Bibliometric Analysis of Smart Grids in Renewable Energy

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Abstract

This article explores the concept of smart grids in renewable energy through bibliometric methods. Emphasizing the need for sustainable energy technologies to replace traditional power sources, the paper investigates the impact of renewable energies on the environment and the economy. With a focus on the significance of smart grids in addressing challenges related to unstable energy production, the article introduces the concept of smart grids. Utilizing bibliometric methods, it quantitatively analyzes information related to research in this field, addressing various questions regarding article counts, active institutions, reputable journals, and hot topics. Data analysis reveals an increasing trend in the number of articles related to smart grids in renewable energy in recent years. International collaborations and key topics are also highlighted as significant outcomes of the analysis.

Keywords— *Renewable Energy, Smart Grids Bibliometric Analysis, Sustainable Energy, Technologies ,Environmental Challenges ,Economic Efficiency*

I. Introduction

Currently, there is a need for sustainable energy technologies to replace traditional power generation sources, especially in developing and developed countries [1]. Fossil fuel-based energy sources have caused detrimental environmental issues, including global warming and climate change [2]. Greenhouse gases released from power generation have sharply increased in recent decades [3]. Therefore, renewable energy technologies such as solar, wind, hydropower, biomass, geothermal, and hydrogen have been introduced to address current environmental challenges [4-6]. Due to their environmentally friendly characteristics and the ability to generate power with zero or nearly zero air pollutants, renewable energy has gained increased importance, particularly with the growing awareness of a clean environment in society [7,8]. Renewable energy not only contributes to sustainability but also holds economic significance. It creates economic efficiency by reducing the cost of electricity production, utilizing natural and renewable resources for energy generation [9]. However, a significant portion of electricity generation still relies on fossil fuels due to the intermittent nature of renewable sources and high initial costs. These characteristics may pose challenges to the power grid. To address these challenges, the idea has emerged to use smart grids. Smart grids have the ability to respond quickly to changes and self-heal. These grids improve the efficiency of energy production and consumption and also support clean energy. In other words, smart grids promote the enhancement of the electricity grid's efficiency from generation to energy consumption [10].

The number of articles on smart grids has recently increased. Articles cover various technologies such as wireless sensors, communications, artificial intelligence, big data, and the Internet of Things. Technological development and organizational innovations are also important. Countries face similar challenges in this field [11].

These days, many researchers use bibliometric methods to quantitatively visualize the perspective and evolution of various research areas. These studies help to quantitatively analyze the outlook and evolutionary patterns in different fields.

This article focuses on the field of smart grids in renewable energy and uses bibliometric methods to quantitatively analyze information related to research in this area. The article begins by introducing research methods, selecting the database, information retrieval strategy, bibliometric methods, and data cleaning strategies. The "**Methodology**" section starts the article, outlining the research process and the use of various methods for collecting and analyzing information. This includes selecting the database, information retrieval strategy, bibliometric methods (article statistics), and data cleaning.

In the next section titled " **Data Analysis in Smart Grids for Renewable Energy**" an overview of the smart grid field in renewable energy is presented. This includes annual changes in the number of articles and citations, active and influential countries, highly published journals, and key articles based on the number of citations.

The following section, "**Visualization Analysis**" addresses the visual representation of keywords and common topics in articles and demonstrates the developments that have occurred in smart grids research in renewable energy. In the final section, "**Conclusions and Limitations**" the research findings and possible limitations are summarized. The article answers four different research questions and provides a more detailed examination of smart grids research details in renewable energy. These four questions are:

1. What is the number of articles and citations related to "smart grids in renewable energy"?
   - Examining the number of published articles on the subject and its annual changes.
2. Which prominent institutions are active in this field?
   - Identifying research institutions and universities that have been more active in this field.
3. What are the reputable journals for publishing in the field of smart grids and renewable energy?
   - Evaluating common and trusted journals that publish articles related to this field.
4. What are the hot topics and recent researches in the field of smart grids and renewable energy?

II. METHODOLOGY

This article presents a systematic review of scientific analysis in the field of smart grids Renewable Energy.

Data Collection and Processing:

Before bibliometric analysis, it is essential to create a dataset containing citation information. Currently, reference databases such as Scopus, ISI Web of Science (WOS), and Google Scholar are available. For this analysis, the Scopus database is utilized.

Bibliometric Analysis Methods:

In this article, various bibliometric methods are employed to analyze the dataset.

Initially, the number of publications (TP) is used to measure quantitative productivity(Ding et al., 2014)[12], while the number of citations (TC) is utilized to gauge the impact (Goran, 2010)[13]. "Citations per document" (TC/TP) indicates the average impact of each article.

Another bibliographic method, as proposed by Hirsch (2005)[14], is the h-index, which represents the number of h articles published in a journal or by an organization that have at least h citations, reflecting the influence and importance of articles.

Some other common methods include identifying the most productive institutions, journals, highly cited articles, average number of authors per article (AN/TP), average number of references per article (RN/TC), and the Impact Factor(IF) (Garfield, 1983)[15].

Finally, the VOSviewer software (see www.vosviewer.com) is used for visualizing bibliographic information in graphical maps. VOSviewer can create bibliometric networks based on data from WOS, Scopus, Dimensions, and PubMed or manager reference files (such as RIS, EndNote, and RefWorks files). This software utilizes distance-based maps to generate collaboration maps of authors, co-citation maps, citation networks, bibliographic coupling networks, and co-reference maps (van Eck and Waltman, 2010)[16].

III. DATA ANALYSIS IN SMART GRIDS FOR RENEWABLE ENERGY

In this section, they first delve into the quantitative information such as the number of articles and citations, prominent institutions, and highly published journals. Subsequently, through visual analysis, patterns and relationships among authors and common concepts in the examined articles are explored. These analyses contribute to a comprehensive understanding of how research is advancing in the field of "Smart Grids in Renewable Energy".

Annual Publications and Growth Trend

A comparative analysis of the number of publications by global researchers reveals that global publications started decreasing after reaching a peak in 2018, continuing until 2021. However, the number of published articles increased annually after 2021, surpassing 823 articles in 2022. Furthermore, in 2023, the number reached 810[**Figure 1**].

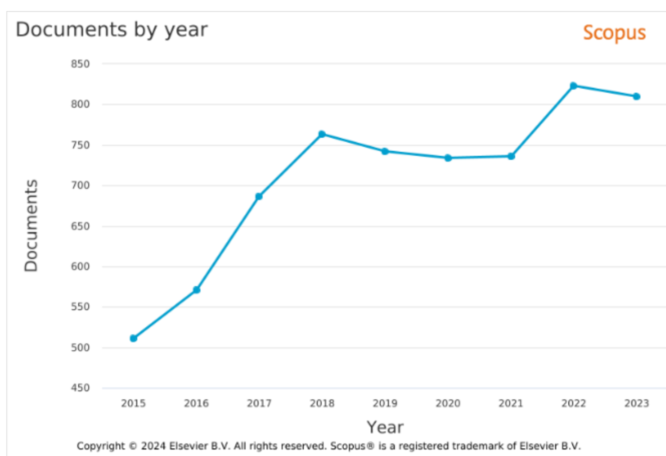

Figure 1 | Annual publications by global scholars in the field of Smart Grids in Renewable Energies.

The volume of publications on intelligent networks in sustainable energy is directly related to the promotion of relevant policies.

For example, in 2010, the National Energy Administration (NEA) initiated the promotion of standardization of intelligent networks with the publication of "Announcement of the

Establishment of the National Smart Culture Group" (National Energy Administration, 2010)[17]. In the same year, China's State Grid Corporation implemented the "Strong Smart Technical Standardization Program," officially addressing the structuring of intelligent networks at the national level (Wang, 2010)[18]. From 2010 onwards, research in this field significantly increased. Similarly, in 2015, the National Development and Reform Commission (NDRC) and NEA implemented the "Guidelines for Promoting Smart Network Development" (National Development and Reform Commission and National Energy Administration, 2015)[19], contributing to the development of smart networks.

In 2016, NDRC and NEA published the "Five-Year Plan for Power Development (2016-2020)," emphasizing the improvement of the power grid structure and the expansion of smart power grids (National Development and Reform Commission and National Energy Administration, 2016)[20]. In 2020, NDRC and the Ministry of Justice released the "Opinions on Accelerating the Formulation of Rules and Policies for Green Production and Consumption" (National Energy Administration and Ministry of Justice, 2020)[21], highlighting increased policy support for distributed energy, smart grids, energy storage technology, and multi-energy balance technology.

TABLE 1 | World scholars' publications characteristics on SG In Renewable Energy from 2015 to 2023.

Years	*TP*	*AN*	*AN/TP*	*TC*	*TC/TP*
2015	511	2,384	5	4,679	*9*
2016	571	2,631	5	4203	*8*
2017	686	2,927	4	6521	*10*
2018	763	3,131	4	6331	*8*
2019	742	3,015	4	5834	*8*
2020	734	2,987	4	4223	*6*
2021	756	3,134	4	6445	*8*
2022	823	3,467	4	8734	*10*
2023	810	3,212	4	7523	*9*

Also, in **Table 1**, common bibliometric indices have been employed. For instance, TP (Total Publications) refers to the total number of articles in a specific year, while AN (Number of Authors) indicates the total number of contributing authors, providing insights into collaboration strength among authors in the studied field. TC (Total Citations) signifies the overall number of citations, typically used to describe the impact of literature. RN (Number of References) points to the total number of cited references, usually used to describe the foundational literature of research. Additionally, TC/TP represents the average annual citation rate of literature, indicating the citation status of publications by scientists (Yu et al., 2020) [22].

These indices include:

- TP (Total Publications):The total number of published articles in a specific year. This measure indicates the overall volume of publications in the examined field.
- AN (Number of Authors):The total number of contributing authors in these publications. This measure can provide insights into collaboration strength among authors in the studied field.
- TC (Total Citations):The total number of citations, usually considered as an indicator of the impact of literature. This measure reflects the importance and influence of publications.
- RN (Number of References):The total number of cited references, aiding in identifying the foundational literature for research.
- TC/TP (Total Citations per Total Publications):This ratio signifies the average annual citation rate of literature and can illustrate the citation status of publications by Chinese scientists. These indices, considered together, can provide a comprehensive picture of research and the global impact of publications in the examined field.

The Most Cited Papers

The analysis of the top articles in the field of "Smart Grids in Renewable Energy," as presented in the **TABLE 2**, reveals a substantial and noteworthy contribution by researchers to this domain. The highlighted articles are highly referenced, with Mengelkamp et al.'s (2018) paper standing out prominently with an impressive 1,075 citations, indicating its substantial impact and influence in the field.

One significant trend observed is the prevalence of international and interinstitutional collaborations evident in the research. This signifies a shift towards global and cross-institutional cooperation in the study of renewable energy, highlighting the importance of collaborative efforts in advancing knowledge and understanding in this field.

The main research topics covered in these top articles include Smart Grid, Batteries and Energy Storage, Electric Vehicles (EV), Internet of Things (IoT), Demand Response, Smart Grid Communication Technology, and Big Data Technology. This diversity of investigations reflects the comprehensive nature of research in the domain, addressing various aspects of renewable energy and smart grid technologies.

Moreover, the analysis underscores the research focus on the impact of Smart Grids on the development of renewable energies and related technologies. Batteries and energy storage emerge as a central theme, receiving the highest citation frequency. This emphasis highlights the crucial role of energy storage in the context of Chinese research on Smart Grids, emphasizing the significance of addressing energy storage challenges in the broader context of renewable energy.

In conclusion, the analysis provides a clear picture of the research landscape in renewable energy, emphasizing international collaboration, topic diversity, and the substantial impact of the research conducted in this field. It showcases a collective effort by researchers to explore and advance knowledge in Smart Grids and renewable energy, contributing to the global discourse on sustainable energy solutions.

TABLE 2 | The top 10 most cited papers on Smart Grids in renewable energy

Rank	Most cited documents	TC	Citation/year	AN	RN	IN	CN
1	Mengelkamp, E. , Gärttner, J. , Rock, K. , ... Orsini, L. , Weinhardt, C2018.	1,075	179	4	190	1	1
2	Deng, R. , Yang, Z. , Chow, M.-Y. , Chen, J2015.	716	79	4	217	1	2
3	Mengelkamp, E. , Gärttner, J. , Rock, K. , ... Orsini, L. , Weinhardt, C2018.	608	101	4	155	3	1
4	Kumar, D., Zare, F., Ghosh, A.2017	521	74	3	45	4	2
5	Abdel-Nasser, M., Mahmoud, K.2019	489	97	2	278	1	1
6	Zhou, X., Chen, S., Lu, Z., ...Ma, S., Zhao, Q.2018	484	80	5	32	8	3
7	Erdinc, O. , Paterakis, N.G. , Mendes, T.D.P. , Bakirtzis, A.G. , Catalão, J.P.S2015.	383	42	5	163	2	2
8	Ramli, M.A.M., Bouchekara, H.R.E.H., Alghamdi, A.S.2018	364	60	3	91	2	2
9	Erol-Kantarci, M., Mouftah, H.T.2015	347	38	2	154	5	2
10	Amrollahi, M.H., Bathaee, S.M.T.2017	315	45	2	44	3	1

TC, total citation; AN, author number; RN, references number; IN, institution number; CN. country number.

IV. VISUALIZATION ANALYSIS

Co-authorship Analysis

The analysis of author collaboration in scientific research examines temporal connections and scientific collaborations among individuals, providing a common tool in studies of institutional and researcher collaborations. This analysis explores how collaboration and sharing of scientific resources occur among authors. In comparison to citation networks, which typically measure connections between articles, author collaboration analysis focuses more on temporal relationships and collaborative contributions among individuals. This analysis offers greater transparency regarding authorship than anonymity in citations, revealing social interactions among researchers.[23]

Co-authorship Between Countries

Table 3 illustrates the number of internationally published articles (collaborations with other countries) and the corresponding number of citations for these international articles. According to the presented data, India has the highest number of articles in this field, followed by China and the United States. However, among the number of articles from these three countries, the United States has the highest citation count, indicating the significant influence and impact of the United States in the scientific research field of smart grids in renewable energy. The international articles' overall count has shown a generally increasing trend, potentially attributed to increased dissemination of technologies and collaborative learning experiences among countries during the initial stages of smart grid research in sustainable energy.

TABLE 3 | International Collaboration and Citation Analysis of Smart Grids in Renewable Energy Research

Country	Documents	Citations
united states	434	12491
china	522	10657
united kingdom	196	4452
italy	286	4639
germany	275	4388
india	530	4356
saudi arabia	110	3223
pakistan	145	2843
canada	157	4207
australia	137	4230
spain	136	2941
iran	144	3370
france	161	2057

The international collaboration rate in the field of Smart Grids for Sustainable Energy is on the rise, with China leading collaborations with other countries. **Figure 2** depicts a network of countries engaged in international collaboration. India, with 530 collaborative articles, stands out as the leadingcollaborator.

However, despite having fewer articles, the collaboration of the United States and China with other countries is more significant. Following India, Australia has 130 collaborative articles, the United Kingdom has 117, and Canada has 109. Larger node sizes indicate more published articles in collaboration between that country and others, while thicker connections imply closer collaboration between two countries. For instance, in Figure 4, the collaboration between the United States and China with other countries in the Smart Grids domain is illustrated. The overall increase in the foreign collaboration rate suggests that Chinese researchers in the Smart Grids domain are increasingly focusing on collaborating with foreign countries.

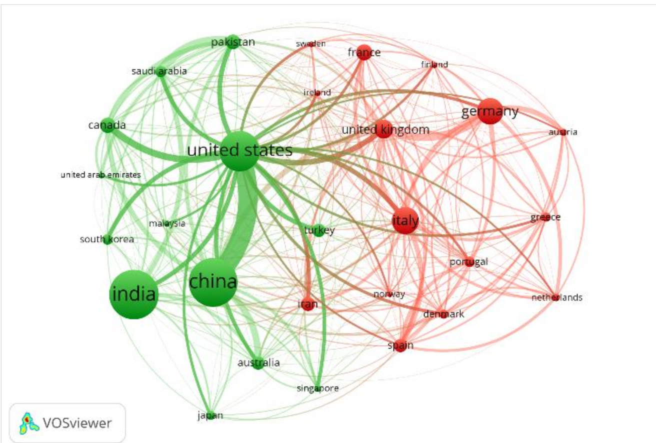

FIGURE 2 | Country co-authorship network in the field of the SG in Renewable Energy.

Co-authorship Between organizations

"To explore collaborative dynamics among organizations in smart networks for sustainable energy research, we employed VOSviewer, resulting in **Figure 3**. Out of 7,685 institutions contributing to this field, the analysis focused on 115 organizations. Each circle in Figure 3 represents the volume of articles from an organization and its collaborators, with larger circles indicating higher publication activity. The thickness of connecting lines signifies the intensity of collaboration.

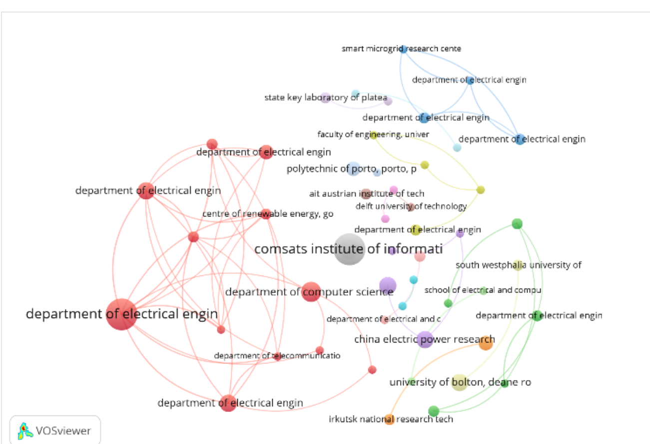

FIGURE 3 | organizational co-authorship network in the field of Smart Grids in Renewable Energy.

Examining collaboration clustering reveals the following:

Red Cluster: Dominated by major organizations like the University of Engineering and Technology in Peshawar, Pakistan, the State Grid Corporation of China, the University of Mardan in Pakistan, and Turabah University College in Taif, Saudi Arabia. This cluster showcases diverse and impactful collaborations, suggesting active engagement in joint projects and research related to smart networks in sustainable energy.

Green Cluster: The second-largest cluster includes universities such as King Saud University in Riyadh, Saudi Arabia, and Mansoura University in Mansoura, Egypt. It reflects multi-faceted cooperation among various universities in smart networks' research, indicating broad collaboration in research and articles related to sustainable energy.

Blue Cluster: This cluster represents collaboration among institutions in a geographic region, featuring Amirkabir University of Technology and the Islamic Azad University, Najafabad branch in Iran. It suggests regional cooperation efforts, where proximity encourages collaboration for enhancing research and projects related to smart networks in energy.

These insights, derived from analysis and visualizations, provide valuable information about collaboration patterns and dynamics among institutions in the smart networks for sustainable energy research field.

Co-occurrence Analysis

Co-occurrence analysis is a common method in bibliometric analysis. This approach, stemming from co-word analysis introduced in the 1980s (Callon et al., 1983)[24], has found widespread application. Keywords co-occurrence, a specific form of co-occurrence analysis, has been particularly valuable in examining and understanding current and popular topics across various fields (Chen et al., 2017)[25].

In simple terms Co-occurrence analysis is a method of examining texts by analyzing the relationships between keywords. If two words frequently appear together in a text, it suggests a connection or co-occurrence between them. This analysis can reveal which topics or keywords are more prominent in a research field and what relationships exist between them. It helps identify patterns and research focuses in a specific field by examining the frequency of keyword occurrences and their associations.

Author-Keywords Co-occurrence Analysis With Three Stages

From 2015 to 2023, the usage of 17,435,786 keywords by authors in research related to smart grids in sustainable energy has been analyzed. Out of this count, 11,786 keywords have appeared only once, and 943 keywords have been used more than 10 times. The research in this field is divided into annual periods from 2015 to 2023, allowing us to investigate the reasons for the increase or decrease in global publications during this time frame.

In this section, a keyword co-occurrence analysis has been conducted in three stages to identify the research axes in each stage. **Figures 4** to **6** present keyword co-occurrence maps in these three stages. In the initial stage, shown in **Figure 4**, the keyword co-occurrence map of articles by researchers in the field of smart grids and sustainable energy from 2015 to 2017 is illustrated.

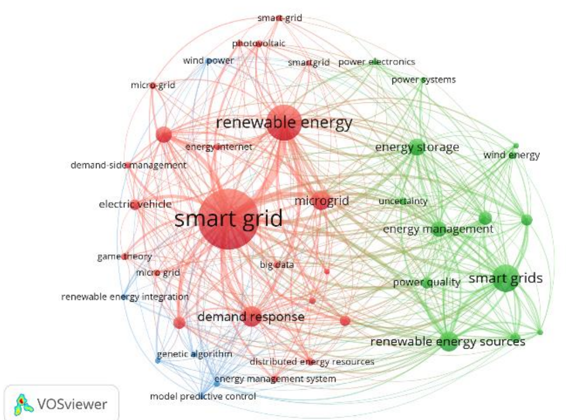

FIGURE 4 | Author-keyword co-occurrence network of smart grids in renewable energy publications in the world, 2015–2017.

Group 1-1(Red color cluster):This group includes keywords such as "smart grid," "demand response," "micro grid," and "renewable energy." This group likely focuses on issues related to smart grids in China from 2015 to 2017.

Group 1-2(Green color cluster):Keywords in this group include "energy storage," "energy management," and "uncertainty." This group is concentrated on issues related to energy storage, energy management, and uncertainty in smart grids in China.

Group 1-3(Blue color cluster):This group contains keywords like "genetic algorithm," "model predictive control," and "energy management system." It appears to concentrate on issues related to genetic algorithms, model predictive control, and energy management systems in a specific stage.

In this stage, smart grids in sustainable energy are emerging, and technical research indicates some experiments. However, the connection between different topics is still weak, with the main focus on renewable energy consumption.

Figure 5 illustrates the co-occurrence map of keywords in the field of smart grids for sustainable energy from 2018 to 2020. Keywords in this stage seem more interconnected, indicating a more dispersed research landscape in various areas. The top ten keywords in this stage are as follows: Demand Response, Electric Vehicles (EV), Microgrid, Wireless Sensor Networks (WSN), Security, Internet of Things (IoT), Distributed Generation, Electricity, IEC61850, and Distribution Network.

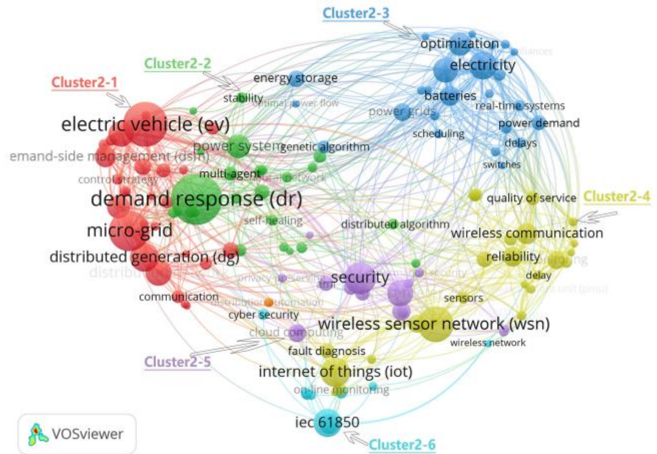

FIGURE 5 | Author-keyword co-occurrence network of smart grids in renewable energy publications in the world, 2018–2020

VOSviewer automatically forms six clusters labeled as Cluster 2-1 to Cluster 2-6. The largest cluster, Cluster 2-1, encompasses 29 keywords related to the integration of distributed energy, including EV, Microgrid, Distributed Generation, and Distribution Network. The second cluster, consisting of 28 keywords, focuses on Demand-Side Management (DSM) to enhance energy efficiency. Cluster 2-3, the next one, includes 25 keywords associated with energy storage, batteries, smart grids, planning, and delays. Cluster 2-4 represents the foundational technologies of Smart Grids, featuring keywords like IoT, WSN, sensors, reliability, and service quality. Security has gained increasing importance, forming Cluster 2-5, covering 16 keywords, including Smart Metering, Cloud Computing, and Advanced Metering Infrastructure (AMI). The final cluster, Cluster 2-6, is primarily dedicated to establishing SG standards, including smart network standards like IEC61850.

This stage is part of the Smart Grid development era in China. With political and technological advancements, keywords are proliferating, primarily reflecting three main themes. Firstly, SG foundational technologies such as IoT and WSN appear concentrated, with Smart Stations being prominent representatives in the IoT domain. Additionally, research on SG standards has emerged, such as investigations related to IEC61850. Secondly, SG leads to the restructuring of the power system. This type of distributed energy, microgrid, and EVs blur the traditional boundaries of the power system, encompassing generation, transmission, substation, distribution, and energy consumption planning. EVs, as a new energy storage method, alongside smart stations, have the potential to improve energy efficiency. SG transforms the power system from a traditional independent link to an interconnected internet, reinforcing mutual enhancement.

Last Stage, covering the years 2021 to 2023, saw a shift in research focus towards new topics such as "energy management," "blockchain," "optimization using machine learning," "energy storage," "artificial intelligence," "electric vehicles," and "deep learning"[**FIGURE 6**]. In this stage, the keyword co-occurrence map is automatically divided into four clusters.

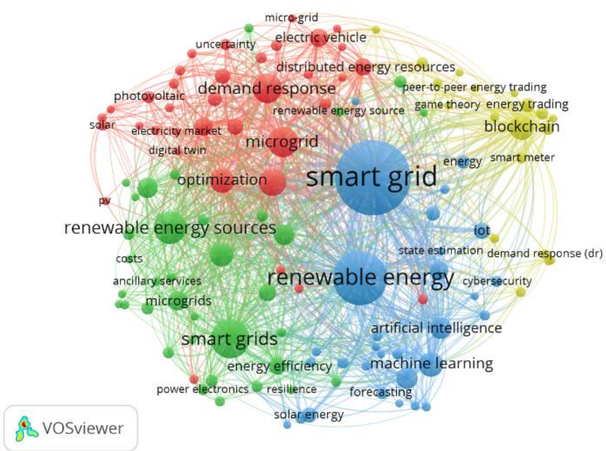

FIGURE 6 | Author-keyword co-occurrence network of smart grids in renewable energy publications in the world, 2021–2023

Cluster 3-1 (Red color cluster):This cluster consists of 36 elements related to issues like "artificial neural networks," "battery," "fuzzy logic," "genetic algorithm," "deep learning," "deep reinforcement learning," "demand response," "battery energy storage," and "smart stations." It primarily addresses concerns related to artificial intelligence, energy storage, and the development of advanced technologies in the smart grid domain.

Cluster 3-2 (Yellow color cluster):Encompassing all aspects of the power system, this cluster addresses issues such as "energy trading," "demand response," "energy storage," "distribution network," "power market," and "microgrids." The main theme of this cluster is the impact of smart grids on the power system.

Cluster 3-3 (Blue color cluster):This cluster independently focuses on issues related to artificial intelligence, specifically "deep learning" and "deep reinforcement learning." This indicates the significant attention AI has garnered as both a consumer and provider of energy, emphasizing its crucial role in energy management.

Cluster 3-4 (Green color cluster):Comprising 14 different aspects related to power system optimization, this cluster explores topics like "improving flexibility," "ancillary services," "cost reduction," "increasing energy efficiency," "process optimization," "economic distribution of energy," and "load management." These aspects generally contribute to enhancing the efficiency and performance of the power system, highlighting their importance in optimizing various resources and processes within the power system.

V. CONCLUSION

The bibliometric analysis of smart grids in renewable energy presented in this article provides valuable insights into the evolution and trends of research in this field. The research focused on various aspects, including the number of publications, citations, prominent institutions, journals, and hot topics.

The analysis revealed a growth trend in global publications on smart grids in renewable energy from 2015 to 2023, with a peak in 2018. The annual number of publications increased after 2021, reaching 810 in 2023. This growth is attributed to the increasing awareness of sustainable energy and the development of relevant policies, as seen in initiatives by the National Energy Administration and State Grid Corporation of Countries.

Prominent institutions and countries actively engaged in research on smart grids for renewable energy were identified. The United States, China, and India were among the leading countries, with the United States having the highest citation count. International collaboration in this field is on the rise, with China leading collaborations with other countries.

The analysis of the most cited papers highlighted significant contributions, with Mengelkamp et al.'s (2018) paper being the most cited, emphasizing the impact of research on smart grids and renewable energy. The research topics covered a wide range, including smart grids, batteries and energy storage, electric vehicles, internet of things, demand response, and big data technology.

Visualization analysis, including co-authorship analysis, international collaboration networks, organizational co-authorship networks, and co-occurrence analysis, provided a comprehensive understanding of the research landscape. The visual representation of keyword co-occurrence maps revealed the evolution of research themes over three stages, emphasizing topics such as energy storage, IoT, and artificial intelligence.

In conclusion, this bibliometric analysis contributes to the understanding of the smart grids in renewable energy research landscape, showcasing global collaboration, diverse research themes, and the impact of key publications. The findings can guide researchers, policymakers, and industry professionals in identifying current trends and future directions in this dynamic and critical field.

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