of the research progress, current state-of-the-art, and future research directions of energy storage systems. With the widespread adoption of renewable energy sources such as wind and solar power, the discourse around energy storage is primarily focused on three main aspects: battery storage technology, electricity-to-gas technology for increasing renewable energy consumption, and optimal configuration technology. The paper employs a visualization tool (CiteSpace) to analyze the existing works of literature and conducts an in-depth examination of the energy storage research hotspots in areas such as electrochemical energy storage, hydrogen storage, and optimal system configuration. It presents a detailed overview of common energy storage models and configuration methods. Based on the reviewed articles, the future development of energy storage will be more oriented toward the study of power characteristics and frequency characteristics, with more focus on the stability effects brought by transient shocks. This review article compiles and assesses various energy storage technologies for reference and future research.

Keywords: energy storage system; CiteSpace; penetration of renewable energy; prospects

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1. Introduction

The demand for additional energy in the modern world seems to be rising steadily. Both businesses and households require large amounts of power. New issues are simultaneously presented to the current energy production methods [1,2]. International agreements seek to control pollution levels, global warming calls for measures to cut carbon dioxide emissions, and several nations have decided against constructing new nuclear power stations in favor of decommissioning existing ones [3]. Additionally, the price of conventional energy sources has increased considerably, and the need for a consistent and undistorted supply of these sources has become vital due to the enormous global increase in energy consumption [4–6]. A result of this evolution is the requirement to switch to new energy production methods. Renewable energy sources and other types of potential distribution generation sources are becoming more prevalent on a global scale. These energy sources, which include wind power, solar power, and hydroelectricity in all its forms, frequently depend on the weather or climate to function effectively [7–9]. The rate of growth of renewable energy generation capacity has been exponential over recent years, and data from IRENA put it that there was a global renewable energy generation capacity of 3083.929 GW in 2021.The largest share of this is hydropower, which accounts for a total capacity of 1360.524 GW (excluding pure pumped storage), followed by wind energy (824.874 GW), solar energy (849.473 GW), bioenergy (143.731 GW), geothermal energy (15.644 GW), and marine energy (524 MW). In terms of installation capacity, wind energy accounted for the largest share of the global total, with a capacity of 623 GW; solar energy accounted for the second largest share, with 586 GW; and wind and solar energy continued to dominate the addition of renewable capacity in 2021, according to the generation capacity of RESs. However, the supply of energy from these sources is frequently disrupted by the intermittency of weather, for example, a lack of wind or sunshine. As a result, it is essential to maintain the power fluctuations of a power system that incorporates a lot of RESs such as solar and wind. Additionally, renewable energy usually is located in a remote site that is far away from the city, which will consume a lot of energy in the process of electricity transmission. The stated challenges of renewable energy sources show the importance of energy storage technology. Energy storage mitigates power quality concerns by supporting voltage, smoothing output variations, balancing network power flow, and matching supply and demand.

Governments and private energy institutions globally have been working on energy storage technologies for a long time [10,11]. The U.S. has positioned large-scale energy storage technology as an important supporting technology to revitalize the economy, realize the New Deal for energy, and ensure national energy and resource security. Large-capacity energy storage technology has been listed as the highest priority demand technology in the Grid 2030 plan [12]. Similarly, Japan has also positioned energy storage as a safeguard technology for its post-abandonment energy strategy (after the Fukushima nuclear meltdown) and promoted the application of the energy storage market through subsidies [13]. Additionally, Europe has over time supported energy storage technology as a strategic new industry in the energy sector [14]. China does not yet have a specific policy or large-scale use of energy storage [15]. However, it is in a critical period of energy and economic development transformation, and the proportion of renewable energy is increasing, which has an increasingly significant impact on grid reliability, grid peaking, and unit energy efficiency, thus energy storage will have a great market demand and necessity.

Haris et al. [16] systematically described the storage, utilization, and transmission of hydrogen energy, especially the integration of hydrogen energy with other renewable energy sources. However, the methodology of its study is still based on traditional reading, and the scope of the study is limited to hydrogen energy storage. Microgrid technology is becoming increasingly central to community power supply research, and the trend toward combined energy storage and electric vehicle response is becoming more apparent. Energy storage has unique advantages for solving fast response problems [16]. However, this study only emphasizes the advantages of energy storage response, and there has not been a comprehensive description of other characteristics. Responding to unexpected conditions such as extreme weather, mobile energy storage devices [17] are significantly effective in addressing transient network reconfiguration and recovery, and a comprehensive expression of the recovery response of mobile energy storage to catastrophic damage. All of the above literature is specific to a particular scenario or a single energy storage component, and the research methodology is limited to the accumulated experience of researchers. In this paper, we use literature research tools to sort out the pulse and extensively study the whole energy storage system hotspots.

As the world races towards the total decarbonization of energy production, clarifying the necessity, feasibility, and realization path of improvement of the technicalities of energy storage has become a research preference global. Hence, this study can inform a directional reference as it presents the progress in ESS development in recent years. With the aim to provide updated knowledge of state-of-the-art research, this study summarizes the outstanding scientific results and the novel methods/models employed for ESS studies in the existing work of literature. This study was set up in the following sections. Firstly, the visual analysis software Citespace (Section 2) is used to visualize the highly cited literature in the last 10 years (2012–2021) and the research hotspots. The research centers on the field of energy storage are obtained through the analysis of the co-citation network and co-occurrence network. In Section 3, different types of energy storage are introduced in terms of development history, working principle, key materials, technical specifications, applications, and future development. The advantages and disadvantages of each type of energy storage are also analyzed to give guidance on the selection of energy storage. In Section 4, the components of energy storage systems and their functions are introduced to fully understand the problems that need to be solved. Finally, a summary is presented in Section 6, and some conclusions are made in Section 6.

2. Materials and Method

To obtain a systematic and reliable review, the article used the WOS Core Collection, which is the one with the most comprehensive data for bibliometrics. The search terms combined energy storage systems and renewable energy as subject terms and keywords. Data sources were restricted to WOS, with publication types of articles and reviews, for the period between 2012–2021. Since this study focuses on the most recent research development and application, we have limited our research scope to the past decade (specifically, the year 2012–2021). The current review provides direction and planning for the development of technology in the next decade.

Complete records of references published were extracted into tab-delimited plain text files, with CiteSpace used to eliminate duplicate content. This article used CiteSpace to analyze the 414 highly cited papers from 2012–2021 for the keywords: "energy storage and renewable energy". Then, co-citation analysis and keyword analysis were performed.

Co-citation implies that two articles are co-cited by an identical article, and frequent co-citations indicate that they share a relevant research topic [18]. Therefore, co-citation analysis allows the grouping of relevant references according to the degree of similarity in content. Then, by analyzing the literature in each cluster, the core themes of the research area can be identified. In addition, compared to pure citation analysis, co-citation analysis is more reliable and provides the necessary information about the data domain [19].

Network nodes are subsequently clustered by using a maximization expectation algorithm based on a series of parameters including frequency of use, BC, first author, number of publications by year, source of publications, and semi-life cycle of articles. BC is a central point used for measuring the weight of how the shortest path in a network crosses this point, demonstrating the contribution of a point and other points connected in this network contribution rate. The half-life cycle of literature is defined as the number of citations of an article that exceeds 50% of all citations in a year. Its purpose is to measure the frontiers of development in the field of investigation. The co-citation network analysis includes literature, authors, and journals to find the most influential points [20].

2.1. Document Co-Citation Network

The cluster uses a combination of titles and a great LLR for de-clustering in CiteSpace. LLR is an algorithm that calculates and determines the individual labels of each bibliography on the behalf of a core concept. Each cluster uses a specialized word to express the depth of coexistence measure quality, an indicator, mediated centrality, in the first 14 clusters all above 0.9, providing a reliable quality due to their proximity to the highest value of 1 (Table 1). The largest cluster #0, which is the "storage technique" contains 41 documents, which is slightly larger than the other clusters, and the main clusters are relative to the updated clusters based on this average citation age. The #9 system and #12 state, on the other hand, are older topics.

Table 1. Summary of the largest 14 clusters.

Cluster ID	Size	Silhouette Score	Label (LLR)	Mean (Cite Year)
0	41	0.916	storage technologies	2020
1	40	0.993	large-scale energy storage	2014
2	40	0.915	transport solution	2015

Table 1. *Cont.*

Cluster ID	Size	Silhouette Score	Label (LLR)	Mean (Cite Year)
3	31	0.983	flexible electricity generation grid exchange	2018
4	31	1	dual-layered film	2018
5	25	0.989	integrated natural gas	2016
6	24	0.956	hydrogen system	2020
7	21	0.951	hydro storage	2013
8	16	0.915	electrical energy storage	2017
9	14	1	microgrid system	2012
10	14	0.988	life cycle assessment	2016
11	13	1	fundamental	2020
12	12	1	state	2012
13	12	0.976	microgrid system	2020

Table 2. Top 10 most cited papers with co-citation frequency.

Citation Counts	References	Cluster
9	Luo et al. [21], 2015, Appl Energy	5
8	Yang et al. [22], 2011, Chen Rev	1
8	Cheng et al. [23], 2017, Chen Rev	4
8	Buttler and Spliethoff [24], 2018, Renew Suet Energ Rev	0
7	Ahmadi and Abdi [25], 2016, Sol Energy	0
7	Beaudin et al. [26], 2010, Energy Sustain Dev	2
6	Schiebahn et al. [27], 2015, Int J Hydrogen Energ	10
6	Lin et al. [28], 2017, Nat Nanotechnol	4
6	Zheng et al. [29], 2017, Nat Energy	4
6	Dunn B et al. [30], 2011, Science	1

The most cited articles are usually regarded as landmarks due to their ground-breaking contributions (Luo et al. [21]). Table 2 shows the top 10 most-cited papers. Through investigating the core articles in each cluster, it is seen that there are several issues, mainly the storage of hydrogen [31], research and development of lithium–sulfur batteries [32], the study of 100% penetration of renewable energy [33–35], electrolysis [36], Steady-state analysis [37], demand-side response [38–41], optimal configuration [42], and power-to-gas [43].

Additionally, in the top 10 co-citation analysis, the literature is in clusters #4, #1, and #0, each representing battery fuel, electrode material, and hydrogen storage. However, the largest cited literature [21] comes from the steady state analysis under the penetration of renewable energy sources. It proposed that the role of energy storage is increasingly important due to the enormous challenges arising from restrictions on greenhouse gas emissions and the uncertainty generated by renewable energy access and provided an understanding overview of EES. There is also one on-demand side response [27] in cluster #10. The main focus was on electricity-to-gas technology, analyzed in terms of different technical approaches, and the safety and reliability of hydrogen storage.

2.2. Author Co-Citation Network

This section shows the frequency of cited authors. It will analyze all the yields, such as one particular author is combined with another, which means that only the first author is considered. The value of this mixed author co-citation network, regarding the contribution to the field of energy storage and renewable energy, is shown in Figure 1. Containing 500 nodes and 2552 supply links, the top authors are Y. Li and H. Chen, being the key points in the network due to their high BC values. This is also used to reflect the potential scientific contribution. In other words, H. Chen tends to be a bridge connecting different stages in the field of energy storage and renewable energy. Table 3 lists the top 10 authors, all with a citation frequency of more than 30.

Figure 1. A visualization of the author's co-citation network.

Table 3. Top 10 most cited authors with co-citation frequency.

Author	Frequency	BC	Author	Frequency	BC
Y. Li	52	0.22	Y. Zhang	38	0.01
Y. Wang	47	0.07	Y. Liu	36	0.05
X. Wang	44	0.08	J. Liu	35	0.03
J. Wang	42	0.02	H. Wang	34	0.03
X. Zhang	42	0.03	Z. Li	31	0.01

2.3. Journal Co-Citation Network

To outline the set of journals that have served the Energy Storage and Renewable Energy research community over the last 10 years, the co-citation network at the journal level is shown in Figure 2. In total, 436 different publications were found, illustrating a diverse body of knowledge that influences studies of energy storage and renewable energy. Ten journal sets with co-citation frequencies of over 109 are listed in Table 4. Applied Energy is the most significant with 229 citations, followed by Energy (209) and Renewable and Sustainable Energy Reviews (200). Journals with a high impact factor are likely to have a higher citation frequency. In terms of BC, P IEEE has the highest BC ratio (0.22) for articles published in the journal that have been cited since 2012. Other journals with high relative BC ratios are J Powersources (0.13), IEEE Tinbelectron (0.10), and Int J Hydrogen Energy

(0.08). Therefore, these four journals are major nodes that establish links with other nodes in the network for the co-citation of energy storage and renewable energy research journals.

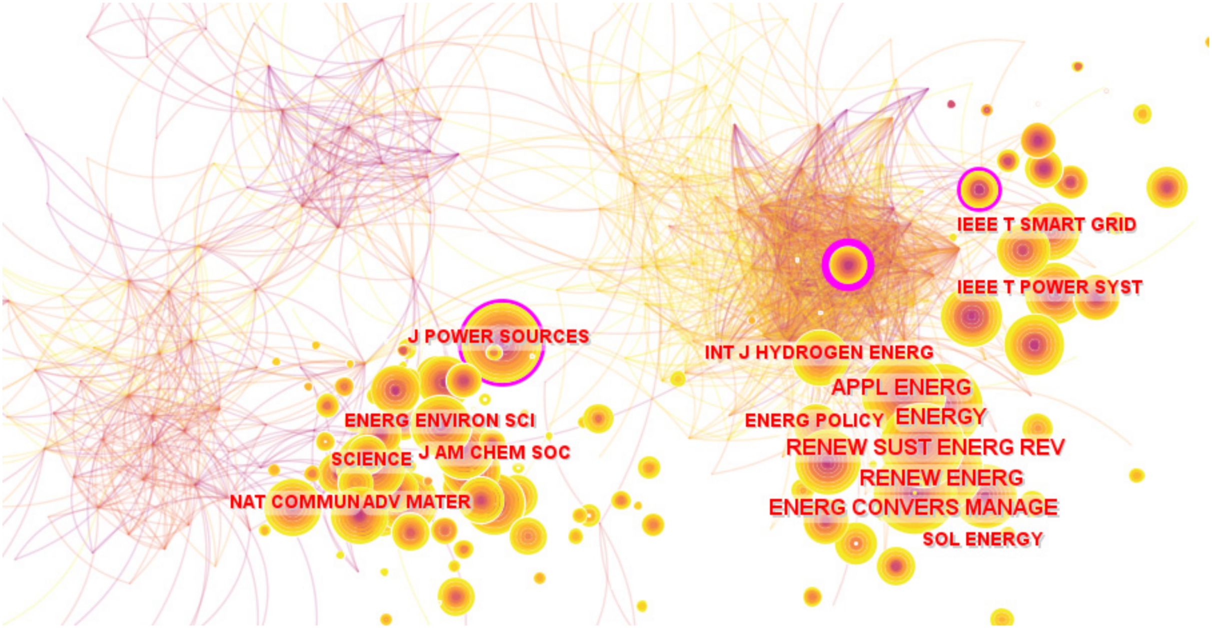

Figure 2. A visualization of the journal co-citation network.

Table 4. Top 10 most cited journals with co-citation frequency.

Journal	Frequency	BC
Applied Energy	229	0.06
Energy	209	0.02
Renewable and Sustainable Energy Reviews	200	0.01
Renewable Energy	170	0.01
Energy Convers Manage	163	0.02
Journal of Power Sources	142	0.13
Energy & Environmental Science	128	0.04
Science	116	0.00
IEEE TPOWERSYST	112	0.03
Energy Policy	109	0.05

2.4. *Emerging Trends of Energy Storage and Renewable Energy*

CiteSpace provides Burst detection to detect large changes in the number of citations at a certain point in time. It is used to detect the decline or rise of a certain subject term or keyword. The top 10 references with the strongest citation bursts are shown in Table 5. As observed, the earliest citation burst started in 2013, which is consistent with the rapid development phase (2013–2018) of Energy Storage and Renewable Energy research and Today's hot stage (after 2018). From 2013 to 2021, the first four emergent terms are considered the starting stage. For electrochemical energy storage technologies and batteries, Yang et al. [22] (S = 3.04) compared four types of electrochemical battery technologies and proposed that the focus of future electrochemical batteries remains on duration, reliability, energy density, etc. Ji et al. [44] (S = 2.71) described lithium–sulfur batteries, which would, theoretically, have a high gravimetric capacity as well as a density capacity five times that of lithium-ion batteries, by creating highly ordered interwoven composites that help capture polysulfides generated by redox processes, with a reversible capacity of 1320 mAh/g. For energy storage systems (ESS), Chen et al. [45] (S = 2.71) proposed a smart energy management system (SEMS) that simplified intelligent management, economic load scheduling, and operational optimization of distributed generation (DG) into a single object optimization problem with load management by genetic algorithms. On the other hand, Dunn et al. [30] (S = 2.62) systematically reviewed the application of sodium–sulfur batteries, low-cost redox flow batteries, and lithium batteries in the grid and the impact of electric vehicle development on grid energy storage.

Table 5. Top 10 references with strongest citation bursts.

References	Year	Strength	Begin	End	2012–2021
Yang Z [22], 2011	2011	3.04	2013	2016	
Chen C [45], 2011	2011	2.17	2013	2014	
Ji X [44], 2009	2009	2.17	2013	2014	
Dunn B [30], 2011	2011	2.62	2013	2015	
Beaudin M [26], 2010	2010	3.63	2014	2015	
Carmo M [46], 2013	2013	2.67	2015	2016	
Gahleitner G [47], 2013	2013	2.54	2015	2017	
Schiebahn S [27], 2015	2015	2.60	2017	2018	
Cheng X [23], 2017	2017	3.40	2018	2019	
Buttler A [24], 2018	2018	2.68	2019	2021	

The next four emergent words are the development phase. On the one hand, with the massive adoption of renewable energy sources, Beaudin et al. [26] (S = 3.63) pinpointed the potential of energy storage to solve the variable renewable electricity resources (VRES) input problem. Special attention is given to the applicability, advantages, and disadvantages of various ESS technologies for large-scale VRES integration. On the other hand, more research is being performed on hydrogen storage and electric-to-gas conversion. Carmo et al. [46] (S = 2.67) presented PEM electrolysis, and Gahleitner [47] (S = 2.54) reviewed international pilot plants for power-to-gas conversion to gain their relevant operational experiences and further improve the efficiency, lifetime, and cost of electrolyzers and fuel cells, and Schiebahn et al. [27] (S = 2.6) presented different pathway process chains for power-to-gas conversion.

The last is today's hot stage, which is studying the poor cycle efficiency and safety problems induced by uncontrolled the lithium-branched crystal growth of lithium metal batteries [23] (S = 3.4) and the status of various water electrolysis technologies in large-scale flexible energy storage [24] (S = 2.68).

2.5. Keyword Analysis

To explore the research direction more intensely, a cluster analysis of the keywords was performed, which is shown in Figure 3. It organizes the documents into different colored clusters. The hot spots and frontiers of the field were discovered by the size of the clusters and the vividness of the colors. A time zone view of keywords/clusters is illustrated in Figure 4. In correspondence to the time of their publication or their peak time, this visualization view arranges keywords.

According to these major keywords over time, the main topics of energy storage and renewable energy research are in electrochemical energy storage, including battery types, electrode materials, hydrogen storage technology, including electrode materials for water electrolysis, storage problems of hydrogen generation, safety assessment, and the study of the configuration problems of related EES systems, etc.

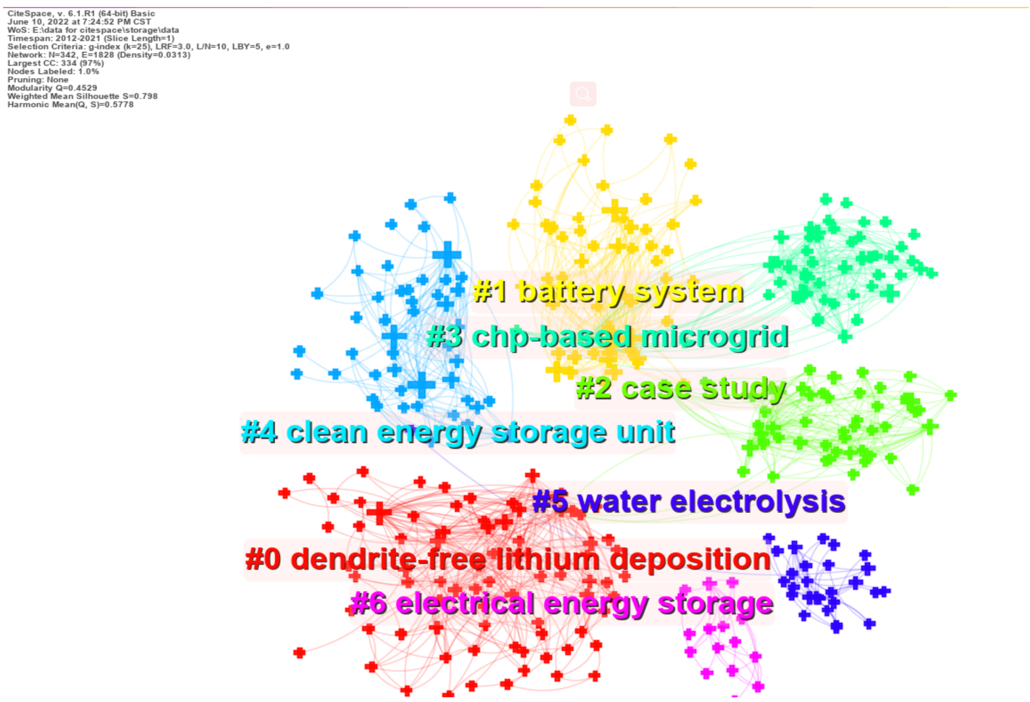

Figure 3. Keyword Cluster Analysis Network.

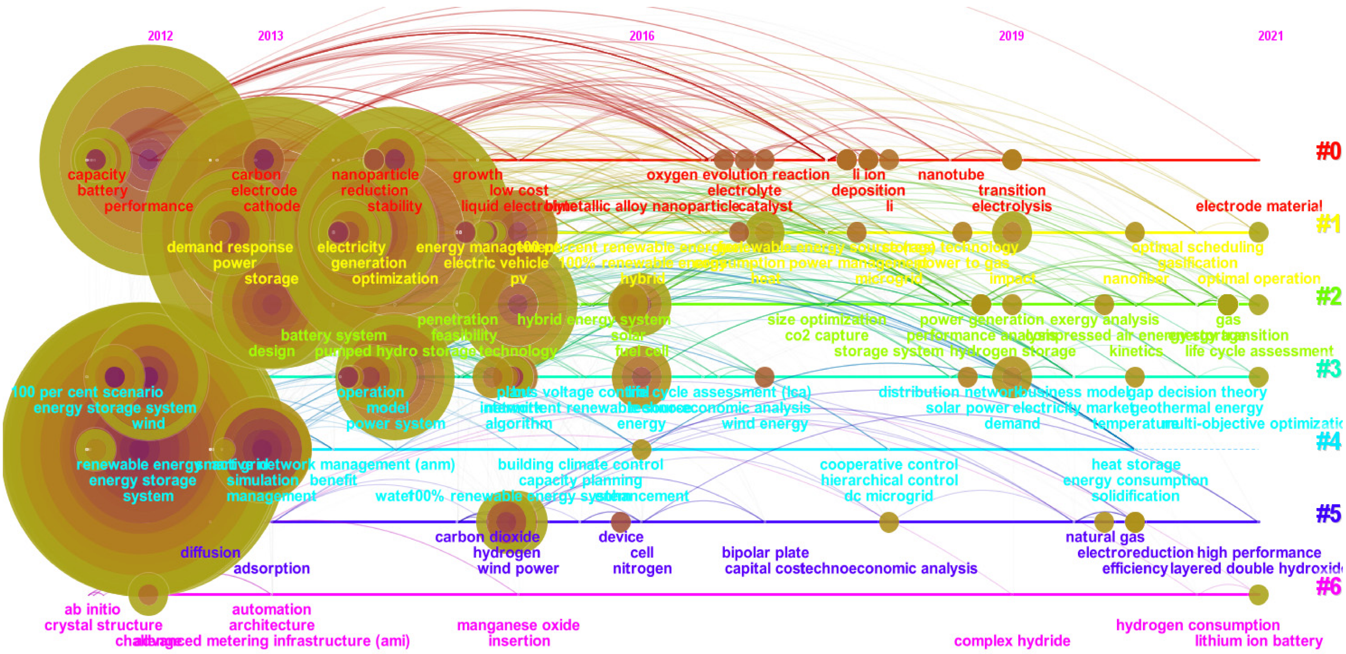

Figure 4. Time zone view of keywords.

3. The Progress of Energy Storage Technologies

The low performance of the battery is limiting the development of stored energy, which is forcing many countries to develop high-performance batteries. Sorted by energy type, there is mechanical energy storage, chemical energy storage, electrochemical energy storage, and thermal energy storage. Saravanan [48] performed the first report on sodium batteries for the large-scale energy storage market. Because of the intermittent renewable resources, the batteries combined high power density, high energy density, and an ultra-long cycle life, which were hopeful for the used energy storage system.

The storage technologies are divided into three sections: the commercialization stage, demonstration application stage, and development phase. At present, there are PSH, lend-acid batteries, and lithium-based batteries in the commercialization stage, in which the technologies are mature. A summary of different energy storage scale and the discharge time is presented in Figure 5. The next section consists of physical energy and electrochemical energy storage, which includes flywheel energy storage and gravity energy storage, flow batteries, and NaS batteries, respectively. In the last section, supercapacitors' energy storage is the hotspot of current research.

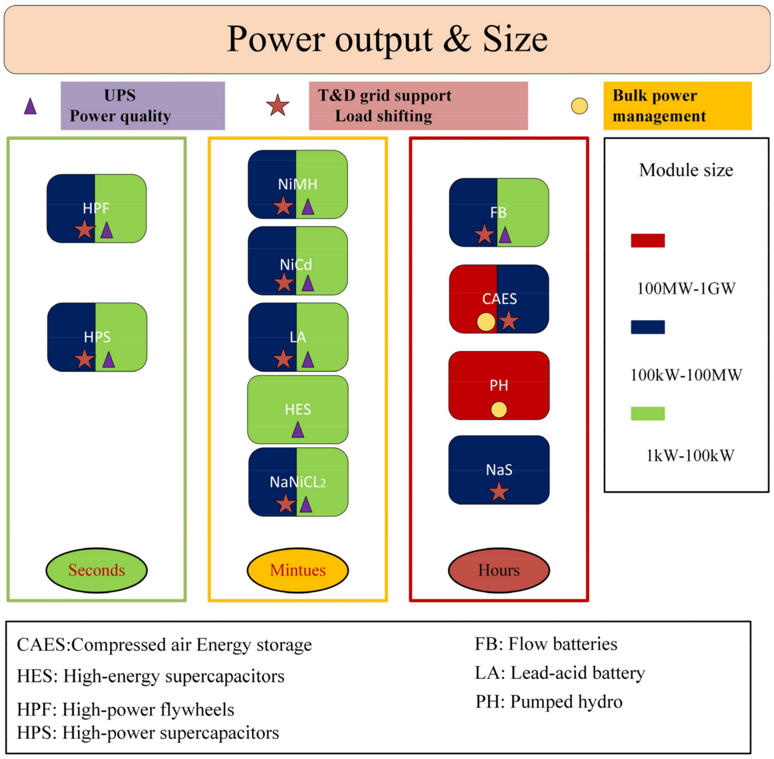

Figure 5. Summarize different energy storage scales and discharge time [49].

3.1. Hydrogen Storage

The most popular ESS technology is hydrogen storage, and this paper focuses on large-scale hydrogen generation, transmission, and combination with renewable energy sources. Buttler and Spliethoff [24] summarized the applications of water electrolysis, which were three types of technologies: alkaline, proton exchange membrane, and solid oxide. Comparison of technologies from different aspects including lifetime, nominal, flexibility, load performance, pressurized operation, available and realized capacity ranges, and investment and maintenance costs. Their study stated that alkaline is the most mature one with the lowest cost and maintains costs. Furthermore, the proton exchange membrane is the most promising technology because of its flexible energy storage requirements. Solid oxide electrolysis is to be applied commercially, which can improve hydrogen production efficiency. It was also conclusively stated that electrolytic water technology was generally moving in the direction of large-scale flexible energy storage applications. García-Olivares [50] et al. presented the current transportation system conversion as one of the bottlenecks encountered in the large-scale use of renewable energy. Their study suggested that the cost of generating hydrogen from wind energy is four times higher than that of direct wind energy for power generation and that hydrogen storage technology remains costly, limiting mass market adoption. Barthelemy [51] et al. presented a study on hydrogen storage, which had three types of gas, liquefied, and solid. Cryogenics and compression are the most mature technologies available. The materials for high-pressure vessels, cryogenic compression, and hydrides are receiving much attention in pursuit of high-pressure compression. Magnesium hydride has become the most promising means of curing technology. Abdelkareem [31] et al. performed a review about the use of renewable energy sources in modern desalination processes. Solar/Geothermal/Wind/Ocean/Hybrid energy was considered. Among them, seaside wind power applications were stated to be the most suitable for desalination, and the hybrid of wind power and photovoltaic was also a good match. Geothermal is considered an excellent renewable energy source that does not require energy storage in addition to geographical restrictions. Tung et al. [52] presented a study on electrocatalysts with efficient oxygen evolution for the electrolysis of water. This robust stability of the technology was attributed to the complementary nature of the defect-free single-crystal electrocatalyst and the reversibly adapted layer.

3.2. Pumped Hydro Storage

PHS, also known as pumped storage power generation, is by far the most widely used large-scale, large-capacity energy storage technology in the world. It accounts for more than 99% of the world's total energy storage capacity and is equivalent to about 3% of the world's total installed power generation capacity. PHS is an EES technology with a long history, high technical maturity, and high energy capacity [53]. The construction of pumped storage power plants is an important part of promoting the development of clean energy on a large scale and is of strategic importance for the large-scale absorption of wind, solar, and other clean energy and for improving the stability of grid operation and power quality. A typical PHS plant uses two reservoirs, vertically separated [54]. In terms of the operational characteristics of pumped storage, it can use high water levels for power generation and peak shaving of the grid, or it can use low valley power or wind and photoelectric abandoned energy for pumping, converting electrical energy into water potential energy and storing it for backup [21]. However, some issues affecting the scale of the pumped storage power plant are still to be solved, focusing on the site selection technology, high dam engineering technology, high head large capacity pump turbine technology, new generator technology, intelligent scheduling, operation control technology, etc. The Ikaria Island power station in Greece will be one of the first wind–hydro-storage hybrid stations [55]. Trends in PHS facilities include the construction of faster and larger capacity hydroelectric units, the installation of centralized monitoring, and the use of intelligent control systems. Connolly et al. [56] compared to the current state of technology. They studied three approaches for PHES facilities with typical scheduling and found that a 24 h optimized operation strategy was the most beneficial. Under this approach, the charging cycle was about 6 h, obtaining almost 97% of the feasible profit. Furthermore, they pointed out that operators must have accurate price forecasts to maximize profits using electricity price arbitrage.

3.3. Lead-Acid Batteries

After 150 years of development, the lead-acid battery has grown considerably in terms of theoretical research and product performance and is the most widely used chemical battery in small and medium-scale systems [57]. According to the Ministry of Industry and Information Technology data, China's lead-acid battery production is 227.36 million kVAh in 2020. Domestic lead-acid battery production reached 273.59 million kVAh in 2022. The anode is made of Pb, the cathode is made of PbO_2, and the electrolyte is sulfuric acid. It has high charge/discharge electrical efficiency (80%), low operation and maintenance cost, mature technology, and a small daily self-discharge rate (<0.3%) [21]. It has the advantages of safety and reliability. Lead-acid batteries can be used in stationary equipment, as backup power for data and telecommunication systems, and in energy management applications [58], being developed as a power source for fully electric and hybrid vehicles [57]. However, the drawback of the short life cycle of lead-acid batteries has not been solved for a long time (design life 8–12 years, actual operating life 3–5 years), as well as the waste of resources due to the hoarding of used batteries, which contain lead, sulfuric acid, and other wastes inside with strong polluting power and non-degradable characteristics [59]. At present, the research and development of lead-acid batteries are mainly focused on two aspects. On the one hand, it is to improve performance, such as extended cycle time and deep discharge capability. On the other hand, it is used in the application of battery technology to wind energy, photovoltaic power integration, and automotive applications. Zou et al. [59] summarized a variety of fractional-order models for lead-acid batteries. Furthermore, the development history is from using fractional-order operators to describe the dynamic behavior of batteries to simplified fractional-order models. Dufo-López et al. [60] estimated the lifetime of lead-acid batteries in stand-alone photovoltaic systems. Their paper pointed out that many of the optimization results do not work as expected in practice because the lifetime metrics depend on the operating conditions of the batteries. However, using the Schiffer weighted model made a good result that is almost the same as the real lifetimes through the comparison of different lifetime prediction models.

3.4. Lithium-Ion Batteries

Lithium-ion batteries are most widely used in modern digital electronics. Among them, lithium iron phosphate batteries have a longer cycle life, high energy density (200 W h/kg), environmental protection, and affordable and good charge and discharge performance (over 95%). They are widely used in electric vehicles and scaled energy storage [61]. Li-ion batteries have millisecond response times, high energy densities, and high cycle efficiencies (up to 97%). However, there are still some problems with their safety, such as the explosion caused by thermal runaways [62]. At present, the research focus of lithium-ion batteries includes cathode consideration towards high nickel NCM/NCA, negative electrode consideration towards Si material, and electrolyte development towards an electrodeless solid electrolyte. The U.S.-based AES Energy Storage already operates a lithium-ion BES system commercially in New York, and AES installed a 32 MW/8 MWh lithium-ion BES system (Laurel Mountain) to support a 98 MW wind farm in 2011 [9]. Li et al. [63] proposed a lithium–sulfur battery, which uses a nanostructured sulfur composition. Three mainstream electrodes were compared, and 3,4-ethylene-dioxythiophene was found to have the highest long-term reactivity and performance. Zheng et al. [64] used a nanofiber material surface to stabilize the performance of more than 300 cycles, with an 80% capacity retention to improve the cycle life of lithium–sulfur batteries. For the study of lithium-ion battery modeling, the following stages were mainly used: the integer model, fractional-order electrical model, fractional-order electrochemical model, and fractional-order thermal model. In particular, for the RC model, the first order circuit mimics ohmic resistance and charge transfer, and the second order mimics ohmic resistance and diffusion behavior. Third-order circuits, although they can produce the full range of processes, employ a larger set of parameters, also risking overfitting [59].

3.5. Flywheels

FES is the use of varying inertia of the object to achieve energy input/storage or output/release. A total of 60 years of development in mechanical bearing technology has matured compared to superconducting magnetic bearings. A modern FES system consists of five main components: a flywheel, a set of bearings, a reversible motor/generator, a power electronics unit, and a vacuum chamber [65]. The working principle of flywheel energy storage is that the flywheel is driven by electric energy to rotate at high speed under the condition of electric affluence, and the electrical energy is transformed into mechanical energy for storage. The flywheel energy storage can realize the deposit and release of electric energy through the acceleration and deceleration of the rotor. Compared with other forms of energy storage technologies, flywheel energy storage has the advantages of a long service life, high energy density, not being limited by the number of times of charging and discharging, being easy to install and maintain, and being less harmful to the environment [66]. At present, flywheel energy storage technology focuses on high-strength composite material technology, high-speed low loss bearing technology, high-speed high-efficiency power generation/motor technology, flywheel energy storage grid-connected power regulation technology, and vacuum technology [67]. High-speed FES uses advanced composite materials as flywheels, such as carbon fiber [43]. The high-speed FES system uses on-contact magnetic bearings to reduce bearing wear, thus increasing efficiency. The applications of high-speed FES are expanding, mainly in the traction and aerospace industries for high power quality and traversing power services [68]. In June 2011, a 20 MW modular power plant built by Beacon Power, the largest advanced EES facility in North America, went into commercial operation in New York [45]. It provides fast-response FM service to the grid using a 200-speed flywheel system, providing 10% of the statewide FM demand [69]. Aydin and Aydemir [70] proposed a simple control method for flywheel energy storage systems, modeled in the charging and discharging states, respectively. In the charging state, current control is mainly considered, and a closed-loop speed detection controller is applied for speed regulation. In the discharging state, the PWM inverter is used as a PWM boost rectifier. It is proposed to use the current reference instead of the speed reference to drive the charging mode. Lee et al. [71] used superconducting energy storage technology to achieve the highest peak energy demand and a significant increase in energy efficiency in a tram track electrical system. The peak energy of the whole system was reduced by 36.7%, and the annual power saving was about 48 MWh.

3.6. Sodium–Sulfur Batteries

NaS battery is one of the most typical secondary batteries with sodium metal as the electrode, and it is a large-scale static energy storage technology with very successful applications [21]. By 2015, sodium–sulfur batteries were leading the way with 40% to 45% of the global electrochemical energy storage. NaS batteries use molten sodium and molten sulfur as the two electrodes and β-alumina as the solid electrolyte. Sodium–sulfur batteries have high specific energy (760 Wh/kg), high capacity (up to 600 Ah), high power density, high Coulomb efficiency (almost zero self-discharge and almost 100% efficiency), pollution-free battery operation, a long life (10–15 years), and a simple battery structure. However, its limitations are the high annual operating costs ($80/kW/year) and the need for additional systems to ensure their operating temperature [72]. Research and development have focused mainly on improving the performance index of the battery and reducing/eliminating the limitations of high-temperature operation [73–76]. During the Shanghai World Expo 2010, the Shanghai Institute of Silicate, the Chinese Academy of Sciences, and Shanghai Electric Power Company collaborated to achieve grid-connected operation of a 100 kW/800 kWh sodium–sulfur battery energy storage system. Cao et al. [77] proposed a new sodium-ion battery for the need for large-scale energy storage due to the use of electric vehicles and renewable energy sources today. They emphasized that sodium-ion batteries are potentially less expensive, safer, and more environmentally friendly than lithium-ion batteries. In the search for a suitable host material, $Na_4Mn_9O_{18}$ accommodates sodium ions and allows reversible and fast ion insertion and extraction.

3.7. Superconducting Magnetic Energy Storage

SMES unit is a device that stores energy in the magnetic field generated by a direct current flowing through a superconducting coil [2]. A typical SMES system consists of three main components, including a superconducting coil unit, a power conditioning subsystem, and a refrigeration and vacuum subsystem. During the discharge phase, the SMES system can release the stored electrical energy back into the alternating current (AC) system through the connected power converter module. The amount of stored energy is determined by the self-inductance of the coil and the current flowing through it. Low-temperature superconducting (LTS) coils with an operating temperature of 5 K and high-temperature superconducting (HTS) coils with an operating temperature of 70 K. Compared to rechargeable batteries, SMES devices are capable of discharging with near full stored energy after thousands of complete cycles with minimal degradation. Popular research lies in the use of high-temperature superconductivity to generate DC electric fields for field-induced superconductivity [52,53] and the ability of superconductivity to confine atomic sequences [54,55].

3.8. Capacitors and Supercapacitors

Capacitors and supercapacitors store electric energy by accumulating positive and negative charges. A capacitor consists of at least two electrical conductors (usually made of metal foil) with a thin layer of insulator (usually made of ceramic, glass, or plastic film) in between [78]. The charge storage capacity in supercapacitors theoretically derives from two types of capacitive behavior: one related to the double-layer structure of the electrode/electrolyte interface and the other to the pseudo capacitance. Capacitors are suitable for storing small amounts of electrical energy and conducting different voltages; they have a higher power density and shorter charging times than conventional batteries. However, they have limited capacity, relatively low energy density, and high energy dissipation due to high self-discharge losses. Due to their characteristics, supercapacitors have applications in rail transportation, renewable energy, consumer electronics, energy buffers for inverter drive systems, and military equipment. An EPSRC-funded project to develop high-performance supercapacitors with enhanced energy densities has been implemented in the UK. Prototypes have been tested for the design of an efficient and sustainable power system. Some results of this project were published in 2013 [79]. Zou et al. [59] investigated supercapacitors seeking efficient storage mechanisms and potential higher-performance electrolyte materials and classified their mathematical models into three categories: integer order, conventional type, and fractional model. A static and dynamic model capable of predicting supercapacitors across the spectrum was presented. Zhu et al. [80] proposed a new integrated supercapacitor that achieved a large increase in performance and a high energy density of 27.2 Wh/kg.

There are some summaries of the different energy storage technologies in Table 6. Table 7 contains some of the relevant technical parameters. From the existing research on energy storage methods, it can be seen that various energy storage technologies have their the advantages and disadvantages, and it is difficult to meet the storage needs of new energy power systems with only one energy storage technology. It is necessary to increase the research and application of energy storage technology to realize a new energy storage technology with large capacity, high efficiency, fast speed, and low cost so that the new energy power system can operate efficiently and stably.

Table 6. Comparison of different energy storage technologies.

Energy Storage Name	Advantages	Applicable Scenarios	Maturity
Pumped Hydroelectric Storage [81]	mature technology, large scale	For large reservoirs	Mature
Compressed air energy storage [82]	large capacity, long-time storage	involved in grid frequency regulation	Used
Flywheel energy storage [65]	high power density, long life	power quality control of the distribution network	Developed
Superconducting energy storage [83]	high conversion rate, fast response	solve power quality problems with sensible heat storage	Developing
Phase change thermal storage [84]	large phase change dazzle, high energy density, small system size		Mature
Li-ion battery [85]	milliseconds response time, high cycle efficiencies		Commercializing
Lead-acid battery [60]	low cycling times		Mature
Sodium–sulfur battery [86]	high pulse power capability	Initially commercialized, suitable for new energy vehicles, power grid field	Commercializing
Liquid flow battery [87]			Developing
Thermochemical heat storage [88]		high heat storage density can realize long-term storage	Developed

Table 7. Related technical parameters.

Energy Storage Type		Typical Power Rating	Rated Energy	Features
Physical Energy Storage	PHS [81]	100–2000 MW	4–10 h	For large scale, mature technology, slow response, and need for geographic resources
	CAES [82]	10–300 MW	1–20 h	For large scale, slow response, need geographic resources
	Flywheel [65]	5 kW–10 MW	1 s–30 min	Higher power ratio, high cost, high noise
Electromagnetic Energy Storage	Superconducting Energy Storage [83]	10 kW–50 MW	2 s–5 min	Response is fast, high specific power, high cost, difficult maintenance
	High Energy Capacitor	1–10 MW	1–10 s	Response fast, high specific power, low specific energy
	Supercapacitor	10 kW–1 MW	1–30 s	Response fast, high specific power, high cost, low energy storage
Electrochemical Energy Storage	Lead-acid battery [60]	10 kW–50 MW	min–h	Mature technology, low cost, short life, environmental problems
	Liquid flow battery [87]	5 kW–100 MW	1–20 h	Long life, deep discharge, suitable for combination, high efficiency, good environmental protection, but slightly lower energy storage density
	Sodium–sulfur battery [86]	100 kW–100 MW	h	Higher specific energy and specific power, high-temperature conditions, and operational safety issues to be improved
	Li-ion battery [85]	kW–MW	min–h	Hour-high specific energy, group life, and safety issues need to be improved

4. Research Classification

It was noticed that no matter what type of energy storage, it runs through the establishment of energy systems, such as hydrogen energy storage in #6clustering. The energy system is to better deal with the process of energy generation, output, transformation, and use; thus, it is particularly critical to study the framework of the energy system. We need to understand the role and significance of each unit in the energy storage system, as well as the research on the current ESS system. For example, the role of the ESS is to pack the power battery into a group and add it to the control system so that it can improve the energy for electric vehicles at the same time. It also becomes an independent energy storage mechanism. After the automotive power battery system enters the end of its life, it can utilize its energy storage to achieve the effect of cascade utilization of the remaining battery to achieve maximum power, which is a very practical system.

4.1. Electrochemical Energy Storage System

The industry chain of the EESS is a vast system, which is made up of an upstream, downstream, and midstream. Furthermore, the chain, in the upstream, includes a battery's raw materials, the suppliers of electronic components, and so on; midstream mainly includes the battery, BMS, PCS, EMS, and other parts suppliers; the downstream incorporates energy storage integration suppliers, energy storage system installers, and the users who rely on the power grid, namely, families, industrialists, businessmen, and wind and/or light power stations. Lithium battery energy storage system composites with PCS, EMS, electric cores, and BMS. EESS is a structure made up of batteries, PCS, BMS, EMS, and other accessories. From the cost of the EESS, batteries account for about 60%, PCS is 20%, BMS is 5%, EMS is between 5% and 10%, and another accessory is about 5%.

BMS is a real-time monitoring system composed of electronic circuit devices, which effectively monitors battery modules and single unit statuses (voltage, current, temperature, SOC, etc.); safely manages the battery cluster's charging and discharging process, alarms, and emergency protection, processing for possible faults; and safely and optimally controls the operation of battery modules and battery clusters to ensure safe, reliable, and stable battery operation [89]. A BMS battery management system's hardware mainly consists of a BMU, BCMS, BMSC, HMI local monitoring unit, and DMU. BMS adopts tree management modes and supports EMS/SCADA and other upper computer master software management and scheduling [90].

An energy management system, or EMS for short, is used by power operators to monitor, control, and optimize the performance of a power generation or transmission system. Moreover, it can be used for small-scale systems, such as microgrids [91]. An energy management system can help industrial production companies plan and use energy wisely while expanding production, reducing energy consumption per unit of product, improving economic efficiency, and reducing CO_2 emissions [92].

It has the following five roles: monitoring, analysis, targets, control, and interaction.

This also shows the basic technologies needed for an energy management system, including a control system responsible for data collection and monitoring systems, as well as smart grids and smart meters that can collect detailed information and help users and generation communicate in both directions. Energy storage converters, also known as the bi-directional energy storage inverters PCS, are used in grid-connected energy storage and micro-grid energy storage, and, in other AC coupling energy storage systems, connecting the battery and the grid (or load) is a device to achieve bi-directional conversion of electrical energy. It can reverse the DC power of the battery into AC power and transmit it to the grid or to the AC load; it can also rectify the AC power of the grid into DC power and charge the battery [93]. An energy storage converter mainly has two working modes: grid connected and off-grid. The grid-connected mode realizes the two-way energy conversion between the battery bank and the grid. It has the characteristics of the grid-connected inverter, such as anti-islanding, automatic tracking of grid voltage phase and frequency, low voltage ride-through, and so on. When the power quality is not good, it feeds or absorbs active power to the grid and provides reactive power compensation [94]. The off-grid mode, also known as isolated network operation, means that the PCS can be disconnected from the main grid, according to the actual needs and under the condition of meeting the set requirements, providing the local part of the load with AC power to meet the power quality requirements of the grid. In a micro-grid system composed of multiple energy sources, the energy storage converter is the core equipment because renewable energy sources such as photovoltaic and wind power are volatile, the load is also volatile, and the fuel generator can generate power but not absorb it [95]. If there are only PV, wind, and fuel generators in the system, the system operation may be unbalanced, and the system may fail when the power of renewable energy is greater than the load power; thus, it is difficult for the PV grid-connected inverter to run in parallel with the fuel generator, the energy storage converter can absorb energy and also emit energy, and the response speed is fast, which plays a balancing role in the system [96].

4.2. Application Scenarios of Energy Storage System

The storage energy is mainly in the three scenes, which are named the generation side, system operators, and user side. From the perspective of the power generation side, the demand endpoint of the energy storage is the power plant. Due to the different impacts of different power sources on the grid and the dynamic mismatch between power generation and power consumption caused by the difficulty of prediction at the load side, there are more types of demand scenarios for energy storage on the power generation side, including six types of scenarios such as energy time shifting, capacity units, load tracking, system frequency regulation, standby capacity, and renewable energy grid connection [97].

The application of energy storage on the grid side is mainly to relieve transmission and distribution blockage, delay transmission and distribution equipment expansion, and reactive power support. Compared with the application on the power generation side, there are fewer types of applications on the grid side, while the effect is more of a substitution effect from the perspective of the effect. The customer side is the terminal of electricity use, and the customer is the consumer and user of electricity. The cost and benefit of power generation and transmission and the distribution's side are expressed in the form of electricity price, which is translated into the cost of the customer; thus, the price of electricity will affect the demand of the customer. The role of the different statuses of energy storage in the power system is summarized in Table 8.

Table 8. The role of energy storage projects.

	Power Generation Side	Grid Side	Customer Side
Program tracking [98]	√		
Smoothing control [99,100]	√		
Peaking [101]	√	√	
Primary frequency modulation [102]	√	√	
Automatic generation control (AGC) [103]	√	√	
Automatic Voltage Control (AVC) [103,104]	√	√	
Reactive support [105]	√	√	
Rotating/non-rotating standby [106]		√	
Transmission and distribution congestion relief [107,108]		√	
Black start [109]	√	√	
Peak shaving and valley filling [110]		√	√
Demand management [37,111]			√
Demand-side response [112]			√
Backup power [113]			√
Electrical energy leveling [114]	√	√	√
Delayed transformer expansion [115]	√	√	√

A detailed description of the operating principles and technical and economic characteristics of mechanical, electrochemical, and hydrogen technologies is presented to derive potential EES utilization [116]. Cho et al. [117] researched commercial battery technologies for EES applications. The feasibility and capabilities of stationary EES systems were considered in terms of obtaining more efficient electrochemical energy storage by comparing efficiency, lifetime, discharge time, and scalability, etc. Eftekhari and Fang [118] studied various electrochemical hydrogen storage technologies. They were fuel storage, battery, and fuel cell supercapacitors. It was finally found that the optimal promising materials for electrochemical hydrogen storage were magnesium alloys and carbon nanocomposites. Koohi-Kamali et al. [119] showed that ESS was a solution for the reliable operation of smart power systems, and the application of each type in the field of power systems was studied, emphasizing the cooperation of these entities with renewable energy.

An efficient daily DC safety-constrained optimal tidal model was proposed to ensure the safe operation of wind power with the transmission grid [120]. The model utilized an energy storage system and a demand response plan to achieve flexibility. Ref. [121] presented a method for ensuring the safe operation of a multi-regional electric energy network under a distributed wind energy and demand response scheme while incorporating an energy storage system.

5. Discussion

5.1. Summary of the CiteSpace Analysis

Through the co-citation analysis network, it was obtained that the spotlight of energy storage and renewable energy is on hydrogen storage technology, electrochemical energy storage technology, and various energy storage systems. The most popular author is Yang Li from the North China Electric Power University, China. His article [122] combined the uncertainty generated by renewable energy inputs for the optimal configuration of isolated microgrid systems, and [123] addressed the feasibility of operating buildings under the influence of renewable energy. The main research area is the uncertainty of renewable energy impact. The most prolific journal is Applied Energy, an engineering technology journal with subdivisions mainly in energy and fuels. The most central is the Journal of Power Sources, with the main focus on resource energy applications related to electrochemistry. The emergence and development of subject terms are consistent with the inductive results of the co-citation analysis, with more explicit thematic studies in terms of detail. In particular, electric vehicles, dual carbon management, and integrated energy have emerged in recent years.

5.2. Summary of Energy Storage

Various forms of energy storage technologies have been developed: Physical energy storage, electromagnetic energy storage, electrochemical energy storage, and phase change energy storage (Figure 6). Physical energy storage includes pumped storage, compressed air storage, and flywheel energy storage; electromagnetic energy storage includes superconducting energy storage and supercapacitor energy storage; electrochemical energy storage includes lead-acid, lithium-ion, sodium–sulfur, and liquid flow battery energy storage; phase change energy storage includes thermal and cold storage energy storage, etc. At present, in distributed power generation systems, superconducting energy storage units are commonly used in island-type wind power generation systems and photovoltaic power generation systems. With the development of wind power generation to scale and industrialization, superconducting energy storage technology will also be applied in grid-connected wind power generation systems.

The battery energy storage system consists of batteries, DC/AC inverters, control devices, auxiliary equipment, etc. It is currently most widely used in small-scale distributed power generation. It is worth noting that lithium-ion batteries, as a new type of high-energy secondary battery that has emerged in recent years, are valued and welcomed for their high operating voltage, small size, high energy storage density, non-pollution, long cycle life, and other characteristics. In addition, the charge/discharge conversion rate of lithium-ion batteries is up to more than 90%, which is higher than that of pumped storage power plants and is more efficient than hydrogen fuel cells for power generation. Pumped storage is mostly used for peaking in modern power grids and is more frequently used in centralized power generation. Compressed air energy storage, phase change energy storage, and other systems are currently not much used in distributed power generation systems and can be used in large-capacity distributed power generation systems in the future.

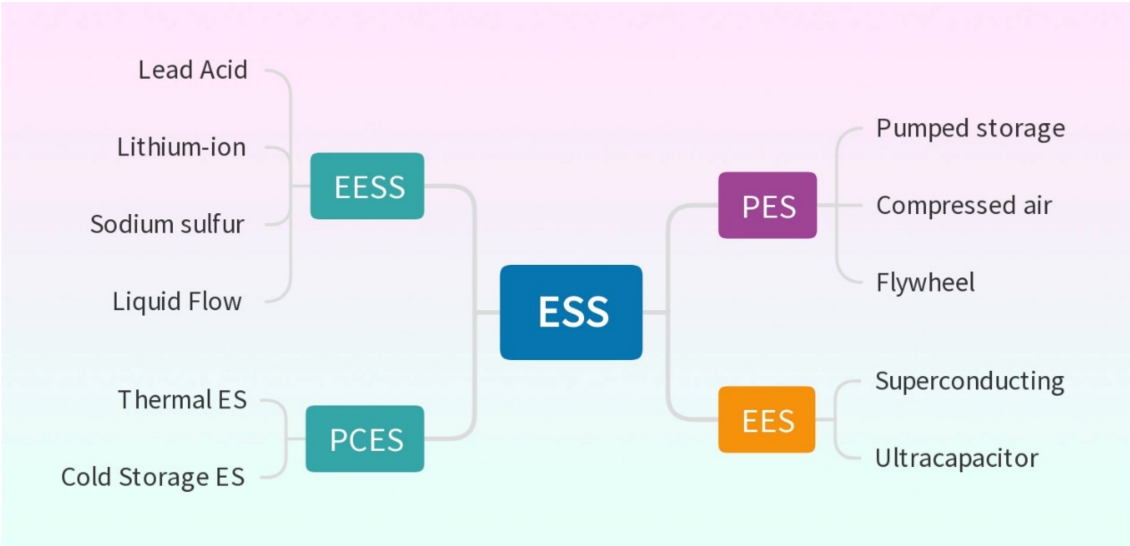

Figure 6. Summarize different energy storage.

5.3. Summary of Future

The future of energy storage lies in the analysis of transient stability. Although so much has been researched, there are very few studies on access to energy storage instantaneously and its continuous stable operation under high-intensity transformation states. With the depth of future research, this continuous time conditions, high-intensity transformation, or, in extreme conditions, energy storage technology for post-disaster reconstruction, the analysis of the reconstruction effect will gradually be paid attention to. At the same time, another trend, more inclined to the study of mobile energy storage, pays attention to the distribution of energy and timely response under the two scales of time and space. Furthermore, research on the sustainability of energy storage in post-disaster situations is also being strengthened so that stability can be restored in a timely manner in the event of extreme weather conditions and continue until power repair time.

6. Conclusions

The depletion of traditional energy sources and environmental pollution have boosted the development of new energy technologies. However, wind and solar energy systems have limitations due to their dependence on natural conditions, leading to volatile and intermittent power outputs. Energy storage technology could address these issues and enable the wider use of renewable energy. With advancements in technology, new energy storage devices have emerged, paving the way for a promising future for energy storage technology.

The energy storage system could play a storage function for the excess energy generated during the conversion process and provide stable electric energy for the power system to meet the operational needs of the power system and promote the development of energy storage technology innovation. This will meet the needs of power system operation and promote the development of energy storage technology innovation. This article presents a bibliographical review and the literature metrology of energy storage systems and renewable energy application research.

Based on the reviewed studies, the use of hydrogen energy technology was found to have a continual and rapid development effect in many countries. Furthermore, the functional applications and commercialization of novel energy storage systems are gradually advancing. The study of frequency response and characteristic curve of energy storage based on fast response is an issue that cannot be ignored in the future. Various challenges attached to electrochemical energy storage, hydrogen storage technology, and optimizing the allocation are highlighted in existing works of literature. Both developed and developing countries can be found on the energy storage research direction map, and this provides the possibility of having global guidance to implement energy storage-related policies.

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Abbreviations

AC	Alternating Current
BC	Betweenness Centrality
BCMS	Battery Cluster Management System
BMS	Battery Management System
BMSC	Battery Management System Controller
BMU	Battery Module Management Unit
DCN	Document Co-Citation Network
DMU	DC Management Unit
EES	Electrical Energy Storage
EESS	Electrochemical Energy Storage System
EMS	Energy Management System
ESS	Energy Storage Systems
FES	Flywheel Energy Storage
HTS	High Temperature Superconducting
IRENA	International Renewable Energy Agency
LLR	Likelihood Rate Weighting Algorithm
LTS	Low Temperature Superconducting
NaS	Sodium–Sulfur Battery
PCS	Power Conversion System
PHS	Pumped Hydro Storage
SMES	Superconducting Magnetic Energy Storage
WOS	Web Of Science

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