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Review Article

Frontiers of Energy Storage Technologies

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Energy storage technologies (ESTs) play a crucial role in ensuring energy security and addressing the challenges posed by climate change. They enable us to overcome the mismatch between energy supply and demand caused by the intermittent and unpredictable nature of renewable energy sources. The identification of research frontiers in ESTs has primarily relied on expert experience and has been limited to specific areas of study. However, there is a relative lack of data-driven approaches to identify these frontiers. In this study, we employed an integrated technique combining bibliographic coupling and sliding window analysis to identify the research frontiers in ESTs and understand their evolution over time. Our study reveals 19 research frontiers in ESTs distributed across four knowledge domains: electrochemical energy storage, electrical energy storage, chemical energy storage, and energy storage systems. Among these frontiers, two noteworthy areas are aqueous zinc batteries (AZBs) and two-dimensional transition metal carbon-nitride composites (MXenes). By identifying these research frontiers, our study provides insights into the potential future directions for research and development (R&D) deployment in energy storage technologies.

1. Introduction

In recent years, fossil energy consumption has further intensified due to population growth and industrial development [1]. As an essential aspect of the long-term strategic planning of the energy system, integrating energy storage technology with renewable energy technology, such as wind and solar, is key to breaking the dependence on fossil energy and improving the level of energy equity [2]. In addition, energy storage technology is vital in terms of competing with fossil energy and overcoming the intermittency and uncertainty challenges of high-proportion renewable energy systems. At the same time, the innovation and development of energy storage technology can initiate and promote a further reduction in the cost of renewable energy technology [3]. The progress and maturity of energy storage technology can help to ensure energy security, manage climate change, create employment opportunities [4], and increase the value of current and future energy systems [5].

The various types of energy storage technologies are diverse [6], the direction of their research and development is uncertain [7], and the relevant expert opinions are divided [8]. It is necessary to conduct foresight research on energy storage technology to quantitatively reveal its significant development direction. The scientific identification of the research frontier of energy storage technology will help decision-makers in the dimensions of R&D deployment, scientific research breakthroughs, investment profitability, policy formulation, and personnel training [9].

At present, the relevant research regarding the research frontier of energy storage technology has two main characteristics: on the one hand, the analysis of the frontier research on energy storage technology relies more on expert experience [10–14]; on the other hand, bibliometric-based analysis of the research frontier focuses on specific techniques such as liquid air energy storage [15], thermal energy storage [16–19], biomass [20], hydrogen energy [21], and lithium-ion batteries [22, 23]. In recent years, a limited number of studies have applied bibliometric methods to analyze the frontiers of energy storage technology through either publication or patent data [24–26]. However, regarding the development of energy storage technology systems that has occurred over the past decade, research on applying the integrated tool of "bibliographic coupling and sliding window" to frontier identification in the field of energy storage technology is relatively limited.

Energy storage technology (also known as energy storage or energy storage systems) has a unified definition in the academic field. It is summarized as an energy technology facility that stores specific energy and preserves it for a certain period [2, 27–32]. Energy storage technology involves three processes: charging (loading), storing (holding), and discharging (unloading). These processes occur in energy converters (charging and discharging), storage units (holding), and peripherals. These components form an entire facility, an energy storage system [2], or an energy storage technology.

However, there has yet to be a consensus regarding the classification of energy storage technologies. The classification of energy storage technology is generally based on three points: the first is the type of energy storage medium [33], such as mechanical energy storage technology and electrochemical energy storage technology; the second is the type of energy source [34, 35], such as electrical energy storage and thermal energy storage; and the third is the application scenario for energy storage [36], such as power quality and distributed energy storage. These three standards can be used either independently or in conjunction. Therefore, researchers adopt the most appropriate energy storage classification for their research purposes.

Energy storage technology is of great significance to the transformation of energy structures in the future. Our current level of energy storage technology has difficulty meeting the needs of energy transformation [2]. Therefore, a series of energy storage technology outlooks has been published. Hadjipaschalis et al. [37] reviewed and compared energy storage technologies for current and future power systems, including both mature and developing technologies. They found that each energy storage technology has an ideal grid application and scale for the environment. Whittingham [38] claimed that within the next 25 years, the combination of energy storage technology and the smart grid will become the future development trend. Turton and Moura [39] explored the vast potential of vehicle-to-grid (V2G) dynamics in power and transportation systems. Lukatskaya et al. [40] reviewed the frontiers of electrical energy storage technologies, outlined the methods of overcoming the current limitations, and proposed devices combining batteries and supercapacitors as next-generation electrical energy storage technologies. Pomerantseva et al. [41] discussed the recent progress of nanomaterials in energy storage devices and outlined the roadmap for future energy storage applications. Pickard et al. [33] clarified that only pumped hydro storage and compressed air energy storage can meet future energy storage needs in the relatively early foreseeable scientific capabilities. Beuse et al. [42] recently employed the system dynamic simulation model to predict the cost of energy storage technology. They found that lithium batteries will eventually become mainstream and will likely cause a technology lock-in. In short, due to the differences in time scale, technology development stage, and research purpose of the institute, different conclusions are drawn about the frontier direction of energy storage technology.

The definition of a research frontier remains controversial. When the concept was first proposed, research frontier was studied, published, and frequently cited in the literature [43]. With the growing prevalence of follow-up research reports, research frontiers are now defined as either the clustering of cocited articles [44, 45], the clustering of cocited articles and citing articles [46], the clustering of highly cited articles (direct citation clustering) [47], or an emerging set of concepts and knowledge bases [48]. Regarding the cocitation examination of documents, Braam et al. [49] and Persson [50] proposed defining cited documents as knowledge bases and citing documents as research frontiers. Based on this view, the research frontier is defined as clusters of literature that cite a shared knowledge base. To track the transformation of research fronts in front identification research, Upham and Small [9] proposed the following five stages of research fronts for qualitative and quantitative analyses: emerging fronts, growing fronts, stable fronts, shrinking fronts, and exiting fronts.

The research frontier analysis of energy storage technology based on expert experience is mainly divided into four categories: (1) reviews of the frontier development of specific energy storage technologies, which includes examples such as Crabtree et al. [10], who introduced the history and predicted the future of lithium-ion batteries, and Arévalo-Cid et al. [51], who reviewed the research on redox flow batteries; (2) reviews of the research frontiers of energy storage technology materials, which includes examples such as Rubloff and Lee [52] summarizing the development of nanoscale tools and Zhai et al. [53] reviewing the research on textile energy storage; (3) reviews of the frontiers of energy storage technology engineering, which includes the example of Pu et al. [13] critiquing the study on lithium-based battery electrodes collected by electrodeposition; and (4) overall energy storage technology overviews, which includes the example of Trahey et al. [54] analyzing the priority order of energy storage technology growth over the next few decades and introducing innovative experimental tools for designing new energy storage technology.

However, a few data-driven EST research frontier analyses have also been published. Mejia and Kajikawa [25] investigated publication data and patent data to reveal emerging topics in both academic and industrial fields, providing a foundation for technology commercialization. Baumann et al. [24] analyzed the patent trends of three energy storage technologies and proposed tools and methods for developing exploratory evaluation blueprints in technology fields. Song [26] adopted a data-driven approach to analyze energy storage technology's dynamic knowledge evolution characteristics from static, dynamic, and future-oriented perspectives.

There are two methods used to identify research frontiers, namely, expert consultation based on expert experience and objective quantitative analysis based on data-driven text mining.

In the data-driven approach, researchers identify research frontiers based on bibliometric tools. Small and Griffith [55] employed cocitations between documents to identify highly interactive literature clusters in a scientific field. Morris et al. [56] distinguished among cocitations and used bibliographic coupling clustering to obtain research frontiers. Shibata et al. [47] detected emerging knowledge domains by employing topological clustering in citation networks and applied the method to the field of regenerative medicine [57]. Wei et al. [58] conducted a comprehensive analysis of keyword frequency and revealed six important research topics in climate strategy modeling. Kleinberg [59] analyzed important information in several documents through word frequency statistics retrieved through text data mining. Pottenger and Yang [60] detected emerging concept content through concept frequency and cooccurrence matrix analysis. Van Den Besselaar and Heimeriks [61] considered that bibliographic coupling has a higher coverage in the literature. Takey and Carvalho [62] analyzed the fuzzy front-end stage of system innovation through a systematic literature review of bibliometrics, social network analysis, and content analysis. Boyack and Klavans [63] compared cocitation, bibliographic coupling, direct citation, and bibliographic coupling-based text mining hybrid methods in the biomedical field and found that bibliographic coupling provided better results than either cocitation or direct citation. Wei et al. [64] verified the feasibility of bibliographic coupling in identifying research frontiers by revealing the frontiers of low-carbon technologies. In addition, Bernatović et al. [65] analyzed the hidden knowledge domain and concluded that bibliographic coupling is more suitable for the research field of recent years and can be used to overcome the shortcomings of direct citation and cocitation that arise from a lack of relevant citation data, which is caused by an insufficient timeframe.

In the field of research, literature with a higher citation frequency, which concentrates on emerging and growing the type of content [66] that reflects the high level of international research [67], is considered to provide more corresponding details than other types of literature [68]. It can detect technological breakthroughs quickly [69]. In identifying the emerging frontiers of science and technology, Upham and Small [9] adopted a sliding window method to further divide the time dimension of the target literature, which is a method that was also applied in the research of Small [66] to the growth forecasts of science fields.

To further enrich the research on the frontier identification of energy storage technology and its evolution over time, the integrated tool of "bibliographic coupling and sliding window" was employed in this study. First, bibliographic coupling and data mining were conducted on the group of highly cited literature in the field of energy storage technology that was published from 2013 to 2022. Second, the coupling results were clustered, and the frontiers were identified. Third, the evolution trend of energy storage technology frontiers was revealed by comparing five sliding window results. Fourth, the international research landscape of the identified growing research fronts was analyzed. Finally, policy implications for promoting the frontier development of energy storage technology were proposed. Generally, this study attempts to answer the following questions: (1) What has the nature of the energy storage technology research frontier been over the past decade? (2) What are the evolution trends of the energy storage technology frontiers? (3) What is the international research landscape for growing research fronts?

This work is organized as follows. Section 2 describes the research framework, methods, and data collection. Section 3 presents the results and discussion. The final section presents the conclusions and policy implications.

2. Materials and Methods

2.1. Research Framework. In this study, bibliographic data related to energy storage technology were searched in the *SCI-E* database of the *Web of Science* (*WoS*) database core collection. Horizontally compared with other databases, the *WoS* database has higher-quality literature records, good standardization, and high consistency. The *WoS* database is widely used in bibliometric research within various fields. The *SCI-E* database is selected for conducting the research in this study. First, using different sliding windows, the highly cited literature in the field of energy storage was identified, and the bibliographic coupling network was obtained through the citation network using the bibliographic coupling method. Then, the clustering method was applied to reveal the research frontiers of energy storage technology over the past decade. Furthermore, this study analyzed the evolution trend of energy storage technology's research frontiers in different sliding windows and identified the types of these research frontiers. In addition, the international research landscape for significant research fronts has been revealed. Finally, research conclusions were obtained, and policy implications for energy storage technology development were proposed. The research framework is shown in Figure 1.

2.2. Bibliographic Coupling. As a method of identifying technology research frontiers, bibliographic coupling was first proposed by Kessler [70–72] in 1963. The definition is as follows: if two articles (articles 1 and 2 in Figure 2) contain a common reference article (article A in Figure 2), there is bibliographic coupling between them. The coupling strength of these two articles depends on the number of cited articles that they share (as shown in Figure 2, the coupling strength of article 1 and article 2 is 2). The coupling strength is positively correlated with the correlation between the two articles. This study identified the literature that has a high correlation to energy storage technology using the bibliographic coupling method. The complete steps of the bibliographic coupling method are shown in Figure 2.

Step 1 (build a citation network). The citation relationships between the articles obtained from the database are preserved and used to form a citation network.

Step 2 (calculate the original citation matrix). The original citation network is transformed into a citation matrix. As shown in Figure 2, article 1 cites articles A, B, and C. It is reflected in the matrix's values in the first row, the second

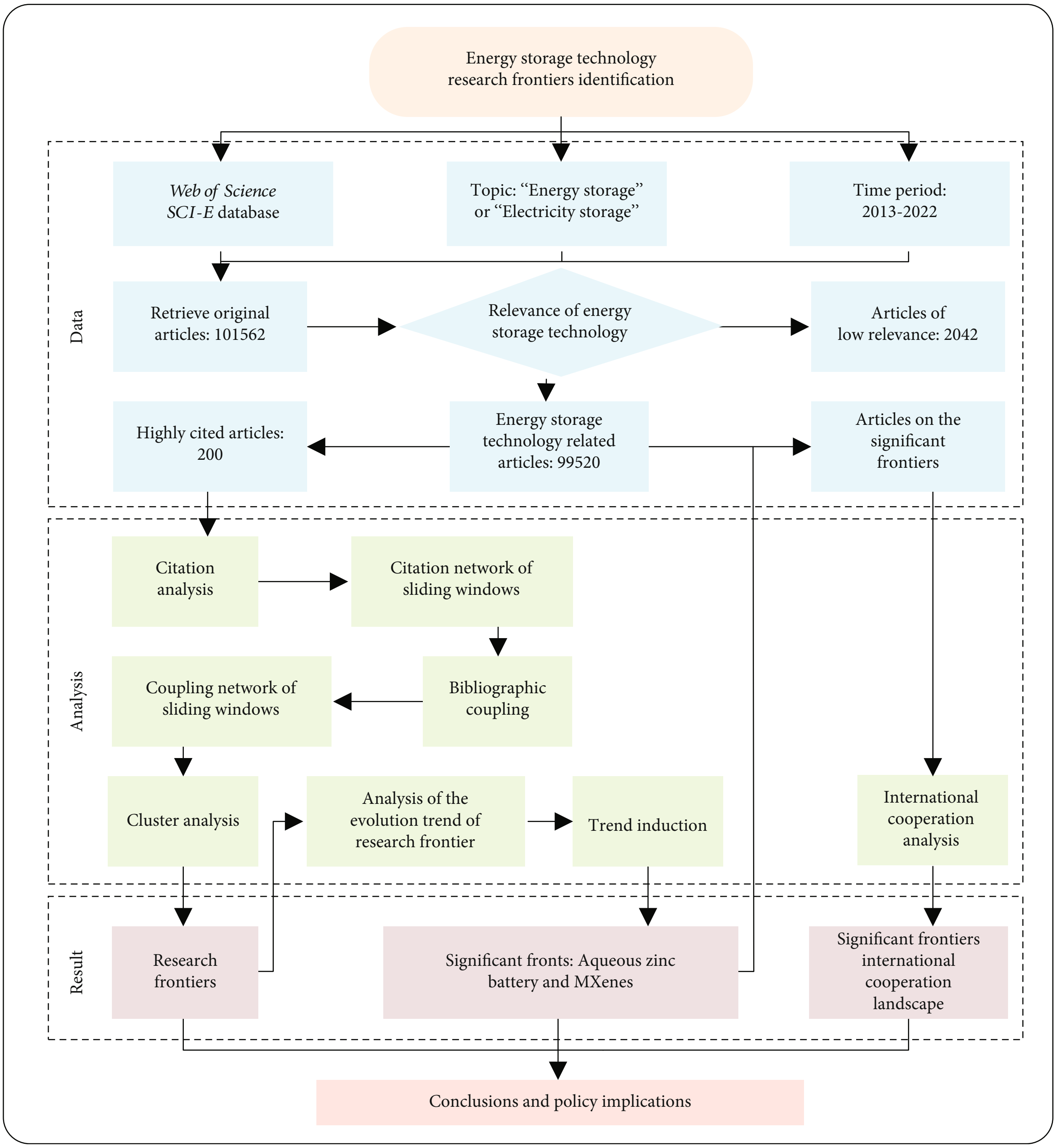

Figure 1: Research framework.

row, and the third row of the first column equal to 1. Article 3 does not cite articles A and B but rather only cites article C, which is reflected in the matrix's value of 0 displayed in the first and second rows of the third column and the value of 1 displayed in the third row.

Step 3 (calculate the bibliographic coupling matrix). The original citation matrix X has now been obtained in the previous steps, and the bibliographic coupling matrix Y is then calculated with the formula $Y = X \times X^T$. The rows and columns of the bibliographic coupling matrix are related to the citing articles. The higher the coupling strength between the two articles, the larger the value of the corresponding row and column position in the matrix.

Step 4 (establish a bibliographic coupling network). According to the above four steps, the original bibliographic data are gradually transformed into coupling matrix data, and the network that is formed represents the bibliographic coupling network.

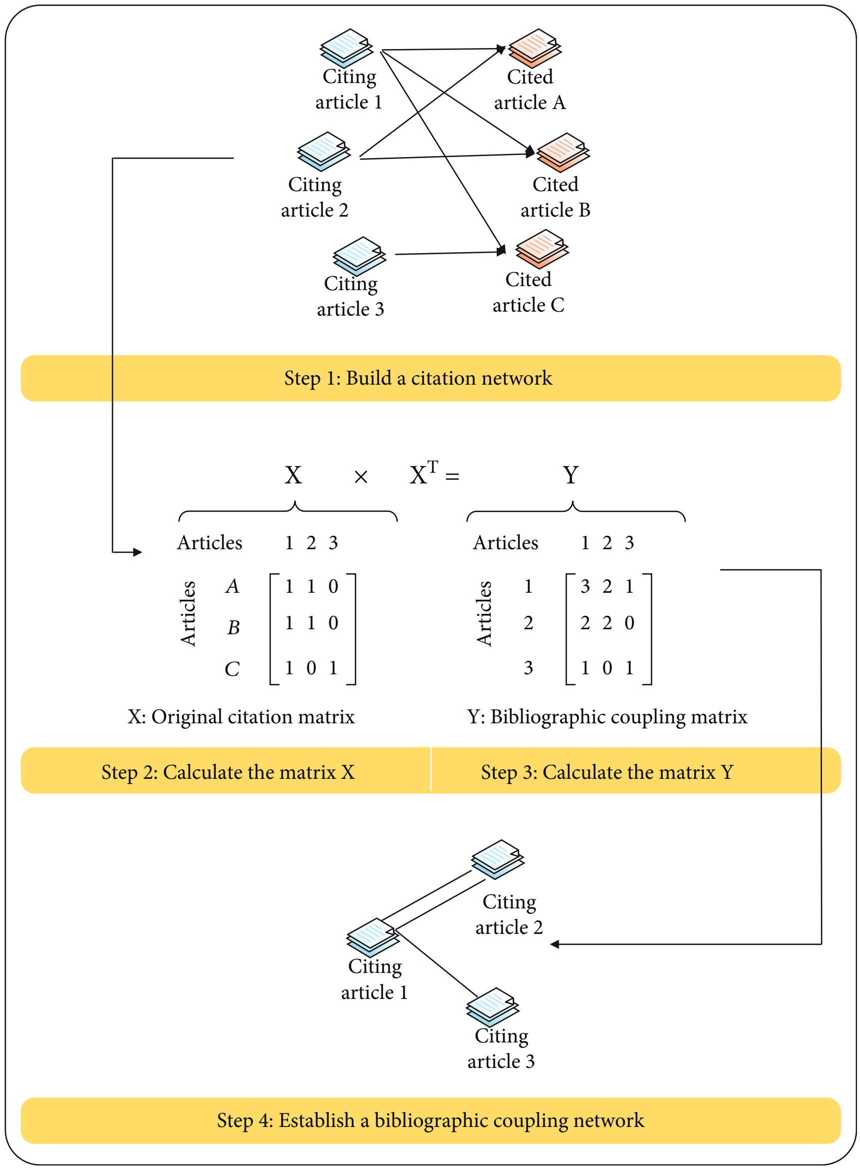

FIGURE 2: Bibliographic coupling process.

2.3. Cluster Analysis. Cluster analysis is a classification method that replaces human subjective consciousness with computers [73]. It was first used by Driver and Kroeber [74] in anthropological research. Clustering identifies natural groups or clusters in multidimensional data based on certain similarity relationships. Clustering is a widely used method in data mining and knowledge discovery research.

In this paper, the similarity between two articles (energy storage technology related) (nodes i and j) is described by the following relationship in a network:

$$w_i = \sum_j b_{ij},$$
$$h = 0.5 \sum_i w_i, \tag{1}$$

where b_{ij} represents the weight of the edge between nodes i and j and it takes a value of 0 if there is no connection between the two nodes. Due to the undirected nature of bibliographic coupling networks, they always contain $b_{ij} = b_{ji}$. $w_i(w_j)$ represents the total weight of all the edges of node i (or j). h represents the total weight of all the edges in the network. For a weighted network, the network modularity M is defined as follows:

$$M = \frac{1}{2} \sum_{i,j} \left[b_{ij} - \frac{w_i w_j}{2h} \right] \delta\left(c_i, c_j\right), \tag{2}$$

where c_i is the cluster in which node i is located and the function $\delta(u, v)$ takes the value 1 if $u = v$; otherwise, it takes the value 0. Considering the rapid and accurate completion of the clustering work with a large amount of data, this study uses the Louvain algorithm [75], which iteratively forms larger clusters from a single network node until the modularity value no longer increases, i.e., $\Delta M \le 0$. For node i in cluster c:

$$\Delta M = \left[\frac{S_{\text{in}} + 2w_{i,\text{in}}}{2h} - \left(\frac{S_{\text{tot}} + w_i}{2h}\right)^2\right] - \left[\frac{S_{\text{in}}}{2h} - \left(\frac{S_{\text{tot}}}{2h}\right)^2 - \left(\frac{w_i}{2h}\right)^2\right], \tag{3}$$

where S_{in} represents the weight of all the edges in cluster c, S_{tot} refers to the sum of the weights of those edges connected to nodes in cluster c, and $w_{i,\text{in}}$ is the sum of the weights of all the edges in cluster c that are connected to node i.

Rachwał et al. [76] utilized the Calinski and Harabasz index to determine the optimal clustering strategy and number of clusters. This study determines the optimal clustering strategy by introducing an expert consultation process. The experts also help validate the titles, abstracts, and keywords of publications on energy storage technologies and identify these clusters as research frontiers. After obtaining the evolution trends of the energy storage technology's research frontiers, consultations with other experts were also carried out to validate the results.

2.4. Data Collection and Processing

2.4.1. Knowledge Domain of Energy Storage Technology. Energy storage technology is divided into five knowledge domains based on three aspects: the research purposes of this article, the definition of energy storage technology in the related review [34], and the classification used in energy storage technology assessment [77]. According to the specific form of energy stored, the five knowledge domains include *mechanical energy storage*, *electrochemical energy storage*, *chemical energy storage*, *electrical energy storage*, and *thermal energy storage*. The specific technologies are then classified in accordance with these domains. Among them, *mechanical energy storage*, including pumped hydro storage, compressed air energy storage, and flywheel energy storage, uses mechanical energy as its medium. *Electrochemical energy storage* stores energy in the form of chemical energy in electrochemical components through electrochemical processes. This domain is mainly divided into secondary batteries (lithium-ion batteries, etc.) and flow batteries (all-vanadium redox flow batteries, etc.). Furthermore, in 2022, the National Energy Administration and the Ministry of Science and Technology issued the "14th Five-Year Plan for Scientific and Technological Innovation in the Energy Field" (National Energy Development Science and Technology (2021) No. 58) [78], which proposed a new generation of energy storage batteries. The new generation of batteries includes sodium-ion batteries, solid-state lithium batteries, liquid metal batteries, lithium-sulfur batteries, aqueous batteries, etc. C*hemical energy storage* uses the chemical energy produced by chemical reactions as an energy storage medium. This domain mainly includes hydrogen energy. In recent years, biomass has also been considered a kind of chemical energy storage [6]. *Electrical energy storage* mainly includes supercapacitors and superconducting magnetic energy storage technologies. *Thermal energy storage* (e.g., molten salt energy storage, water tank thermoelectric energy storage, and high temp. phase-change material energy storage) can be divided into sensible heat storage, latent heat storage, and thermochemical energy storage. In addition, research on energy storage systems (e.g., power architecture, power converter, and auxiliary system) comprises a single category of energy storage technology research.

2.4.2. Highly Cited Literature on Energy Storage Technology. The highly cited energy storage technology literature is used as the basis for revealing the evolution trend of research frontiers. The "highly cited literature" defined in this study refers to the 20 most cited articles in the energy storage field during the period from 2013 to 2022. Since there was no tie among the 20, 20 highly cited articles were selected each year. This study compiled five sliding window datasets according to the following periods: 2013-2018, 2014-2019, 2015-2020, 2016-2021, and 2017-2022.

In this study, referencing the study of Mejia and Kajikawa [25], the search formula used in the *SCI-E* database of *WoS* was $TS = (\text{``}energy\,storage\text{''}\ \text{OR}\ \text{``}electricity\,storage\text{''}\ \text{OR}\ ((energy\ \text{OR}\ electric^*)\ NEAR/2\ storage))$. The time range was 2013 to 2022, and the document type selected was "article." The original data acquisition time for this study is May 7, 2023.

2.4.3. High Coupling Strength in the Literature on Energy Storage Technology. This study focuses on high coupling articles to reduce the interference of weakly correlated articles with low coupling strength and frequency on the results [79]. Following Chen and Morris [80] in visualizing evolutionary networks, Morris and Boyack [81] in anthrax research, and Yang et al. [82] in investigating cystic fibrosis body components, we select a value of five as the ideal threshold for coupling strength. Articles and coupling relationships with a strength of less than five were thus filtered out for better cluster results.

2.4.4. The International Research Landscape of Significant Research Frontiers. After analyzing the evolution trend of the research frontiers, two of the significant fronts were selected. The corresponding literature was collected from the original dataset of the energy storage technology-related literature. Then, the international research collaboration pattern was analyzed. The international research collaboration network of the related technology was captured by analyzing the nationality of the authors, including the first author. Moreover, the number of person-time collaborations, the betweenness centrality of the collaboration network, and the international research landscape were also analyzed.

3. Results and Discussion

3.1. Energy Storage Field Research

3.1.1. Bibliographic Coupling Analysis of EST. The results indicate that the number of articles in this field has grown rapidly over time, showing an increasing trend. In the five sliding windows, the number of clusters representing the number of research frontiers remains consistent overall.

Table 1: Clustering results of research fronts.

Clustering results	2013-2018	2014-2019	2015-2020	2016-2021	2017-2022
Articles	97	93	90	86	79
Clusters	10	10	10	11	12
Coupling pairs	313	329	315	327	281
Coupling strength	2442	2606	2753	2514	2727

Notes. (1) Compared with previous years, the literature in the later window is relatively new, so only high coupling strength is selected, and the number of articles is theoretically expected to decrease. (2) Due to the rapid growth of publications in this field, the coupling strength increases with an increasing total number of articles. In summary, the total coupling strength does not show a single trend of rising or falling over time but rather has inevitable fluctuations.

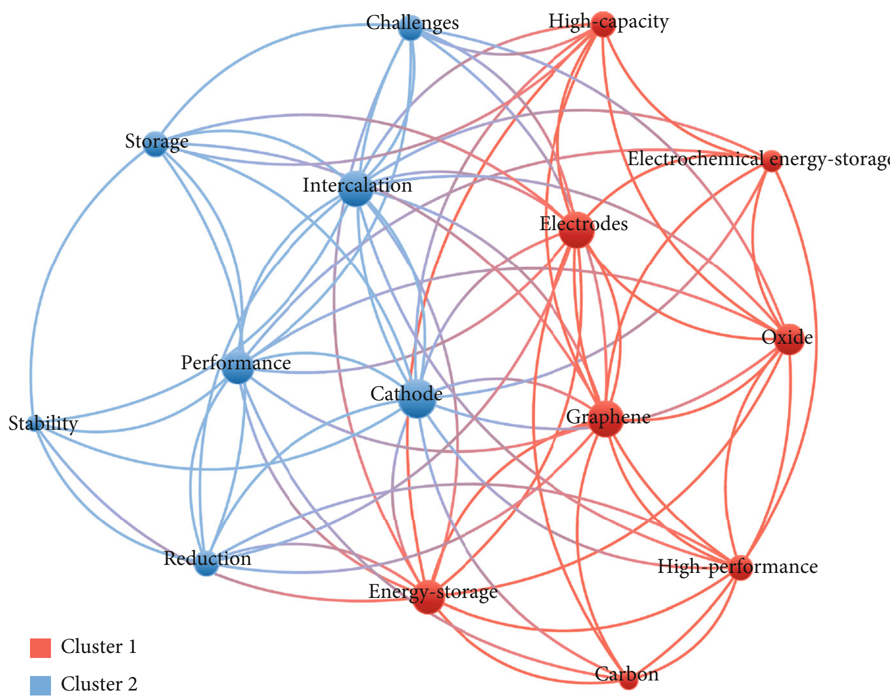

Figure 3: Keyword cooccurrence network visualization map for EST.

After further analysis, some of the research frontiers are stable and have undergone a number of article changes. In addition, the research frontier that occupies the most important position is not always the same. The frontier named *nanocomposite capacitor electrode materials* has 23 highly cited papers and is the largest frontier in the first sliding window (2013-2018). Subsequently, *lithium batteries* and *aqueous zinc batteries* became the largest frontier in the second sliding window (2014-2019). The frontier named *aqueous zinc batteries* is also the largest in the third sliding window (2015-2020), and it is tied with *two-dimensional transition metal carbon-nitride composites*. The frontier of *two-dimensional transition metal carbon-nitride composites* is also the largest in the fourth sliding window (2016-2021), along with *research on cathodes of aqueous zinc batteries* that was split from *aqueous zinc batteries*. The frontier *research on cathodes of aqueous zinc batteries* is also the largest in the fifth sliding window (2017-2022), which contains 23 highly cited articles.

The 20 articles most cited per year, as displayed in Table S1, were selected for further analysis in this study. Furthermore, five sliding windows for processing bibliographic coupling, namely, 2013-2018, 2014-2019, 2015-2020, 2016-2021, and 2017-2022, were selected for analysis in this study. Table S2 shows the bibliographic coupling frequency results. In Tables S3, S4, S5, S6, and S7, the fact that these clusters meet the actual subject research situation is illustrated. The clustering results are presented in Table 1. Highly cited articles are considered to reflect the meaning of their relevant research fronts, which aligns with the data-driven analysis results.

3.1.2. Keyword Cooccurrence Analysis of EST. Figure 3 illustrates a network visualization map of cooccurring keywords in the literature on energy storage technologies. This map comprises 15 representative keywords. Alongside the keyword *energy storage*, representing energy storage technologies, it encompasses the following: *carbon*, *graphene*, and *oxide* signifying carbon-based materials; *electrochemical energy storage*, *high performance*, and *high capacity* indicating supercapacitors; *cathode*, *intercalation*, and *reduction* representing battery material research; and *performance*, *stability*, and *storage* signifying battery performance research.

As depicted in Figure S1, the optimal number of clusters was determined to be 2 based on the Calinski and Harabasz index. Additionally, through inertia analysis, the optimal

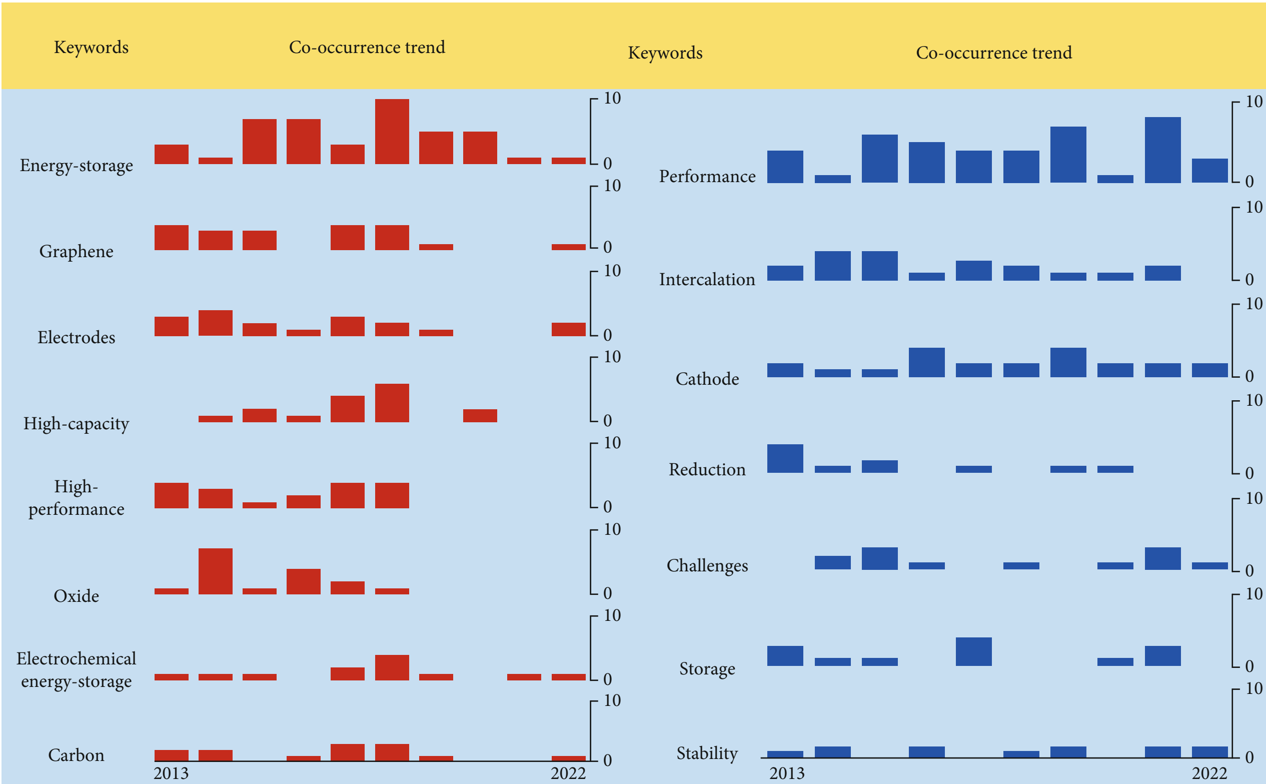

Figure 4: Keyword cooccurrence frequency evolution trend from 2013 to 2022 (red represents cluster 1, and blue represents cluster 2).

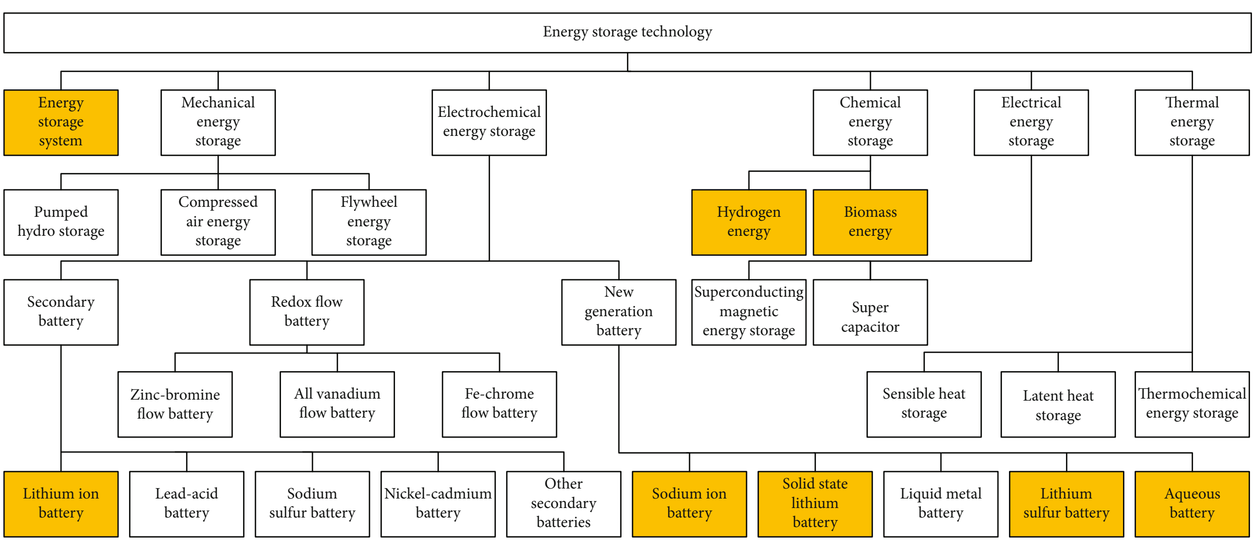

Figure 5: Knowledge domain map of energy storage technology research frontiers.

number of clusters is also identified as 2-4. Compared to inertia, the Calinski and Harabasz index provides a more accurate estimate of the optimal cluster number.

Based on the determined optimal cluster count, the cooccurrence network of keywords is clustered, resulting in cluster 1 primarily centered around capacitors and carbon-based materials and cluster 2 primarily focused on battery technologies.

Figure 4 illustrates the variation in cooccurrence frequencies of the aforementioned 15 keywords over 10 years. The keywords in cluster 1 exhibit an overall declining trend, while the keywords in cluster 2 display a relatively stable state with certain fluctuations. We hypothesize that the research frontiers in cluster 1 are experiencing a decrease in popularity, while the research frontiers in cluster 2 are maintaining stability with potentially concurrent rising and falling trends. Through further analysis using bibliographic coupling network-based clustering identification, we aim to validate these conjectures.

Notably, many of the keywords within cluster 1 experienced significant shifts after 2020. Research associated with

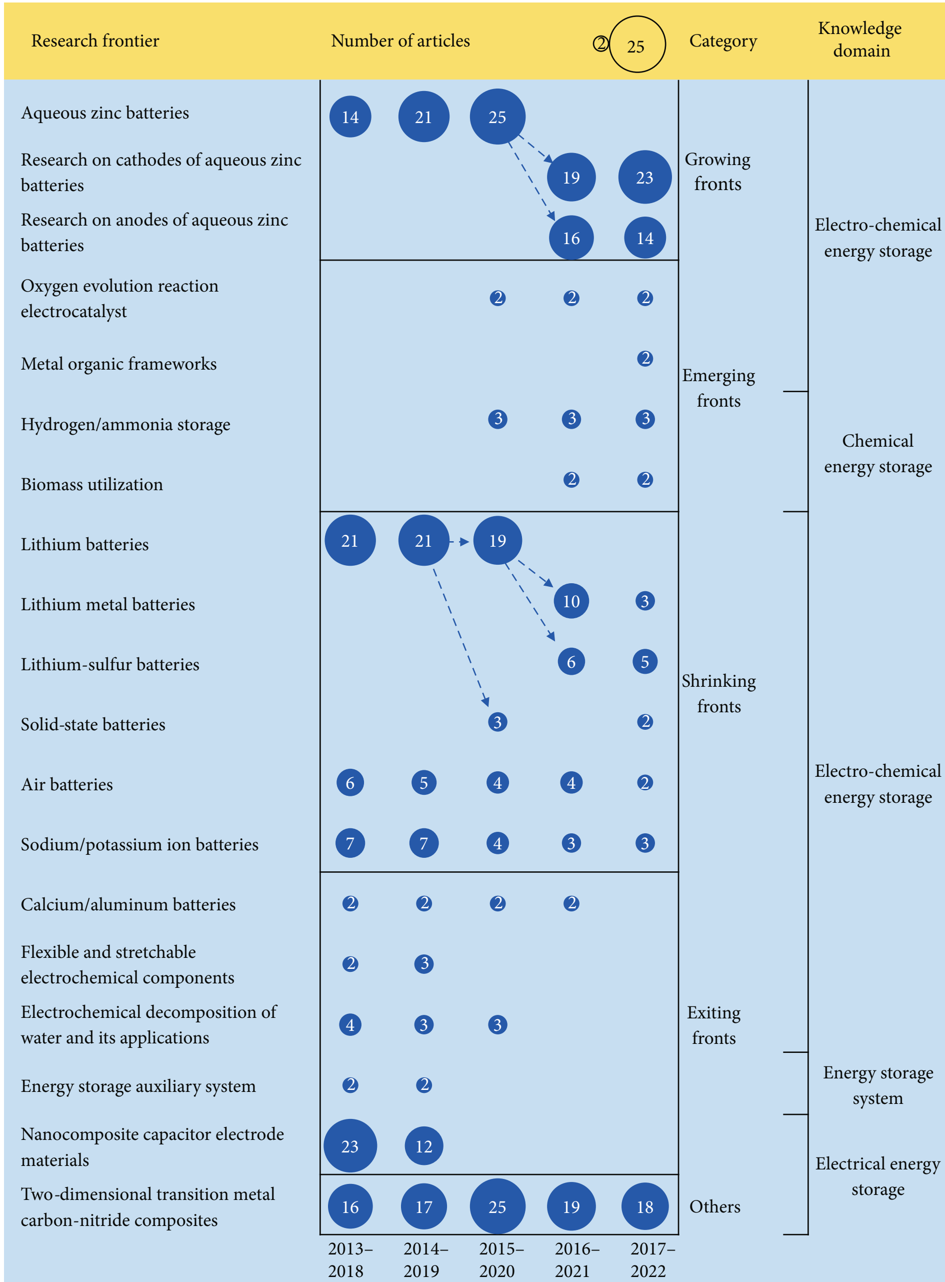

Figure 6: Evolution map of the energy storage technology research frontiers.

carbon-based materials and electrochemical capacitors showed a marked decrease in popularity following 2020.

3.2. Evolution Trend of Energy Storage Technology Research Frontiers

3.2.1. Research Frontier Distribution in the Knowledge Domain Map. In this study, 19 research frontiers were identified. The knowledge domains proposed in Figure 5 describe the distribution of frontiers in the knowledge domains. Among them, the research frontiers are distributed in the following four knowledge domains: electrochemical energy storage, electrical energy storage, chemical energy storage, and energy storage systems.

After verification with relevant studies and consultation with certain energy storage experts, we confirmed that the study's results align with the experts' opinions. Furthermore, these research frontiers are considered important frontiers of energy storage research. This study validates the notion that the bibliographic coupling method can effectively be used to explore the research frontier of energy storage technology.

3.2.2. Evolution Trend of Energy Storage Technology in the Five Sliding Windows. According to the classification of research frontiers proposed by Upham and Small [9], Figure 6 reveals the evolution paths of ESTs' research frontiers.

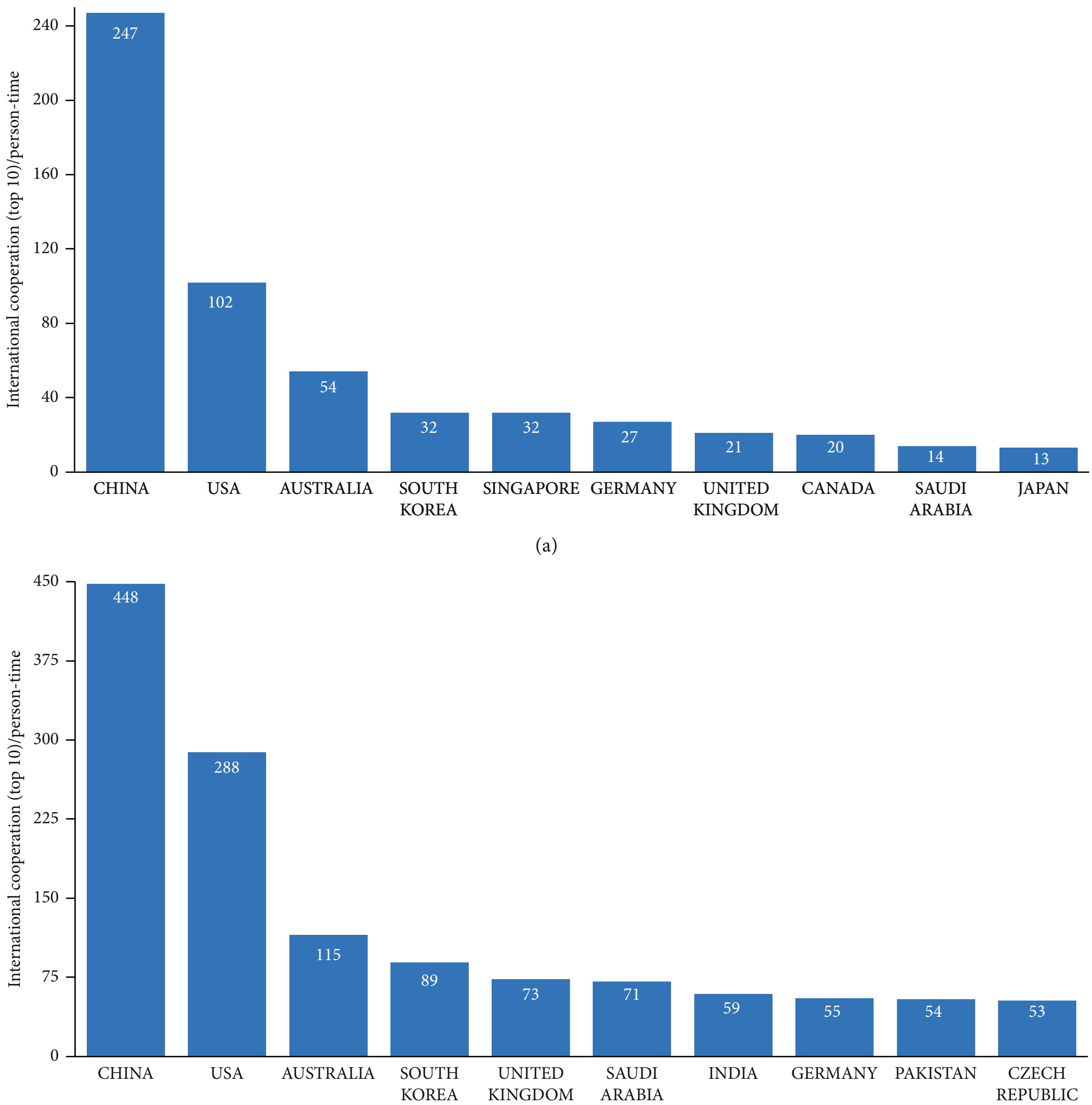

Figure 7: International research landscape of significant research frontiers (2013-2022): (a) the international research landscape of *aqueous zinc batteries* (*AZBs*); (b) the international research landscape of *two-dimensional transition metal carbon-nitride composite materials* (*MXenes*).

The number of articles in the research frontier of *aqueous zinc batteries* (or aqueous zinc ion batteries, AZIBs, AZBs) grows continuously through the first three sliding windows. In the last two sliding windows, the frontier *aqueous zinc batteries* splits into two specific new frontiers: *research on anodes of aqueous zinc batteries* and *research on cathodes of aqueous zinc batteries*. The number of highly cited articles has continued to increase. Based on the definitions of growing fronts, aqueous zinc batteries can be treated as a growing front.

The context of frontier *two-dimensional transition metal carbon-nitride composites* (*MXenes*) is complicated. It depicts an upward trend in the first three sliding windows and is integrated with the frontier *nanocomposite capacitor electrode materials*, while the number of highly cited articles decreases in the last two sliding windows. Although its evolving trend cannot be determined, its absolute number of articles is still among the top two in the last three sliding windows. Therefore, *MXene* and the growing front *aqueous zinc batteries* are considered two significant EST frontiers in 2013-2022.

The frontier named *lithium batteries* shows a high number of articles in the first three sliding windows and has since evolved into three frontiers over the last three sliding windows: *lithium metal batteries*, *lithium-sulfur batteries*, and *solid-state batteries*. In the last two sliding windows, the number of articles related to the frontier *lithium batteries* decreases, showing a shrinking front. In addition, the research frontiers evolved from *lithium batteries* have gradually become more specific and independent of each other.

Altogether, among the six knowledge domains of energy storage technology, this study identifies four knowledge domains that contain research frontiers. Among them, electrochemical energy storage includes 2 emerging fronts and 1 rapidly rising growing front. Chemical energy storage includes 2 emerging fronts, electrical energy storage includes 1 exiting front and 1 other front, and the energy storage system includes 1 exiting front.

3.3. The International Research Landscape of Significant Research Fronts. For *aqueous zinc batteries* (*AZBs*) in Figure 7(a), a growing research front, the country (or region) with the highest number of international collaborations is China. China has 247 collaborations, followed by the United States, Australia, South Korea, Singapore, Germany, the United Kingdom, Canada, Saudi Arabia, and Japan. In this field, China has the highest level of betweenness centrality (460.1) in the collaboration network, followed by South Korea (108.6) and Germany (63.8). The high betweenness centrality indicates that these three countries (or regions) are essential to the international research network.

In terms of *two-dimensional transitional metal carbon-nitride composite materials* (*MXenes*) in Figure 7(b), as one of the top two frontiers in the last three sliding windows, China is the country (or region) with the highest number of international collaborations. China has 448 collaborations, followed by the United States, Australia, South Korea, the United Kingdom, Saudi Arabia, India, Germany, Pakistan, and the Czech Republic. China is the country with the highest level of betweenness centrality (474.8) in the collaboration network, followed by the United States (250.2) and India (165.9). Analogous to aqueous zinc batteries, these three countries (or regions) are influential intermediaries in the international research in this field.

4. Conclusions and Policy Implications

This study applies an integrated tool involving bibliographic coupling and a sliding window to reveal the research frontiers of ESTs and their evolution trends over the last decade (2013 to 2022). The main conclusions are as follows:

(1) While the frontiers of energy storage technology are diverse, they are concentrated on electrochemical energy storage technology. In four domains, 19 energy storage technologies have been identified as energy storage research frontiers, including *lithium batteries*, *supercapacitors*, and *new-generation batteries*. Among them, the growing fronts and emerging fronts occur in the domain of *electrochemical energy storage* and *chemical energy storage*. These energy storage knowledge domains reflect the frontier direction of future research on energy storage technology

(2) In addition to the evolution of the frontier itself, there are also connections among the frontiers of energy storage technologies. Aqueous zinc batteries (AZBs) and two-dimensional transition metal carbon-nitride composites (MXenes) represent significant fronts in energy storage technologies. This study has identified 1 growing fronts, 4 emerging fronts, 4 shrinking fronts, 5 exiting fronts, and 1 other front. The AZBs from *aqueous batteries* and the MXene materials used in *supercapacitors* are identified as significant fronts in EST research, with a rising trend and many citations

(3) China is the leading country in developing aqueous zinc batteries (AZBs) and two-dimensional transition metal carbon-nitride composite materials (MXenes). In the international research collaboration networks of the two technologies, China ranks at the top regarding network betweenness centrality and national collaboration. China plays a crucial leading role in the research process

Based on the above conclusions, this study proposes the following policy implications:

(1) To achieve the goal of energy transformation, the pros and cons of the development of diversified technologies in energy storage must be evaluated. The joint development of multiple frontier technologies can provide more possibilities, but at the same time, the variety of technologies can also create greater uncertainty for technological development. Whether the diversified development of energy storage frontiers is conducive to achieving the goal of energy storage technology needs to be evaluated on the basis of its pros and cons

(2) The evolution laws existing within and between frontier technologies need to be studied and utilized so that researchers can better track and understand significant frontiers. The new generation of battery technology, especially aqueous batteries such as aqueous zinc batteries (AZBs) and two-dimensional transition metal carbon-nitride composite materials (MXenes), deserves special attention. Focusing on AZBs and MXenes, predicting their technological development trends, and evaluating their technical and economic development levels help advance the layout of these key frontier technologies

(3) Countries that make important contributions and play key roles in the research of significant frontier technologies should receive more support and attention. Through these measures, international cooperation and the development of frontier technologies can be further promoted. Further research and development cooperation between China, the United States, and other countries (or regions) regarding ESTs would promote the innovation of energy storage technology fundamental research and industrial practice

In the analysis of keyword trends, the reasons behind the changes approximately 2020 remain unknown. Among them, the COVID-19 pandemic that occurred in 2020 and its subsequent impacts on the economy and the energy sector are likely factors associated with this phenomenon. Validating this conjecture and uncovering the influence of

COVID-19 on the advancement of energy storage technology frontiers could offer further avenues for subsequent research.

In this study, we propose extending integrated bibliographic coupling and sliding window analysis to other research domains to identify research frontiers. This tool holds potential for a wide range of applications, including R&D deployment, scientific research breakthroughs, investment profitability, policy formulation, and personnel training. For the identified aqueous zinc batteries (AZBs) and two-dimensional transition metal carbon-nitride composite materials (MXenes), it is critical that we conduct continuous technology monitoring and business model innovation research. The preliminary results can help develop intelligent tools for evaluating and predicting novel energy storage technologies.

This study has three further research avenues: firstly, exploring the integration of other bibliometric methods with the present approach to uncover deeper insights; secondly, conducting technology mining and monitoring for aqueous zinc batteries (AZBs) and two-dimensional transition metal carbon-nitride composite materials (MXenes) based on the findings of this study; and thirdly, investigating the impact of specific events, such as the COVID-19 pandemic, on the evolution of technologies. Additionally, we intend to continue dynamically monitoring shifts in research frontiers within the energy storage technology field in future studies.

Data Availability

Data is available upon appropriate request from the corresponding authors.

Conflicts of Interest

The authors declare no competing financial interests.

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Supplementary Materials

Table S1: energy storage technology literature and highly cited articles (2013-2022). The table lists the number of articles related to energy storage technology and the number of highly cited articles selected for this study. Table S2: bibliographic coupling frequency. The table shows the bibliographic coupling frequency results. Table S3, S4, S5, S6, and S7: research frontiers of 2013-2018, 2014-2019, 2015-2020, 2016-2021, and 2017-2022. The fact that these clusters satisfy the actual subject-matter study case is illustrated. Figure S1: the Calinski and Harabasz index and inertia of keyword cooccurrence clustering. *(Supplementary Materials)*

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