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Leveraging heterogeneous networks to analyze energy storage systems in power systems and renewable energy research: a scientometric study

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The transition to renewable energy sources is critical for sustainable development, yet integrating these sources into existing power systems poses significant challenges. Energy Storage Systems (ESS) are essential in enhancing the reliability and efficiency of renewable energy systems. Despite growing research, a comprehensive scientometric analysis mapping development and trends in this field is lacking. This study addresses this gap by conducting a detailed scientometric analysis of power systems and new energy research from 2014 to 2023. The novelty of this study lies in its systematic use of advanced bibliometric tools to provide a thorough analysis of the research landscape. Utilizing 425 research articles from the Web of Science database, the study employs CiteSpace to visualize academic networks, identify research hotspots, and outline current trends. Specific methodologies include burst detection to identify significant shifts in research focus, centrality measurement to determine the influence of key studies, and heterogeneous network analysis to map the interconnectedness of various research themes. The analysis reveals extensive international collaborations, with China leading in publication volume (344 articles) and centrality (0.69), followed by the United States (29 articles, centrality 0.53). Significant contributions come from institutions like North China Electric Power University, China Electric Power Research Institute, and Tsinghua University. The findings underscore the importance of international cooperation and the need for broader geographical representation in this research field. This study provides valuable insights into the evolution and current state of power systems and renewable energy research, offering essential guidance for future research and development. The results highlight the critical role of ESS in the transition to renewable energy and suggest directions for future investigations, particularly focusing on enhancing ESS efficiency and reliability and expanding international research collaborations.

KEYWORDS

renewable energy, energy storage systems, energy efficiency improvements, scientometric analysis, CiteSpace visualization

1 Introduction

In recent years, the field of power systems and new energy has seen rapid growth in research. The number of related journal papers published in the Web of Science database has increased from 3 in 2014 to 125 in 2023. CiteSpace, a prominent visualization tool, is chosen to analyze the academic structure of the field and identify emerging trends in related knowledge areas. When examining complex networks in scientific literature, quantitative research methods are used to gain insights into patterns and intelligence in areas such as electrical energy storage and renewable energy (Chen, 2006). The comprehensive analysis and visualization of these networks allow researchers to spot emerging trends and temporary patterns in their research. The utilization of CiteSpace for systematic quantitative research across different energy and power sectors has received limited attention in the last decade. However, CiteSpace has demonstrated notable effectiveness specifically within the realm of electrical engineering (Zhang et al., 2024).

Bibliometric methods are utilized in a novel manner to improve the analysis of extensive literature databases. This survey showcases visual depictions of collaboration networks, explores evolutionary trends, pinpoints research areas of focus, and contrasts various methodologies within the realm of power systems research (Geissdoerfer et al., 2017; Bjornbet et al., 2021). In essence, this study lays the groundwork and offers direction for the advancement of power systems and new energy sources.

In the realm of power systems and electric vehicles, studies have indicated that North China Electric Power University, China Electric Power Research Institute, and China State Grid Corporation engage in significant collaboration (Zhang et al., 2020; Wang S. J. et al., 2022). This exemplifies the close partnership among key research countries and institutions, underscoring the value of collective efforts in advancing research within this domain. Such collaboration facilitates the exchange of knowledge, resources, and expertise, ultimately enhancing the research capacities of the involved institutions.

In the fields of thermodynamics and sustainable development science, there is notable collaboration among major countries like China, the United States, and the United Kingdom (Ke et al., 2020; Wu H. Y. et al., 2021; Geng et al., 2023). As a result, research attention has shifted towards energy management systems (EMS) specifically tailored for battery energy storage systems (BESS). Distributed mobile energy operation control methods have demonstrated significant potential in energy management applications for large-scale BESS (Liu et al., 2016; Linnenluecke et al., 2020; Ding and Yang, 2022).

Previous research in the field of renewable energy and electrical energy storage, as discussed in reference (Demiroren and Yilmaz, 2010), focused on system configuration and cost analysis using HOMER software to explore the utilization of solar energy, wind energy, and batteries for powering Gokceada Island. Reference (Jindal et al., 2019) also delved into the current status and gaps in distributed renewable energy communication standards, proposing potential pathways for enhancement. Additionally, reference (Dumitrascu et al., 2019) analyzed Romania's renewable energy potential, the impact of climate change on renewable energy, and associated environmental challenges. These studies offered valuable insights into the development of renewable energy, covering aspects such as cost, communication standards, climate change, and local environmental impacts through practical applications. Reference (Guo et al., 2023) introduced a stochastic optimization method based on the simulated annealing algorithm for optimizing off-grid solar-wind energy and electric energy storage systems. Furthermore, reference (Wang and Liu, 2023) examined the impact of incorporating Bi(Mg2/3Nb1/3)O3 on the electrical energy storage performance of 0.76Bi(0.5)Na (0.5)TiO3-0.24SiTiO3 ceramic, as well as exploring the electrical energy storage capabilities of electronic ceramic materials. Reference (Maghrabie et al., 2023) also highlighted the role of energy storage systems in ensuring fresh water supply by integrating renewable energy with seawater desalination systems. The above references offered innovative ideas in electrical energy storage through novel system optimization methods, material combinations, and system integrations.

In comparison with the current research works, our analysis focuses on the collaboration of major countries in this research field and the co-occurrence of keywords. However, there is a gap in knowledge about bibliometric reviews on topics related to new energy sources in power systems. Therefore, this study aims to:

1) Data Sources and Research Methods: Collect and analyze 425 research articles from the Web of Science database, focusing on publications from 2014 to 2023. Utilize CiteSpace for visualizing academic networks, identifying research hotspots, and outlining current trends through burst detection, centrality measurement, and heterogeneous network analysis.
2) Data Analysis: Examine yearly publication trends to understand research growth in new energy power systems. Identify leading countries and significant international collaborations. Assess contributions from major institutions and their collaborative networks.
3) Visualization Results Analysis: Conduct cluster analysis of keywords to identify prominent research areas and emerging trends. Explore research frontiers and shifting trends through keyword timeline analysis. Review the most influential papers to understand key contributions and foundational research.
4) Discussion of Trends and Research Frontiers: Discuss the effectiveness of CiteSpace in analyzing bibliometric data. Analyze publication trends in major journals, focusing on IEEE Transactions on Power Systems. Examine the evolving focus on distributed generation within power systems, identifying emerging trends and future research directions.

By achieving these objectives, the study offers a comprehensive overview of the current state and future prospects of power systems research.

2 Research methodology and data sources

2.1 IC, BC, limitation of the study and presumptions

This study aims to provide a comprehensive scientometric analysis of power systems and new energy research from 2014 to

2023. In this context, the following components are critical to understanding the scope and boundaries of the research:

1) International Collaboration (IC): The study highlights the extensive international collaborations in the field, focusing on contributions from leading countries such as China, the United States, and the United Kingdom. These collaborations are essential for advancing research and development in new energy technologies, sharing knowledge, and leveraging global expertise.
2) Bibliometric Coverage (BC): The research is based on 425 documents sourced from the Web of Science database. This comprehensive dataset provides a broad view of the developments in power systems and new energy research over the past decade. The use of advanced bibliometric tools, particularly CiteSpace, allows for a detailed analysis of academic networks, research hotspots, and emerging trends.
3) Limitations of the Study: Despite the extensive data collection and analysis, the study has several limitations. First, it relies solely on publications indexed in the Web of Science database, which may exclude relevant research published in other databases or non-indexed journals. Second, the bibliometric analysis is inherently retrospective, potentially missing the most recent developments that have not yet been widely cited. Third, the study focuses on specific keywords and topics, which may not capture the entire scope of research in the field.
4) Presumptions: The study presumes that the Web of Science database provides a representative sample of the most significant research contributions in the field of power systems and new energy. It also assumes that the bibliometric tools and methods used, such as CiteSpace, accurately reflect the structure and dynamics of the research landscape. Furthermore, the study presumes that the identified trends and hotspots are indicative of broader developments in the field.

2.2 Data sources

Web of Science is a comprehensive multidisciplinary core journal database. This article utilizes two databases from the core collection of WOS, namely, the Web of Science Core Collection (Science Citation Index Expanded - SCIE, Social Sciences Citation Index - SSCI) as data sources. The search was conducted using the formula [TS = "power system*" AND "new energy*"] with a search time of 2023-12-23. A total of 477 documents were retrieved using this search term, including 437 research articles, 37 review articles, 1 conference abstract article, and 2 other articles. Of these, Note, Editorial, Business article, Letter and Data Paper type articles are not available. From these, only the 437 research articles were screened, and English-language articles were selected. After carefully reviewing the article titles, abstracts, and contents, any articles that were deemed irrelevant were excluded from the study. This process narrowed down the initial pool of articles to a final selection of 425, which met the criteria for scientific measurement. The distribution of these articles, in terms of the number published each year.

2.3 Research methods

This study utilized a text form of the collected article data, which included complete records and citations. The data was then subjected to in-depth analysis using CiteSpace 6.1. R6 software. The study followed CiteSpace's standard operational procedures for constructing knowledge maps, which include time slicing, threshold setting, modeling, trimming, merging, and mapping. By leveraging CiteSpace's key features such as burst detection, centrality measurement, and heterogeneous network analysis, this research visually represents the trajectory of research development, identifying key issues and frontiers in the field (Freeman, 1977; Ghosh and Mount, 1991; Attiratanasunthron and Fakcharoenphol, 2008). In the diagrams depicting networks, every individual node symbolizes authors, institutions, countries, or keywords. The occurrence or citation frequency of each node determines its size, whereas the time of occurrence or citation is represented by the color of the nodes. Notably, nodes with purple borders indicate entities with high betweenness centrality, which mark key turning points or hotspots in the research area (Zheng and Wang, 2019; Li et al., 2020; Wang et al., 2020). Centrality analysis uncovers key nodes within the research network, representing elements with significant influence in the field. This has been demonstrated by Chin et al. (2014) in their development of cytoHubba, a tool for identifying central objects in complex interaction groups, and by Liang et al. (2017) in their bibliometric analysis of acupuncture treatment for low back pain over a 20-year period using CiteSpace (Antoniotti et al., 2013; Chin et al., 2014; Liang et al., 2017; Modrák and Vohradsky, 2018; Wang et al., 2021; Zhang et al., 2021). In this article, we employ the quantitative tools provided by CiteSpace to conduct an extensive bibliometric analysis of research in the field of power systems and new energy. Through critical reading, we extract key research results and gain insights into future development trends in the field.

2.4 Data analysis

We used Web of Science analysis tools to classify and archive the collected literature. A quantitative analysis of the annual publication volume, contributing countries, institutions, and authors was conducted using an Excel spreadsheet. Additionally, we employed CiteSpace (6.1. R6) software to analyze co-words, co-occurrences, and emergent words of important noun phrases in document titles, abstracts, and keywords. The objective of this analysis was to identify the development trajectory and research hotspots of new energy technology innovation in power systems. In CiteSpace, we set a 10-year time span with annual time nodes. The node types selected were 'Country' and 'Keywords', with 'Cosine' used as the node intensity and a threshold of 'Top 20'. To simplify the network, we used the 'minimum spanning tree' option, and for analyzing changes in keywords over time, we utilized the 'time zone' function.

3 Visualization results analysis

3.1 Analysis of publication trends

A scrutiny of the yearly dissemination of scholarly works concerning power systems and new energy exploration in the

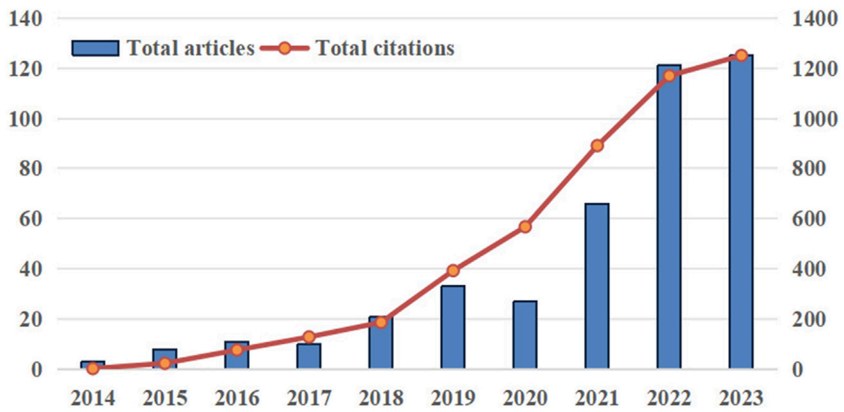

FIGURE 1
(2014-2023) Temporal evolution of the total number of articles and citations in the WOS database.

TABLE 1 (2014-2023) The total count and proportion of each article type.

Type	Count	Proportion (%)
Research Article	437	91.61
Review	37	7.76
Conference Paper	1	0.21
Note	0	0.00
Editorial	0	0.00
Business article	0	0.00
Letter	0	0.00
Data Paper	0	0.00
Other	2	0.42
Total	477	100.00

principal database of scientific literature, Web of Science core collection, throughout the preceding decade exposes that the mean count of publications within this timeframe solely reached 75. Nevertheless, there exists notable advancement in research, which is consistently advancing. In recent times, the quantity of publications and references has exhibited unfaltering expansion. As shown in Figure 1, the number of documents was relatively small before 2014, but experienced rapid growth after 2018. Similarly, the number of citations increased from an initial count of 14 to a total of 1863. Although the number of studies has not yet reached a high level, research efforts are rapidly developing. Furthermore, based on research trends, there is considerable research potential in the coming years, indicating that the research volume will continue to grow.

Table 1 presents the total count and proportion of various article types within the domain of power systems and innovative energy storage solutions. The analysis includes research articles, reviews, conference papers, and other types of scholarly contributions. The predominant type of publication is the research article, comprising 437 entries, which accounts for a significant 91.61% of the total publications. Reviews follow with 37 entries, representing 7.76% of the total. Conference papers are scarce, with only 1 entry, constituting 0.21%. Other types of publications, including notes, editorials, business articles, letters, and data papers, were either absent or minimally represented, with the category labeled “Other” contributing just 2 entries (0.42%). The significant proportion of research articles underscores the intensive investigative efforts and the development of new insights and technologies. The relatively smaller percentage of reviews indicates a need for more comprehensive synthesis of existing research, while the minimal presence of other publication types suggests potential areas for further scholarly exploration.

Table 2 delineates the categories and proportions of research articles in the Web of Science (WOS) database related to power systems and innovative energy storage solutions. This categorization provides a detailed overview of the diverse research areas contributing to this field.

The majority of the research articles fall under the category of Engineering, with 163 articles, making up 37.30% of the total. This indicates a strong focus on engineering aspects in the development and optimization of power systems and energy storage solutions. Following this, the Energy Fuels category includes 87 articles, representing 19.91%, reflecting significant research interest in fuel sources and energy efficiency. The Science Technology category encompasses 56 articles (12.81%), showcasing advancements and technological innovations. Computer Science, with 22 articles (5.03%), highlights the integration of computational methods and data analysis in energy research. The Physics category includes 19 articles (4.35%), indicating the foundational scientific principles being explored. The “Other Topics” category includes 28 articles (6.41%), covering miscellaneous subjects related to the field.

The categorization of research articles underscores the multidisciplinary nature of the study of power systems and innovative energy storage solutions. By understanding the distribution of research efforts across various scientific and technological categories, this study provides insights into the current trends and potential future directions. The significance of this research lies in its ability to inform policymakers, researchers, and industry stakeholders about the focal points of scholarly activity.

TABLE 2 (2014-2023) The categories and proportion of research articles are in the WOS database.

Web of science categories	Count	Proportion (% of 437)
Engineering	163	37.30
Energy Fuels	87	19.91
Science Technology	56	12.81
Computer Science	22	5.03
Physics	19	4.35
Environmental Sciences Ecology	14	3.20
Thermodynamics	13	2.97
Materials Science	10	2.29
Mechanics	7	1.60
Telecommunications	7	1.60
Instruments Instrumentation	6	1.37
Automation Control Systems	5	1.14
Other Topics	28	6.41
Total	437	100.00

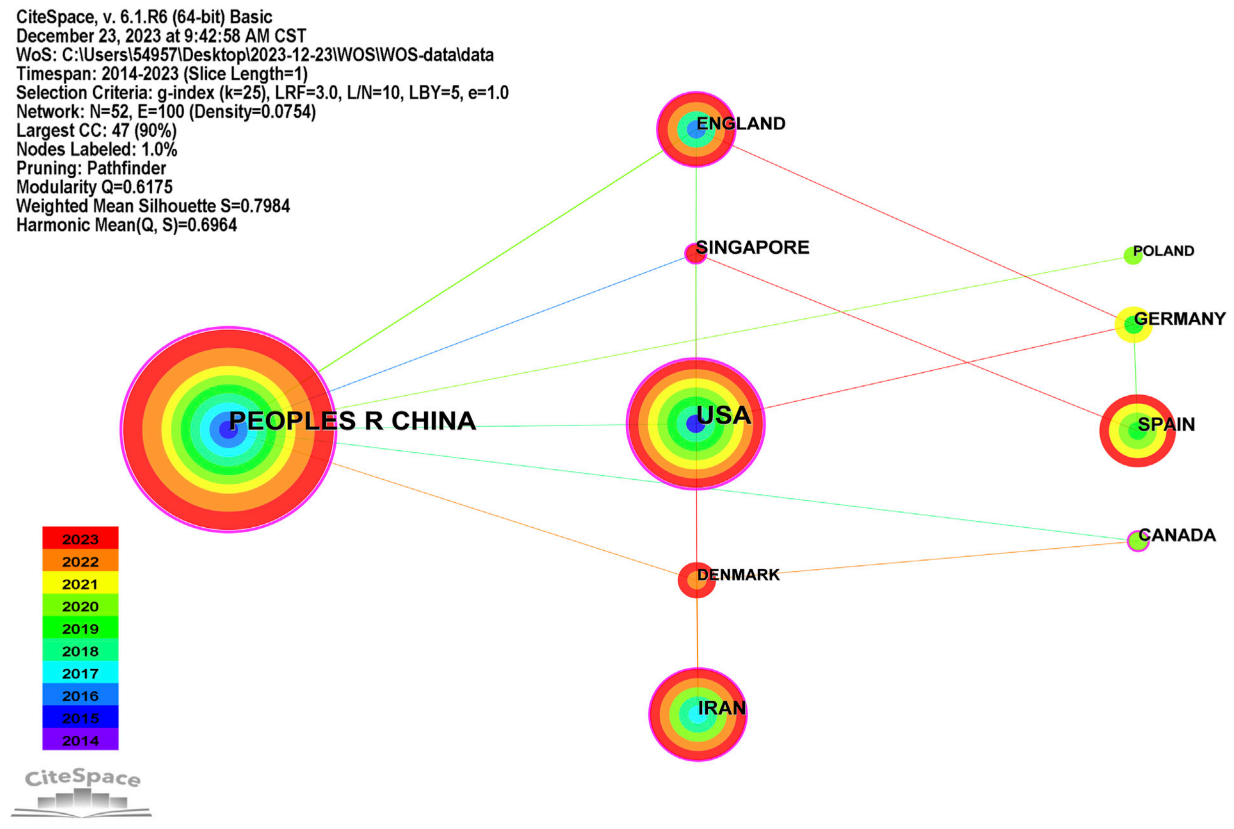

FIGURE 2
(2014-2023) cooperation networks of top 10 countries.

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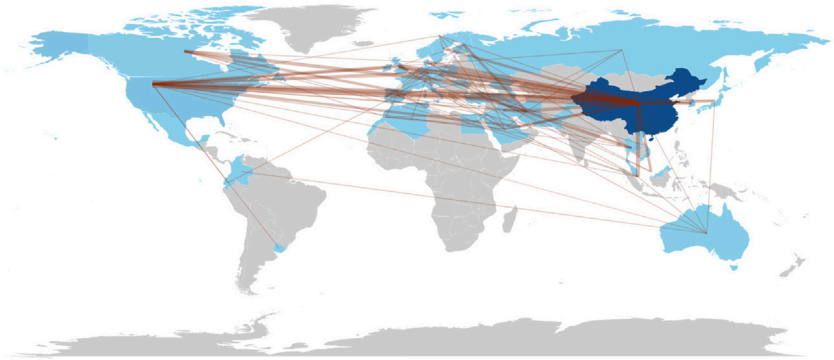

FIGURE 3
(2014-2023) Geographic distribution of Top 10 Countries.

3.2 Country and institutional analysis

3.2.1 Country analysis

This study aims to identify the main countries conducting research in the field of new energy research in power systems and examine the academic exchanges and cooperation between these countries. Quantitative analysis was performed on the countries that have published research papers. The analysis utilized CiteSpace software and covered the time period from 2014 to 2023. Figure 2 shows that this analysis is conducted annually, with a top 10 threshold. The resulting analysis produced 52 networks, represented by a country analysis map consisting of nodes and 100 connections. The density of the analysis was calculated to be 0.0754. The importance of a node in the network, based on its position, can be understood by examining the thickness of the purple circle. This measure is known as betweenness centrality and provides insights into the significance of a node in the network (Newman, 2003; Wang et al., 2018; Tao et al., 2022).

In the map (Figure 3), each line represents a collaborative relationship, with the number and color intensity of the lines indicating the frequency of cooperation. Darker and thicker lines denote more frequent collaborations, while lighter and thinner lines indicate less frequent interactions. The map reveals that China and the United States are central hubs in this global network, with numerous and intense lines connecting them to various countries, indicating high levels of international cooperation. Other significant nodes include England, Germany, and Canada, which also show substantial collaboration frequencies with multiple countries. This network visualization underscores the pivotal roles of these countries in driving international research efforts and fostering academic exchanges in the field of new energy systems.

The network density calculated in two parts of this study represents the level of interconnectedness and collaboration among countries in the field of research on new energy in power systems. Network density is a crucial metric as it quantifies the extent of collaboration and information exchange between different countries. A higher network density indicates a more cohesive and integrated research network, where countries frequently collaborate and share knowledge, leading to more robust and comprehensive advancements in the field. The necessity of calculating network density lies in its ability to highlight the collaboration patterns and the central roles of specific countries within the global research network. By understanding these patterns, researchers and policymakers can identify key players, potential collaborators, and gaps in international cooperation. This insight is essential for fostering more effective and strategic partnerships, promoting knowledge dissemination, and accelerating the development of innovative solutions in power systems and energy storage technologies.

Figure 4 and Figure 5 display the top 10 countries with the highest frequency. Frequency indicates the number of times a country is mentioned, while centrality represents the country's position within the field. The centrality metric reveals the interconnectedness between countries, meaning that the more connections a country has, the higher its centrality. A higher centrality indicates a more significant role in research, reflecting the country's importance.

Figure 4 and Figure 5 show that China is the leading country in the field of research on new energy in power systems, with 344 publications, which is significantly more than other countries. This indicates China's strong interest and rapid advancement in hydrogen fuel cell technology, positioning it as a frontrunner in this domain (Xu et al., 2020; Cheng and Lv, 2021; Shi et al., 2024). China's centrality is 0.69, suggesting that cross-border cooperation is relatively common for China. The United States ranks second with 29 publications, while Iran ranks third with 16 publications. In terms of centrality, the United States and Iran have significantly different centrality values compared to China, indicating relatively little international cooperation for these two countries. Spain, Poland, and Denmark have the lowest centrality values and almost no international cooperation. On the other hand, England, Canada, and Singapore have centrality values exceeding 0.1, indicating that research in these countries is the result of cooperation among multinational researchers. The research on China, the United States, and Iran started in 2014 and has shown a relatively high frequency, highlighting the foundational role played by these three countries.

3.2.2 Institutional analysis

An institutional analysis map was generated using institutions in CiteSpace, revealing a network of 236 nodes and 196 connections.

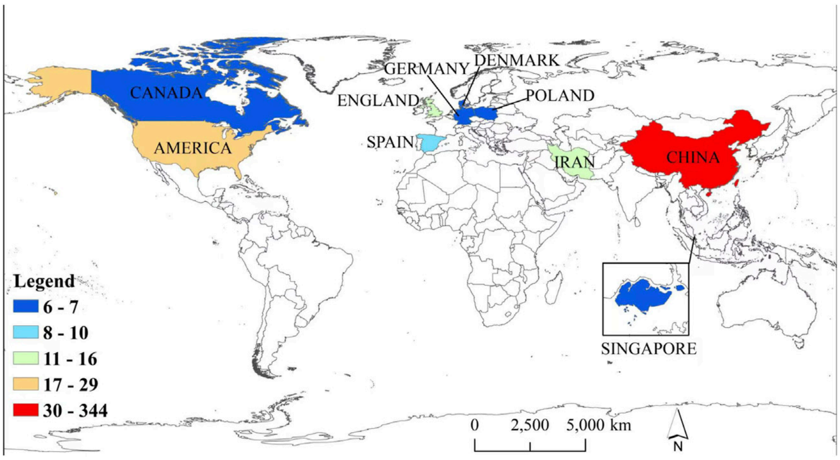

FIGURE 4
Total number of publications issued by the Top10 Countries/Regions. (Top 10 countries that have issued new energy journal articles for power systems in the past 10 years).

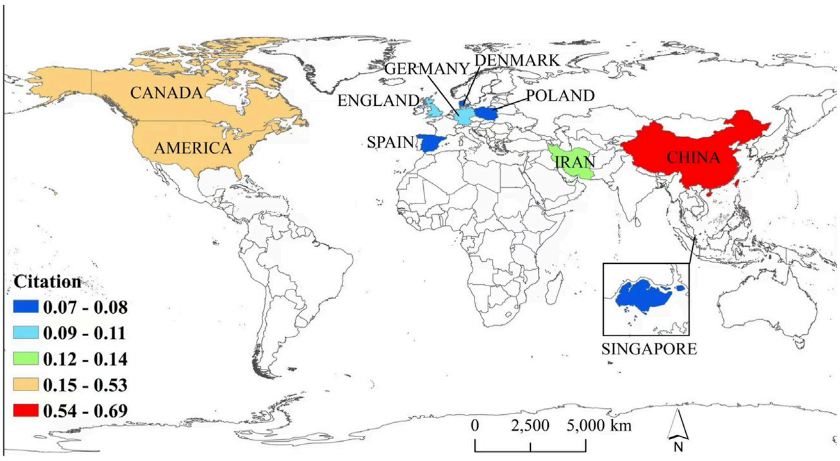

FIGURE 5
Centrality of publications issued by the Top10 Countries/Regions. (Top 10 countries that have issued new energy journal articles for power systems in the past 10 years).

The density of this network was calculated to be 0.0071. The nodes representing North China Electric Power University, China Electric Power Research Institute, and Tsinghua University were found to be densely connected and primarily focused on data. This suggests that these institutions play a central role in the research field. The visual clustering and thick connecting lines further indicate that these institutions are involved in extensive collaborative efforts and engage in high levels of research activity. These findings provide evidence of strong academic exchanges in the field of power system blockchain technology research (Wang N. et al., 2019; Gu et al., 2024; Shukla et al., 2024).

Many research institutions in Figure 6, such as North China Electric Power University, China Electric Power Research Institute, Tsinghua University, Southeast University, and China Three Gorges University, actively engage in collaborations. These partnerships exhibit distinctive regional characteristics, highlighting the importance of cross-institutional research and collaboration in fostering academic exchanges within the Source-grid-load system research field (Wen et al., 2016; Xi et al., 2018; Zhou et al., 2020; Gu et al., 2021; Lu et al., 2021; Guo et al., 2022).

This article also presents a ranking of the top 10 publishing institutions in the field of new energy research, as shown in Figure 7 North China Electric Power University has the highest number of publications, with 47 articles, surpassing other institutions. On the other hand, Guangxi University ranks relatively low, indicating that it publishes more frequently but has less collaboration with other institutions. This observation can also be deduced from the publication years. North China Electric Power University and China Electric Power Research Institute published their research earlier, suggesting their significant contributions to photovoltaic

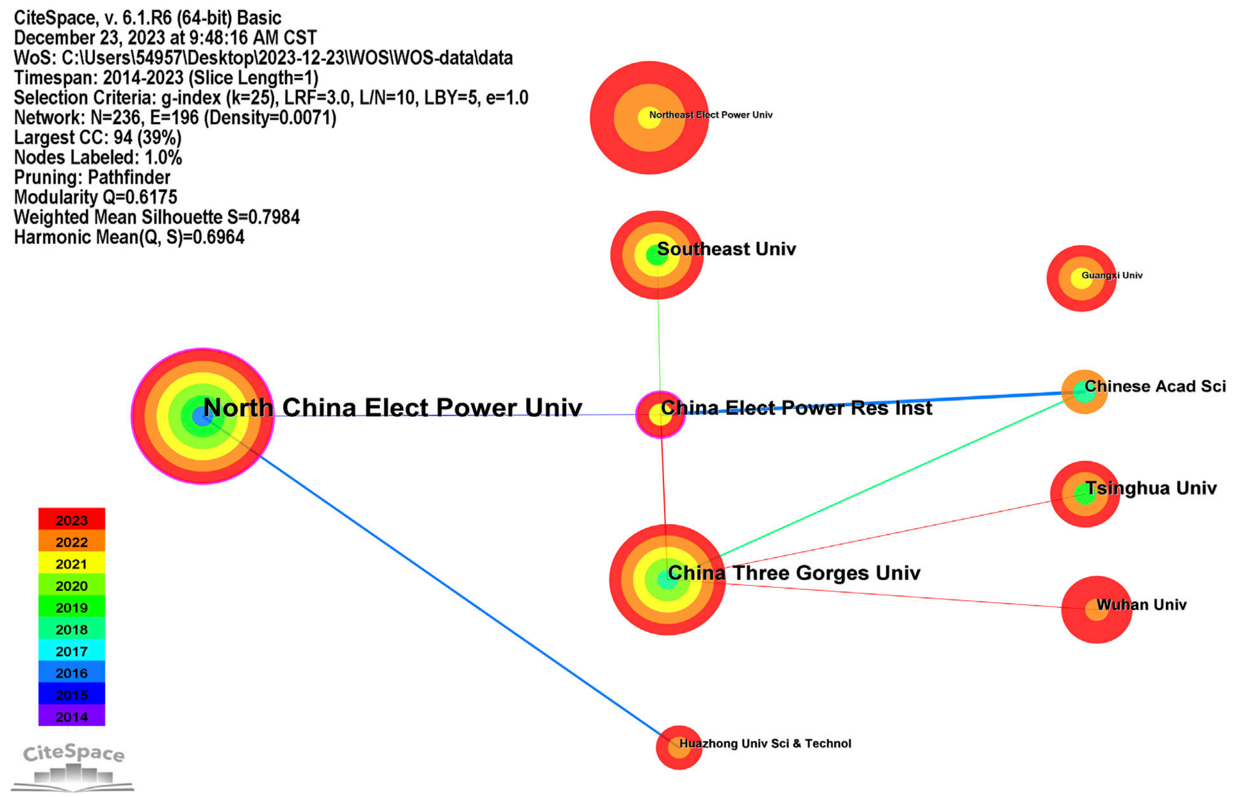

FIGURE 6
Network of top 10 article publishing organizations in the last decade.

system research. China Three Gorges University, with 11 publications, secured the fourth position. It is noteworthy that these publications were made in 2018, indicating a relatively late focus on wind energy research by China Three Gorges University. However, this institution's centrality value of 0.08 is relatively high, suggesting recent attention towards wind energy research. China Three Gorges University has conducted in-depth research on new energy reliability assessment and has provided valuable insights into the current cutting-edge research direction.

3.3 Current research hotspot analysis and frontier and trend analysis

3.3.1 Research hotspot analysis

The present study utilizes Citespace software to perform cluster analysis on keywords. In order to ensure the accuracy of cluster classification, the panthfinder algorithm is employed to cut connections. The findings of this analysis are visually presented in Figure 8, which effectively depicts the research topics pertaining to power systems and new energy over the course of the previous decade. The cluster numbers assigned in the figure correspond to the topics derived from clustering the keywords through the LLR algorithm. Furthermore, the results reveal a total of 11 distinct clusters, and the detailed information regarding the clustering for each cluster is provided in the accompanying figure.

3.3.2 Research frontier and trend analysis

3.3.2.1 Research frontier

The objective of this research is to examine the evolution of keyword hotspots in the realm of new energy research within the field of electrical engineering. To achieve this, we employed the Bursts detection algorithm from Citespace software for analysis. The primary aim of this study is to identify the emergence of keywords and showcase their intensity in the domain of new energy in the power system. For a comprehensive understanding of the emergence intensity and the duration of hotspots, please refer to Table 3. The presented information displays blue lines indicating the time intervals of emergence, while the red line segments represent the start and end years of burst durations within each topic category.

According to Table 3, the hot spots in the energy field were prevalent from 2014 to 2018. During the period between 2016 and 2018, the research focus shifted towards integration, management, and emission. However, with the passage of time, 2019 witnessed the emergence of new topics and hot spots, including photovoltaic systems, efficiency, synchronous generators, and stability. These developments highlight that new energy power generation systems, power system stability, and power system efficiency are currently at the forefront of research in this field.

3.3.2.2 Research trend

This study utilizes Citespace to analyze the changes in keywords over time in the field. The analysis node selected for generating the keyword time graph is Timeline. To generate the current graph,

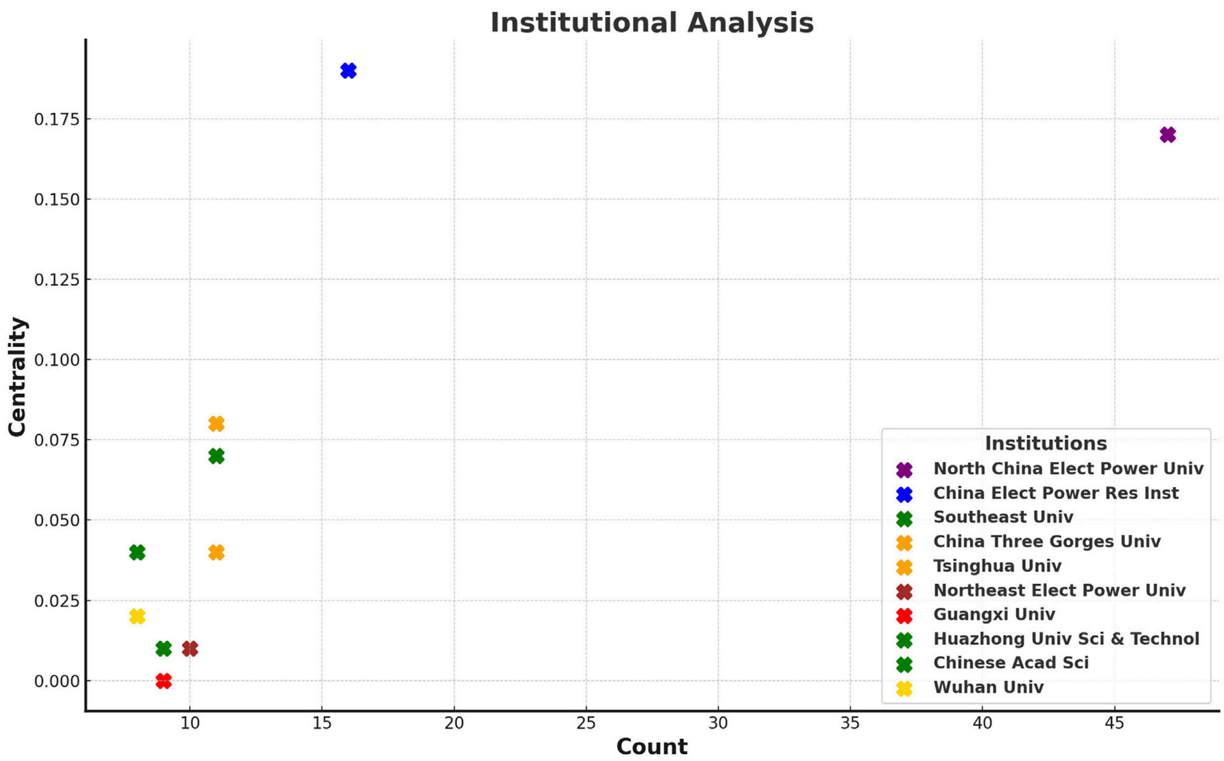

FIGURE 7
Centrality vs Count by Institution. (Top 10 organizations that have published articles on the field of new energy and power system in the last decade).

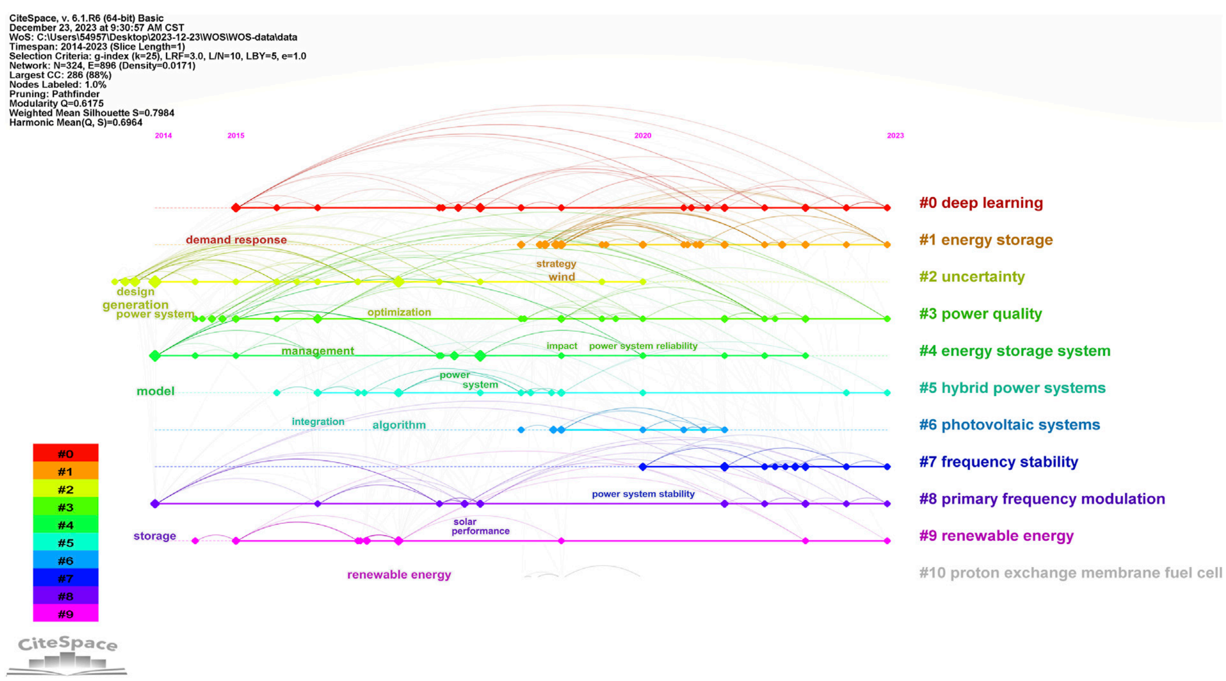

FIGURE 8
Clustering of Top11 keywords in the field of new energy for power systems in the last decade.

TABLE 3 (2014-2023) top 20 keywords with the strongest citation bursts.

Top 20 keywords with the strongest citation bursts				
Keywords	Strength	Begin	End	2014–2023
Energy	2.7	2014	2018	
Integration	3.76	2016	2020	
Management	3.3	2016	2019	
Emission	1.64	2016	2018	
Power System	1.58	2016	2016	
Algorithm	1.96	2017	2018	
Battery	1.44	2017	2019	
Technology	2.26	2018	2019	
Model	1.88	2018	2019	
Photovoltaic System	2.1	2019	2021	
Efficiency	2.08	2019	2020	
Synchronous Generator	1.75	2019	2021	
Stability	1.56	2019	2019	
New Energy Power System	1.56	2021	2023	
Wind Energy	1.56	2021	2023	
Virtual Synchronous Generator	2.1	2022	2023	
Genetic Algorithm	1.45	2022	2023	
DC Converter	1.45	2022	2023	
Wind Turbine	1.45	2022	2023	
Reliability Assessment	1.45	2022	2023	

keywords with smaller nodes are omitted, with the specific indicators and thresholds as follows: time slice set to 1 and the threshold chosen as g-index = 5.

The timeline presented in Figure 9 illustrates the distribution of keywords over time in the research fields of energy, power systems, and modeling. The relatively even distribution of keywords indicates that research topics in these fields are constantly evolving and becoming more diverse. This suggests a dynamic academic environment where researchers continuously adapt and expand their focus to address the evolving theoretical and practical challenges in these fields. The emergence of new keywords over time reflects the natural evolution of the field, driven by factors such as new technologies, changes in regulations, and shifts in global energy demand. These changes necessitate the development of new modeling and system analysis methods in the power and energy sectors. Specifically, during the period of 2016–2017, the field of 'Advances and Innovations in Renewable Energy Integration' witnessed the emergence of themes such as integration, management, emission, and power systems. This indicates that the initial focus of renewable energy integration was on power systems, and it continued to prioritize power system research (Li et al., 2016; Wang X. et al., 2019; Lago et al., 2019; Liu Z. C. et al., 2021; Wang W. Z. et al., 2022; Lu et al., 2024). During the period of 2017–2018, the research field of 'Source-Grid-Load-Storage Coordination Planning Technology' focused on the hot topics of 'technology' and 'model'. This indicated a strong emphasis on integrating new energy resources into power systems, with a central focus on the technological and modeling aspects (Yang et al., 2018; Wu H. et al., 2021; Chen et al., 2022). Between 2019 and 2021, the research field of 'Regional Photovoltaic Power Systems' experienced a surge in themes such as photovoltaic system efficiency, synchronous generator, and stability, highlighting the evolving focus on these aspects of photovoltaic power systems (Lei et al., 2014; Wang S. et al., 2023; Wang S. J. et al., 2023). In the years 2023–2024, the research domain of 'Hybrid Renewable Energy' witnessed emerging themes such as virtual synchronous generators, wind turbines, and reliability assessment, reflecting the evolving priorities in this field (Anderson and Grover, 2003; Al-Rawashdeh et al., 2023; Liu D. et al., 2023).

3.4 Analysis of the most cited references

Based on Table 4, the publication that garnered the most citations between 2014 and 2023 is titled 'Enhancing Intraday Load Forecasting Accuracy by Utilizing Customer Behavior Similarities in Smart Meter Data' from the academic journal IEEE TRANSACTIONS ON SMART GRID, with a total of

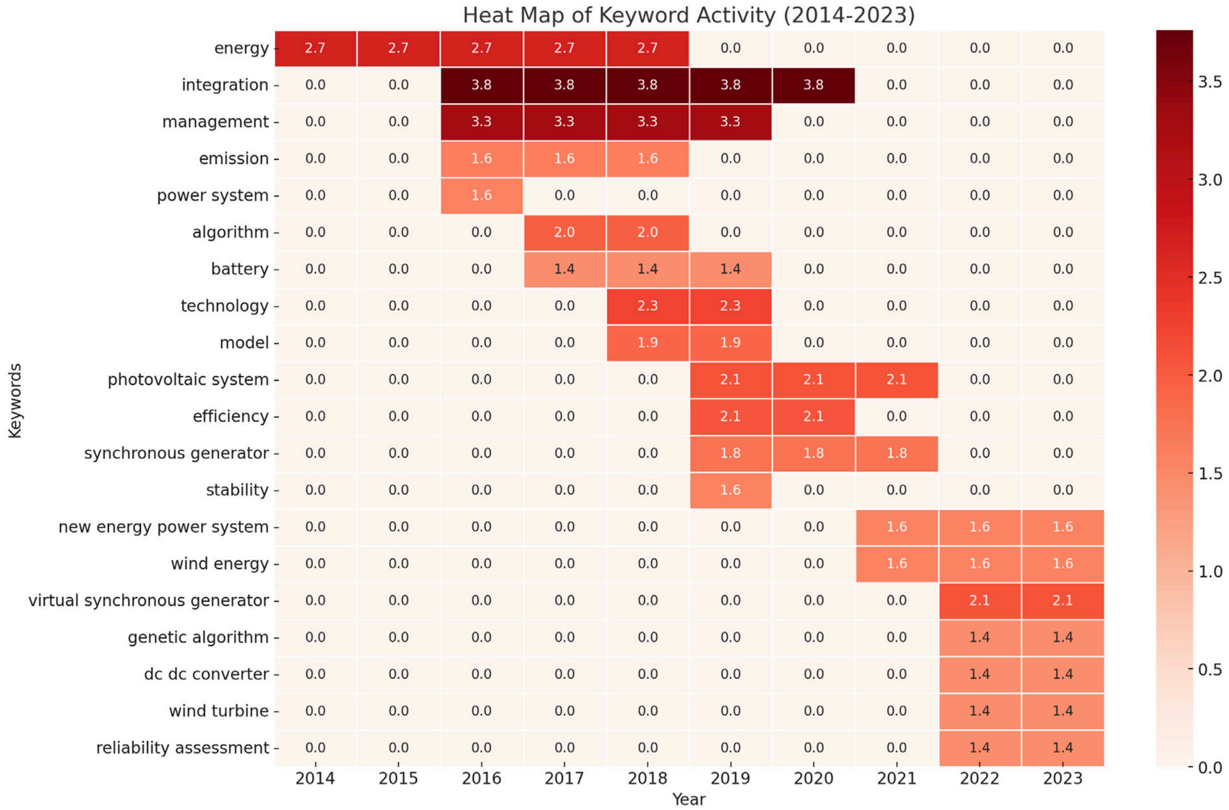

FIGURE 9
Heat Map of Keyword Activity. (Emergence of Top 20 keywords in the field of new energy in power systems in the past 10 years, and the shade of red represents the magnitude of centrality).

301 citations. Conversely, the periodical APPLIED ENERGY boasts an impact factor of around 11 over the previous 5-year period and has accumulated 187 citations, hosting the article 'A Comprehensive Review of Recent Advancements and Evolving Challenges in Peer-to-peer Energy Systems for Interconnected Communities'. These two articles delve into advanced energy technology. The first article presents a decision-making framework, while the second article focuses on predictive modeling using machine learning algorithms (Quilumba et al., 2015; Jindal et al., 2016; Tushar et al., 2021; Du et al., 2023; Wang et al., 2024; Yan et al., 2024). The most cited recent study, titled 'Energy Management and Operational Control Methods for Grid Battery Energy Storage Systems,' provides a comprehensive examination of advancements in battery energy storage systems and their applications. The study specifically focuses on how these systems can enhance the flexibility, economy, and security of power systems. It delves into various application scenarios and management techniques for large-scale battery storage systems. This study, conducted by Li and Wang in 2021, is a valuable resource for understanding the potential of battery energy storage systems (Tong et al., 2017; Li and Wang, 2021; Huang et al., 2023). Moving on to the next two articles, the first one is titled 'Research and application of a new hybrid forecast model - taking wind speed forecasting in China as an example.' This article highlights the importance of forecasting and planning in energy systems. It particularly emphasizes the need for effective strategies and models to forecast and manage energy demand, taking into account the variability of renewable energy sources. By focusing on wind speed forecasting in China, the authors, Wang, J., Wang, Y., and Jiang, P., in 2015, aim to provide insights into developing more accurate and reliable forecasting methods (Wang et al., 2015; Verma et al., 2016; Galván et al., 2021). The second article discussed in this paragraph is titled 'Designing a low-carbon UK power system in 2050 that is robust to spatial, temporal, and inter-annual changes in weather.' This article also emphasizes the significance of forecasting and planning in energy systems, specifically in designing resilient low-carbon power systems. The authors, Zeyringer, M., Price, J., et al., in 2018, highlight the importance of considering the variability and unpredictability of weather conditions in the design of future power systems. Their research aims to provide insights into developing power systems that can withstand and adapt to these changes (Huang and McElroy, 2015; Zeyringer et al., 2018; Liu Z. M. et al., 2024).

4 Discussion of trends in major publications and research frontiers

4.1 Citespace for databases such as WOSCC

The literature data collected in this manuscript are obtained from WOSCC, while the CiteSpace software utilizes information from not only WOSCC but also other database networks. Other popular bibliometric

TABLE 4 (2014-2023) Top 5 most cited documents.

	Title	Journal	Research area	Journal 5-year impact factor	Citations	Year	First author
1	Using Smart Meter Data to Improve the Accuracy of Intraday Load Forecasting Considering Customer Behavior Similarities	IEEE TRANSACTIONS ON SMART GRID	Smart Grid Technology, Load Forecasting, Data Analytics, Customer Behavior Analysis, and Smart Meter Data Utilization	10.4	301	2015	Quilumba, FL
2	The study and application of a novel hybrid forecasting model - A case study of wind speed forecasting in China	APPLIED ENERGY	Wind Energy, Forecasting Models, Renewable Energy, Hybrid Models, and Applied Energy Research	11	128	2015	Wang, JZ
3	Designing low-carbon power systems for Great Britain in 2050 that are robust to the spatiotemporal and inter-annual variability of weather	NATURE ENERGY	Low-Carbon Energy Systems, Power System Design, Climate Resilience in Energy Systems, Spatiotemporal Weather Analysis, and Renewable Energy Integration	63.9	133	2018	Zeyringer, M
4	Peer-to-peer energy systems for connected communities: A review of recent advances and emerging challenges	APPLIED ENERGY	Peer-to-Peer Energy Trading, Smart Grid Technology, Community Energy Systems, Energy Management, and Technological Advancements and Challenges in Energy Systems	11	187	2021	Tushar, W
5	Energy Management and Operational Control Methods for Grid Battery Energy Storage Systems	CSEE JOURNAL OF POWER AND ENERGY SYSTEMS	Energy Management, Battery Energy Storage Systems, Operational Control Methods, Grid Integration of Energy Storage, and Optimization in Energy Systems	6.8	125	2021	Li, XJ

software options include VOSViewer and NetDraw. Specifically, CiteSpace, which was developed by Professor Chaomei Chen, is highly regarded in the field of knowledge mapping due to its efficient techniques for visualizing information (Xie, 2015a; Chen C., 2018; Lin and Zhang, 2023). The collected literature data in this manuscript are derived from WOSCC, and the CiteSpace software uses information from a variety of database networks, not just WOSCC. Among the popular bibliometric software tools available, VOSViewer and NetDraw are also commonly used. Notably, CiteSpace, developed by Professor Chaomei Chen, is widely respected within the field of knowledge mapping because of its highly effective approaches for visualizing information (Synnestvedt et al., 2005; Xie, 2015b; Chen C. M., 2018). The articles excel in exploring various aspects of a field, such as collaboration, key points, internal structure, trends, and dynamics (Awad et al., 2014; Wang et al., 2016; Xu et al., 2021; Qin et al., 2022; Sabe et al., 2022; Qian et al., 2023). It is evident that bibliometric software possesses unique advantages, with CiteSpace being a comprehensive tool.

4.2 Trends for IEEE Transactions on Power Systems publications

This research paper presents a comprehensive scientometric analysis of the field of Power Systems & Electric Vehicles, focusing on Distributed Generation research. It explores various factors such as publication outputs, international collaborations, and co-occurrence analyses of subject categories and keywords. The findings indicate a significant increase in research interest over the past decade, with a total of 751 journal articles published in this field. However, the distribution of this interest is not equal worldwide, with North America, Europe, and Asia being the main areas of focus (Wang and Wang, 2015; Connell et al., 2017; AlKuwaiti et al., 2024; Schneider et al., 2018; Park et al., 2012; Du and Mohammadi, 2023). One of the noteworthy observations from this analysis is the substantial international collaboration between different regions. The United States and China emerge as the most active contributors, accounting for half of the global publications. Interestingly, the United States shows a higher level of collaboration compared to China (Yang et al., 2013; Li et al., 2014; Muratori and Rizzoni, 2016; Liu Q. P. et al., 2021). In addition, several prolific institutions like the United States Department of Energy (DOE), Argonne National Laboratory, Tsinghua University, Nanyang Technological University, and Nanyang Technological University National Institute of Education (NIE) Singapore are involved in extensive inter-institutional cooperation, as evident from their publications (Zeng et al., 2014; Wang and Chiang, 2016; Hoang et al., 2021; Barth et al., 2023; Liu J. et al., 2023). These findings highlight the global interest and collaboration in the field of Distributed Generation research within the Power Systems & Electric Vehicles domain. The research community, particularly in North America, Europe, and Asia, has shown significant engagement and involvement in advancing knowledge and understanding in this area. The active participation of institutions such as the United States Department of Energy, Argonne National Laboratory, Tsinghua University, Nanyang Technological University, and Nanyang Technological University National Institute of Education (NIE) Singapore further strengthens the collaborative efforts in this field (Brenna et al., 2013; Wanik et al., 2015; Bai et al., 2018; Sun et al., 2019; Zhou et al., 2022; Kurundkar and Vaidya, 2023).

4.3 The changing trend and future prospect of the research direction of distributed generation in power system

This research presents numerous distinct benefits. Initially, it conducts a methodical examination of the investigations on dispersed generation of sustainable energy via bibliometrics, supplying a comprehensive guide for scholars intrigued by this realm (Ali et al., 2016; Chen et al., 2018; Wei et al., 2023a). Furthermore, unlike conventional reviews, bibliometric analysis has the potential to offer a more all-encompassing comprehension of the prevalent and state-of-the-art concerns in the field. Notwithstanding the escalating inquiries in the sphere of new energy automobiles, most researchers and institutions hail from the United States and China, leading to an evident regional characterization (Azizi et al., 2022; Wei et al., 2023b; Gao et al., 2023). Further exploration and continuous observation are required to determine whether institutions and researchers from various nations are producing profounder, more avant-garde insights into this subject matter. However, there exist certain limitations to this study. The restricted accessibility of literature in this domain curtails the outcomes of the quantitative analysis of the literature and may not entirely exemplify all facets of the research area (Esmaeilion et al., 2022; De Castro et al., 2024; Su et al., 2024). Furthermore, the design of the software presents challenges in depicting recently published high-level literature in visual analysis outputs in comparison to older studies. Future enhancements in these realms will be crucial for augmenting the accuracy of trend forecasting (Azari et al., 2024; Liu C. et al., 2024; Jiang et al., 2024).

4.4 The changing trend and future prospect of the research direction of ESS, RES, and EES

In recent years, the research direction of Energy Storage Systems (ESS), Renewable Energy Sources (RES), and Energy Efficiency Systems (EES) has undergone significant changes, reflecting the evolving priorities and technological advancements in the field. The integration of RES into existing power grids has highlighted the critical role of ESS in ensuring grid stability and reliability. This integration necessitates advancements in EMS designed for BESS and the implementation of distributed mobile energy operation control methods.

The trend analysis indicates a growing focus on deep learning and artificial intelligence applications to optimize the performance and efficiency of ESS. Researchers are increasingly exploring the use of machine learning algorithms to predict energy demand and supply, enhance battery management systems, and improve the overall efficiency of renewable energy systems.

Moreover, there is a notable shift towards enhancing the power quality and reliability of RES through advanced control strategies and optimization techniques. The development of hybrid systems combining multiple energy storage technologies is also gaining traction, offering a more resilient and efficient solution for renewable energy integration.

Looking forward, the future research directions in this domain are expected to focus on several key areas:

1) Enhancing ESS Efficiency and Reliability: Continued research into advanced battery technologies, including solid-state batteries and flow batteries, is essential to improve the energy density, lifespan, and safety of ESS.
2) Integration of AI and Machine Learning: The application of AI and machine learning in energy management and control systems will be crucial for optimizing the performance of ESS and RES, enabling smarter and more adaptive energy systems.
3) Development of Hybrid Energy Storage Solutions: Exploring the synergy between different energy storage technologies will provide more flexible and robust solutions for balancing energy supply and demand.
4) International Collaboration and Knowledge Sharing: Strengthening international research collaborations will facilitate the sharing of knowledge, resources, and best practices, accelerating the development and deployment of innovative energy solutions.

5 Conclusion

We address the issue of understanding the development process and knowledge frontiers of power systems and new energy research from 2014 to 2023. The conclusions are given as follows:

1) Significant International Collaboration: The study reveals extensive international cooperation, with major contributions from countries such as China, the United States, and the United Kingdom. Leading institutions like North China Electric Power University and China Electric Power Research Institute play pivotal roles in advancing research.
2) Key Research Areas: The analysis identifies critical research areas including Energy Management Systems (EMS) for Battery Energy Storage Systems (BESS), distributed mobile energy operation control methods, and the broader implications for power system stability and efficiency. These areas are essential for the effective integration of renewable energy sources into power systems.
3) Emerging Trends and Shifting Focus: Recent years have seen a shift towards topics such as deep learning, power quality, and renewable energy integration. These emerging trends reflect the evolving priorities and technological advancements in the field, highlighting the dynamic nature of power systems research.
4) Future Research Directions: The study provides a roadmap for future investigations, emphasizing the need to enhance the efficiency and reliability of Energy Storage Systems (ESS). It calls for greater international collaboration and the exploration of new technologies and methods for renewable energy integration. Future researchers are encouraged to build on these findings to address the identified gaps and push the boundaries of current knowledge.

By achieving these objectives, this study offers a comprehensive overview of the current state and future prospects of power systems research, emphasizing the critical role of ESS in the transition to renewable energy. The insights provided serve as a strategic guide for future research and development efforts, ensuring that the most critical and impactful areas receive the necessary attention and resources to advance sustainable energy systems.

6 Limitations analysis

In this study, we exclusively utilized the main Web of Science database for quantitative analysis. The search terms were limited to the subject part of the content. Although we made efforts to ensure literature saturation and conducted a thorough review during literature selection, it is possible that certain gaps in the literature still exist. Consequently, some relevant literature might not have been included in our search. It is important to acknowledge that the results obtained from this study may be subjective.

Author contributions

BD: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. ZG: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Software, Writing - original draft. AM: Data curation, Funding acquisition, Project administration, Writing–review and editing YT: Funding acquisition, Investigation, Resources, Writing–review and editing. ML: Data curation, Funding acquisition, Writing–review and editing. YY: Funding acquisition, Visualization, Writing–review and editing. XL: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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