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Review

Comprehensive Bibliometric Analysis on Smart Grids: Key Concepts and Research Trends

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Abstract: Over the years, a rapid evolution of smart grids has been witnessed across the world due to their intelligent operations and control, smart characteristics, and benefits, which can overcome several difficulties of traditional electric grids. However, due to multifaceted technological advancements, the development of smart grids is evolving day by day. Thus, smart grid researchers need to understand and adapt to new concepts and research trends. Understanding these new trends in smart grids is essential for several reasons, as the energy sector undergoes a major transformation towards becoming energy efficient and resilient. Moreover, it is imperative to realize the complete potential of modernizing the energy infrastructure. In this regard, this paper presents a comprehensive bibliometric analysis of smart grid concepts and research trends. In the initial search, the bibliometric data extracted from the Scopus and Web of Science databases totaled 11,600 and 2846 records, respectively. After thorough scrutiny, 2529 unique records were considered for the bibliometric analysis. Bibliometric analysis is a systematic method used to analyze and evaluate the scholarly literature on a particular topic and provides valuable insights to researchers. The proposed analysis provides key information on emerging research areas, high-impact sources, authors and their collaboration, affiliations, annual production of various countries and their collaboration in smart grids, and topic-wise title count. The information extracted from this bibliometric analysis will help researchers and other stakeholders to thoroughly understand the above-mentioned aspects related to smart grids. This analysis was carried out on smart grid literature by using the bibliometric package in R.

Keywords: bibliometric analysis; energy consumption; smart home; smart building; smart meter; smart grid

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1. Introduction

Smart grids are rapidly evolving across the world. This is not only applicable to macrogrids but also to microgrids namely buildings, homes, and cities [1,2]. Smart grid technology enables customers, prosumers, and utilities to benefit from effective energy management. The key characteristics of smart grids such as bidirectional flow, automatic restoration, energy control, and comfort have a significant impact on the energy sector. These characteristics empower the utilities to comprehend their customers' requirements and energy consumption behavior, enabling further handling of various other grid functionalities. Smart grids are of great importance as they can be integrated with renewable energy resources and contribute towards alleviating environmental pollution and managing the insistent growth of load profiles [3]. Various works on different trends and concepts are described below.

The literature works on key concepts such as energy consumption behavior, forecasting energy consumption, load forecasting, the Internet of Things, non-intrusive load monitoring, smart meters and smart meter data, smart home reasoning systems, smart buildings, smart grids, and assimilation of variable renewable energy resources with power systems are discussed in Table 1. These works present the details related to the implementation of various methods and technologies with respect to smart grids.

Table 1. Review of key concepts related to smart grid research.

Year	Key Concept	Literature Works Carried Out	Ref.
2022	Data anomalies	A systematic analysis was conducted to enumerate the duplicate records in the energy consumption data of smart buildings	[4]
2022		A systematic analysis was conducted to identify the behavior of redundancy in smart home power consumption	[5]
2022		A systematic three-step method was conducted to learn the abnormal records in smart home power consumption	[6]
2022		Machine learning-based techniques were implemented to handle various data anomalies in smart home power consumption	[7]
2021		The missing-reading information in smart home power consumption was detected by implementing an effective and easy approach	[8]
2021	Energy consumption behavior	Identification of the hidden patterns and anomalies in smart home power consumption was accomplished by executing a framework	[9]
2020		To comprehend the energy requirement of customers, a framework relying on machine learning was realized on smart meter data	[10]
2021	Forecasting energy consumption	To predict the energy utilization statistics in smart buildings, a deep learning-based hybrid model was executed	[11]
2019		To gather the details of energy utilization in individual residential buildings, a convolutional neural network (CNN) and long short-term memory (LSTM) based model was implemented	[12]
2019		A detailed review of conventional and artificial intelligence (AI- based models was performed to forecast energy consumption	[13]
2021	Load forecasting	An online adaptive recurrent neural network (RNN) method was applied for load forecasting	[14]
2021		To estimate short-term loads, time-series forecasting was suggested. Further, a business case was presented for analyzing various clusters to comprehend the behavior of consumers	[15]
2019		To address challenges and analyze smart meter data, a clustering-based approach was executed to achieve productive demand-side management and load forecasting	[16]
2019		To forecast short-term loads, a framework relying on LSTM-RNN was recommended	[17]
2018		To anticipate the load profiles of residential consumers, a pooling-based deep RNN was executed	[18]
2020	Internet of Things (IoT)	A smart meter with IoT technology was discussed to cope with the challenges in the smart grid environment	[19]
2019		A broad review was conducted on the feasibility of employing advanced metering infrastructure (AMI) and smart meter technologies in smart grids for reliable monitoring and better power quality	[20]
2021	Non-intrusive load monitoring (NILM)	A deep learning (DL)-based multitask learning approach was executed for NILM in smart meter data	[21]
2019		To detect the appliance usage and their patterns, a new NILM approach was implemented to find the appliance utilization patterns for better load identification and estimation	[22]
2018		To realize the appliances' status in a network, a voltage–current (V-I) trajectory-based NILM algorithm was implemented	[23]
2018		For load profile disaggregation, a novel framework based on "segmented integer quadratic constraint programming" and "hidden Markov models" was discussed	[24]

Table 1. *Cont.*

Year	Key Concept	Literature Works Carried Out	Ref.
2021	Smart meters and smart meter data	A robust, reliable, and ML-based advanced infrastructure was discussed to investigate and observe smart meter data and further provide enhanced security to smart meters	[25]
2021		Several applications were discussed for monitoring and protecting distribution systems with the participation of smart meters	[26]
2021		An algorithm was implemented to disaggregate household solar energy consumption by reducing the parameters of smart meter data	[27]
2020		A scalable strategy was discussed using smart meter data for targeting residential consumers to be part of energy efficiency programs that, in turn, reduce consumption	[28]
2019		To sense the non-technical losses in the utilities, a methodology based on analyzing consumers' behavior with the contribution of supervised learning methods on real-time smart meter data was discussed	[29]
2017		A sparse representation approach was presented to reduce voluminous smart meter data and further extract unseen patterns in energy consumption data	[30]
2021	Smart home reasoning systems	A methodical literature review was performed to study the characteristics, applications, and challenges of smart home reasoning systems	[31]
2020	Smart buildings	A CNN model was implemented to calculate building occupancy in real-time by using AMI data	[32]
2021	Smart grids	A study was performed to learn the developments and the challenges involved in the implementation of DL technologies in smart grid systems	[33]
2021		Two models, viz. sampling approach and AlexNet, were realized to detect the abstraction of electricity in smart grids	[34]
2021		A thorough survey was performed on the implementation of blockchain technology in smart grids to secure them from the cyber world	[35]
2020		A comprehensive survey was conducted to learn the opportunities, developments, and future directions of smart grid technologies	[36]
2020		The significance and difficulties of big-data analytics in forthcoming power grids were discoursed to guide the researchers	[37]
2019		A detailed survey was performed on the problems of privacy and security in smart grid networks	[38]
2019		A wide-ranging survey was performed on the security issues of AMI and key safeguarding mechanisms in the smart grid	[39]
2021	Renewable energy integration	A broad review was carried out on the practice of AI in assimilating variable renewable energy resources with the power systems by reducing the integration costs	[40]

1.1. Problem Statement and Rationale of the Proposed Work

Although indexing databases such as Scopus, Web of Science (WOS), EndNote, etc., can provide analysis of bibliometric data to some extent, users need to subscribe in order to gain access. So, individual researchers cannot access the full functionalities of these databases without a proper license/subscription. Moreover, novice researchers may not have sufficient knowledge of what to search in these databases related to bibliometric data on a particular research area. Further, to the best of the authors' knowledge, this kind of comprehensive bibliometric analysis on smart grids with respect to identifying key concepts and research trends is not available in the literature. Thus, being an open-access article, this paper can be a one-stop solution that can be easily accessible to all researchers to systematically acquire the crucial information on smart grid literature.

1.2. Contribution of the Paper

The fundamental objective of this paper is to perform a comprehensive bibliometric analysis of smart grids, thereby highlighting key concepts and trends related to smart grid research. By doing this, this paper aims to provide all the key information required for novice smart grid researchers in one place. This includes emerging research areas and keywords, high-impact journals, most-cited publications, top authors and their collaborations, most-published affiliating institutions, most-cited countries, and annual production of various countries and their collaborations. This proposed work is carried out through a bibliometric analysis approach. It is a quantitative and systematic method used to measure and assess various aspects of scientific literature and derive valuable insights such as research impacts, identifying trends, appraising individual/institutional performance, etc., that greatly helps upcoming research studies.

Based on the above-mentioned objective of this paper and the literature given in Table 1, the desired outcomes are derived by framing suitable research questions (RQs) given as follows. These help in the synthesis of previous research findings by the researchers and in identifying further research advancements. The primary advantage of answering these RQs is that, from a vast amount of bibliometric data, it discovers influential studies, journals, authors, institutions, and countries in the examined area over a period of time.

1. RQ1: What are the important keywords relevant to smart grid research?
2. RQ2: Which keywords are mostly used and how do they co-occur with other keywords?
3. RQ3: What is the annual production of articles from 2017 to 2022?
4. RQ4: Which are the most relevant sources in smart grid research?
5. RQ5: Which authors have published the most relevant articles on this topic?
6. RQ6: Which are the most relevant and impactful affiliations?
7. RQ7: How many annual country-collaborated publications are present in terms of country, affiliation, and author?
8. RQ8: What is the country-wise scientific production in smart grid research?
9. RQ9: What are the most cited countries in smart grid research?
10. RQ10: Which countries conducted and collaborated on the most relevant studies on smart grids?
11. RQ11: What are the most cited global documents in smart grid research?
12. RQ12: Which keywords are mostly used and how they are related to other factors (authors, countries, etc.)?
13. RQ13: What are the themes identified from smart grid research?
14. RQ14: Which are the most popular topics explored and how they are related to other topics in different clusters?

The implementation of this analysis is carried out using the library "biblioshiny()" which is available under the bibliometrix package in R. The detailed steps involved in this bibliometric analysis are discussed in the methodology section. The other sections of the paper are ordered as follows: Section 2 designates the proposed methodology and its implementation, Section 3 presents the comprehensive results that are obtained through the conducted bibliometric analysis, and finally Section 4 summarizes the overall observations and provides the conclusions of this study.

2. Methodology

To better comprehend the importance of smart grids, a systematic literature review on smart grids was conducted in the Scopus and WOS databases utilizing the "preferred reporting items for systematic reviews and meta-analyses (PRISMA)" model as shown in Figure 1. For this, a search was undertaken using the keywords, viz. energy consumption readings, energy consumption data, power consumption data, power consumption readings, smart building data, smart meter data, smart meter readings, and smart home data.

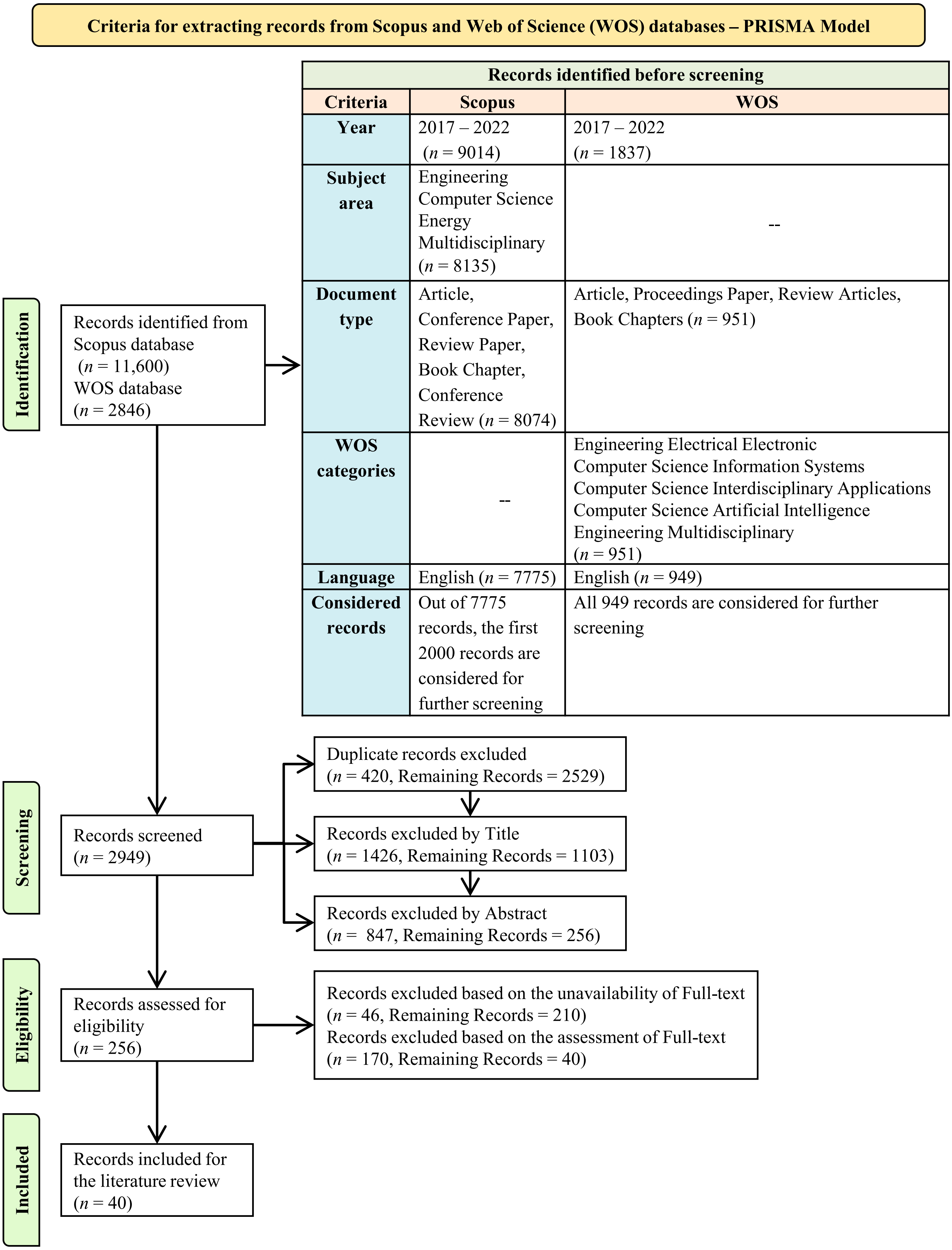

Figure 1. PRISMA model for extracting records from Scopus and WOS databases.

The search process for the proposed bibliometric analysis is given in Figure 2. Further, the detailed research steps and flow for extraction of records from the Scopus/WOS databases are shown in Figure 3. In the identification stage, the initial search extracted 11,600 and 2846 records from Scopus and WOS databases, respectively. Several criteria such as year, subject area, document type, WOS categories, source type, and language were considered for reducing the number of extracted records. The number of records extracted based on the considered criteria was 2000 out of 7775 from Scopus and 949 from WOS. These records were merged from both Scopus and WOS files [41].

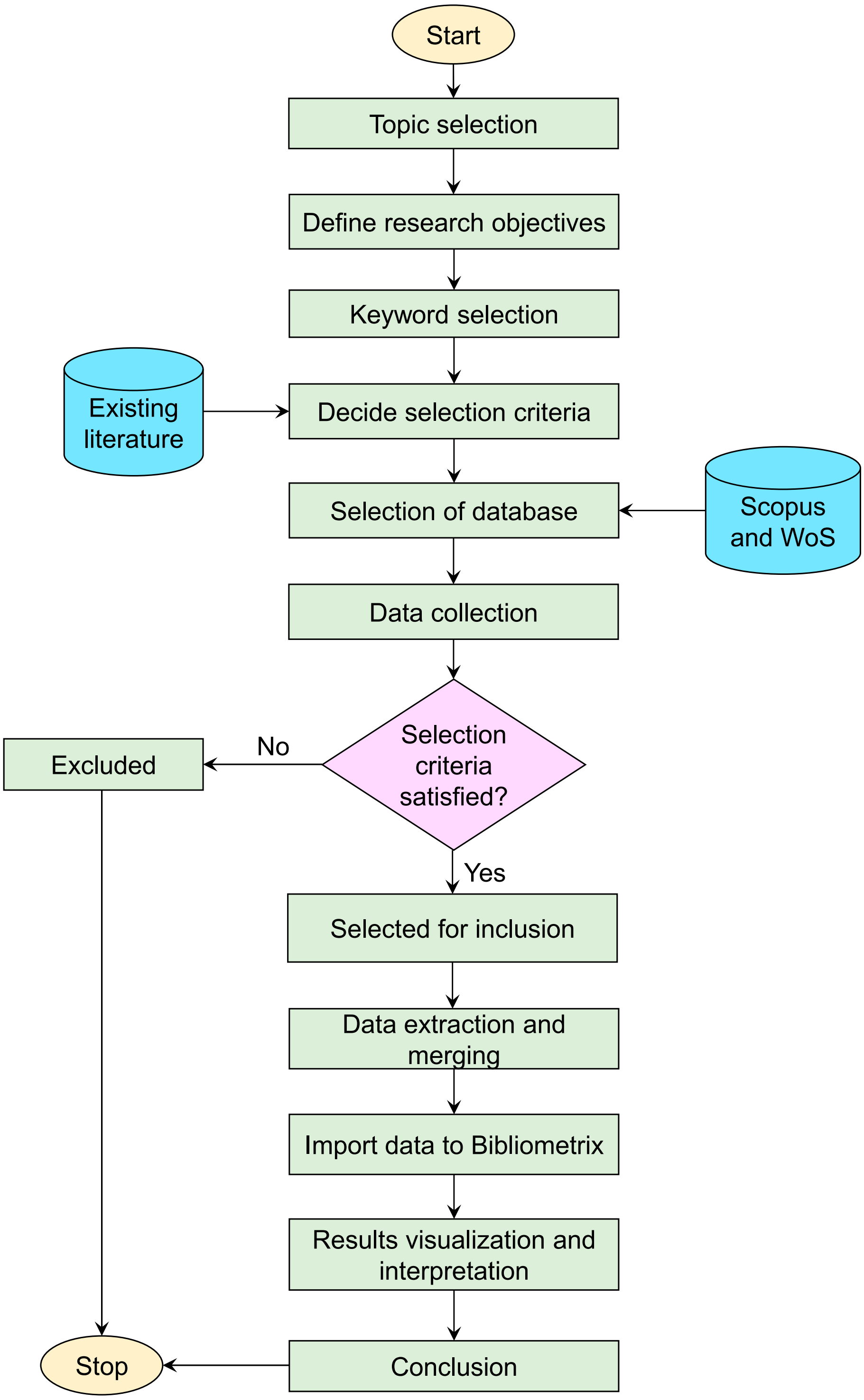

Figure 2. Research steps in the proposed bibliometric analysis.

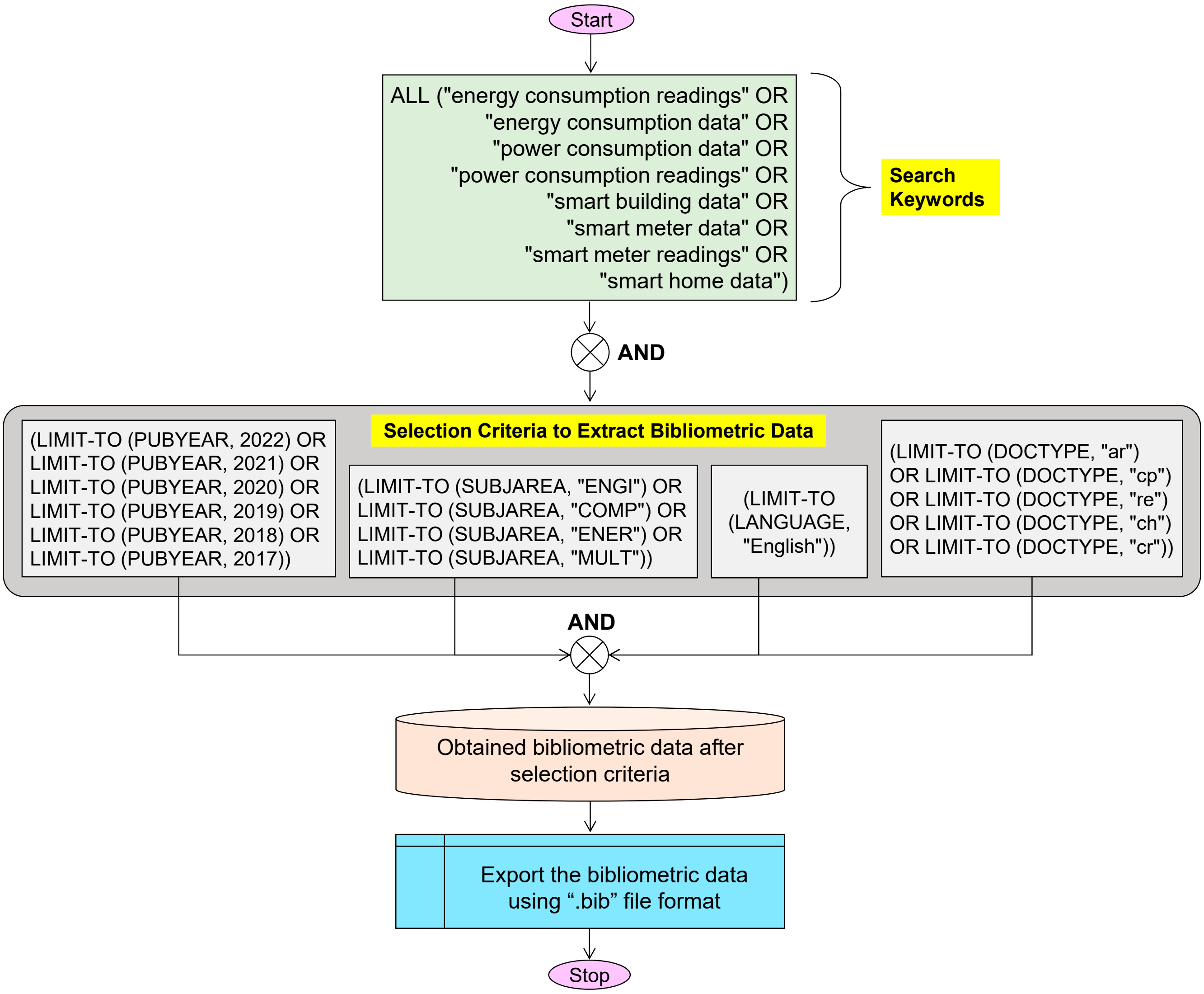

Figure 3. Proposed search process.

The records (2949) extracted in the identification stage were further scrutinized in the screening stage. During this screening, duplicate records are observed. Here, duplicate records refer to the articles recorded in one database that are also recorded in two or more databases. The duplicate records (420) were identified and excluded; this resulted in 2529 unique records.

After reading the titles, 1426 records were found to be irrelevant to the study and they were excluded. This resulted in 1103 records. After reading the abstract, 847 records were found to be irrelevant and they were excluded. This resulted in 256 records. Further, the eligibility of these 256 records was verified in the eligibility stage based on the availability and assessment of the full text. Out of 256 records, 46 records were found to have unavailability of full text and they were excluded. After scrutinizing the available full text, 170 records were found to be ineligible for the study and they were excluded. By following the above criteria, 40 records were eligible and included in the literature review.

Extraction of Topic-Wise Title Count from Merged Dataset

The extraction of topic-wise titles and their count is vital to understanding the importance of the topic in smart grid research. The process starts with the installation of the required packages (readxl, stringr) and the loading of the respective libraries. After this, the reading of the merged dataset (records included from Scopus and WOS) is executed and it is saved into an object. Then the columns in the dataset are observed and the titles column is selected for extracting the titles by using string-matching. The extracted titles are saved into a CSV file for further processing. Finally, the count of topic-wise titles is retrieved and printed. The complete steps of this extraction process are given in Table 2.

Table 2. Extraction process for finding the topic-wise title count from the merged dataset.

Extraction Process Steps
1. Install essential packages (readxl, stringr) and load the libraries to read the Excel file and perform string-matching
2. Read the merged dataset that contains records from both Scopus and Web of Science and store them in "object name" using *object name ← read_excel ("path of the excel file")*
3. Read the column names from the "object name" using *colnames (object name)*
4. Extract the titles from the "object name" based on the string-matching and save them in the object "titles". This is performed using *titles ← object name %>%* *filter (str_detect (column name of the title, "title name to be matched ǀ title name to be matched ǀ . . . . ǀ title name to be matched"))*
5. Store the details of extracted titles in a CSV file using *write_csv (titles, "path of the file name to be saved")*
6. Calculate the count of titles and store it in the object "count of titles" using *count of titles ← nrow (titles)*
7. Print the object "count of titles" for the count using *print (count of titles)*

3. Results and Discussions

The word cloud of the keywords used in literary works is shown in Figure 4. From this figure, it is evident that the keywords "smart grid", "machine learning", "smart meter", "deep learning", "smart meters", and "energy consumption" are very frequently used in the smart grid research work (RQ1). Because the size of the appearance denotes how frequently these keywords are used, if the size of the keyword is big then it represents that the keyword is frequent, and if the size of the keyword is small then it represents the little usage of that keyword.

The co-occurrence network of the keywords is shown in Figure 5. From this, the impact of the keywords and their co-occurrence with the other keywords can be understood. It is observed that there is a strong connection between the keywords "smart grid" and "smart meter". There is another keyword named "machine learning", which has a high impact similar to the keyword "smart grid". It can also be noticed that the keywords "deep learning", "energy consumption", etc., have co-occurrence with the keywords "smart grid" and "smart meter" (RQ2). The annual scientific production of the works on the smart grids has increased year by year as shown in Figure 6. From this, it is evident that from the years 2017 to 2022, there is a gradual increment in the production of articles. However, from the year 2021, there is a drastic change in the annual production, and the highest production of articles (1150) is observed in the year 2021 and the next highest production of articles (925) is in 2022 (RQ3).

The top 10 journals that have published research works on smart grids are shown in Figure 7. From this, it is observed that the journal *Energies* is in the top place with 132 documents. The journal *IEEE Transactions on Smart Grid* is in second place with 102 documents published on smart grid research work (RQ4).

The top 10 most relevant authors that have the highest number of documents on smart grid research work are identified and presented in Figure 8. From this, it is evident that

Wang Y has published 52 documents (RQ5). The top 10 affiliations that have published research works on smart grids are shown in Figure 9. From this, it is revealed that Tsinghua University has published the highest number of articles (57) on smart grid research work. The North China Electric Power University is in second place with 44 articles published on smart grid research work (RQ6).

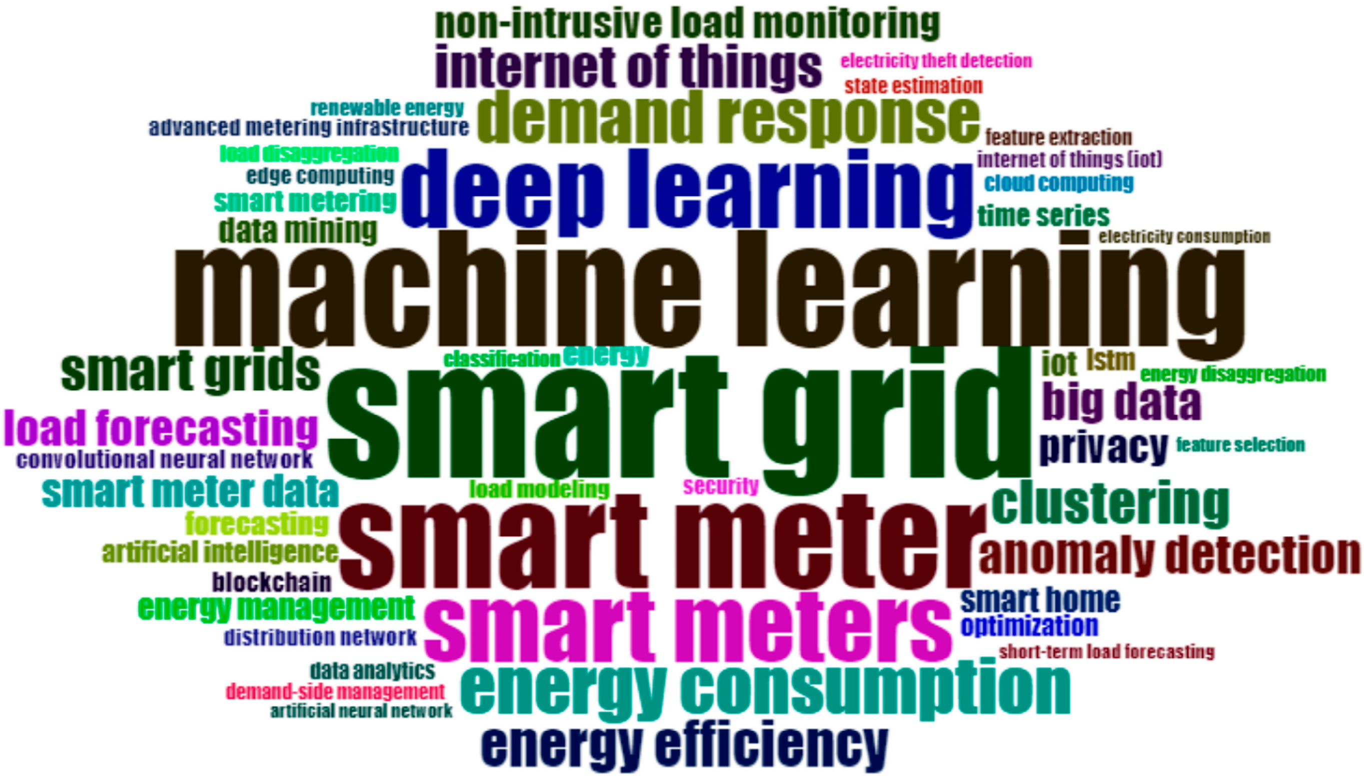

Figure 4. Important keywords related to smart grid research.

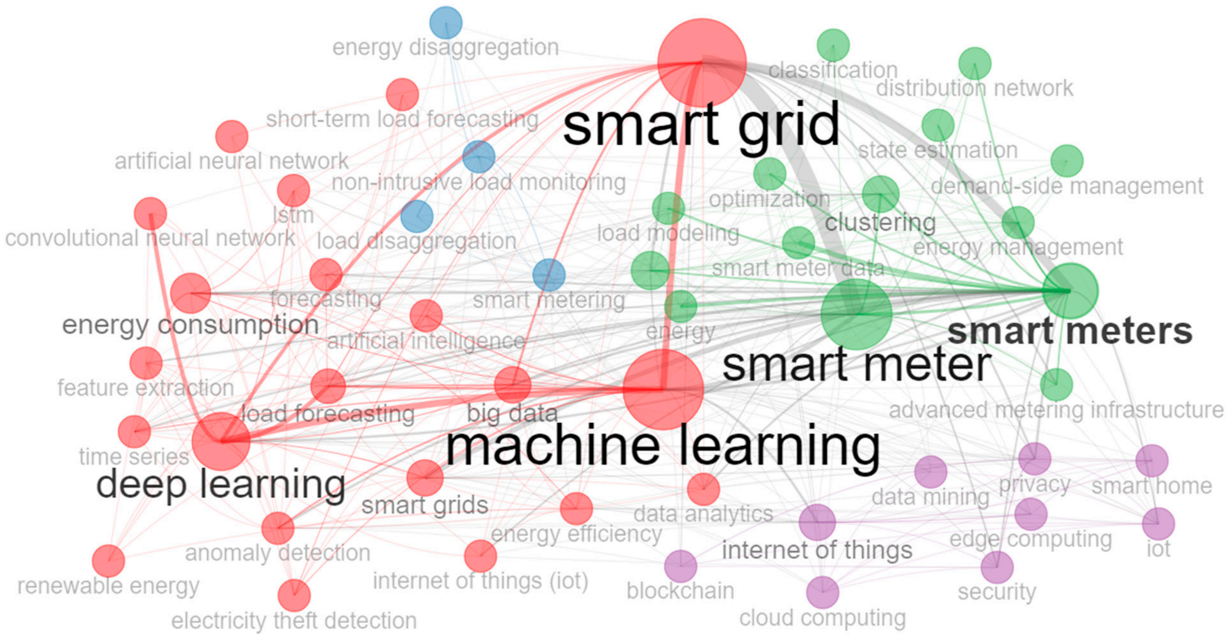

Figure 5. Keyword co-occurrence network.

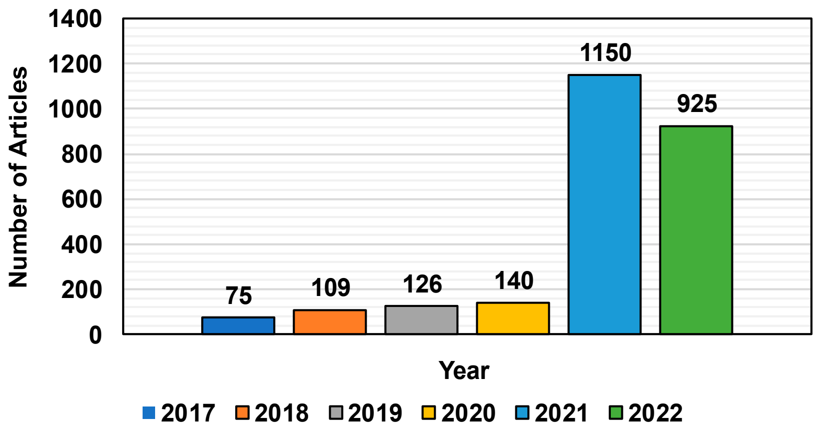

Figure 6. Annual production of articles from 2017 to 2022.

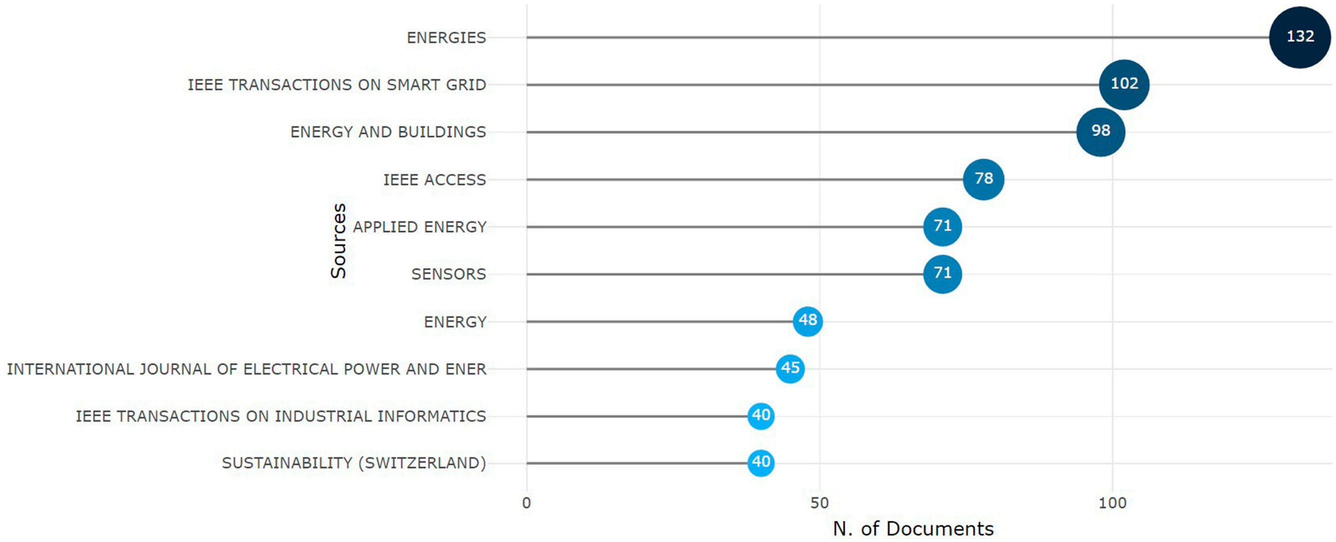

Figure 7. Most relevant sources in smart grid research.

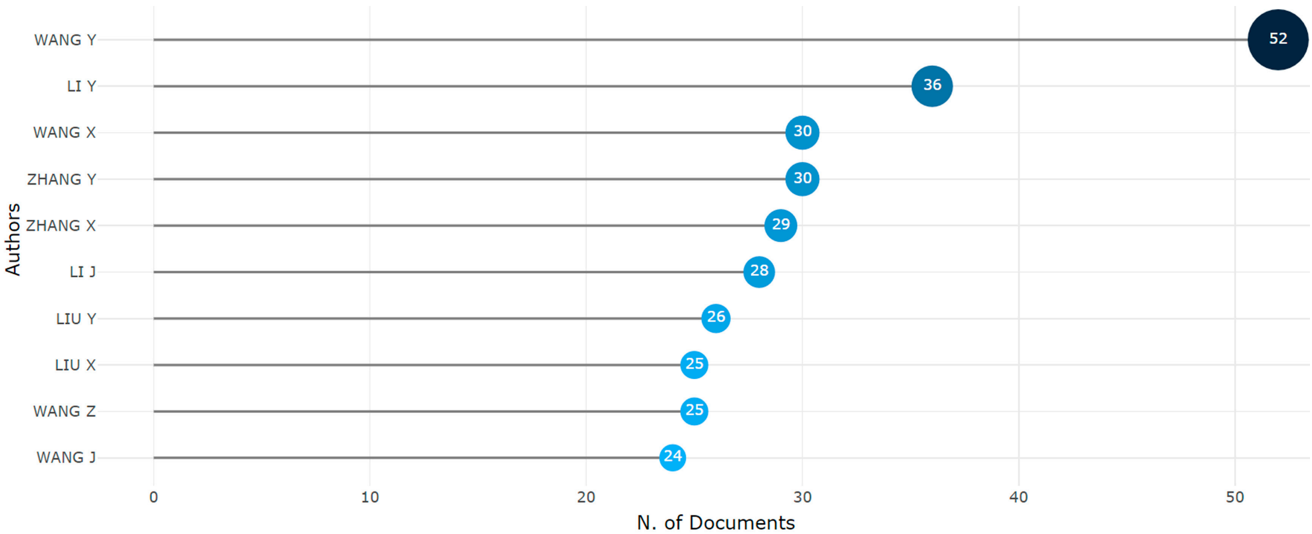

Figure 8. Most relevant authors in smart grid research.

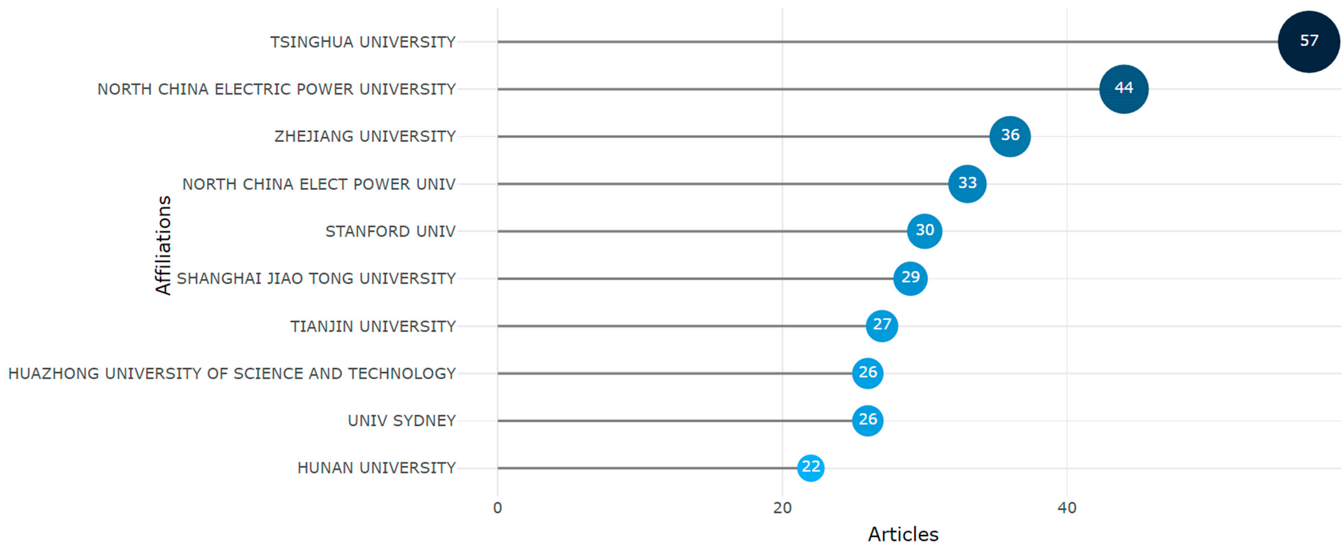

Figure 9. Most relevant affiliations in smart grid research.

The distributions of annual collaborated publications from the viewpoints of country, affiliation, and author are presented in Figure 10. The top nine countries were selected for collaboration analysis. This analysis reveals that the highest number of single-country publications and the highest number of multiple-country collaborative publications on smart grids are from China. The second-highest number of single-country publications are from the USA. The second-highest number of multiple-country collaborative publications are from the United Kingdom (RQ7).

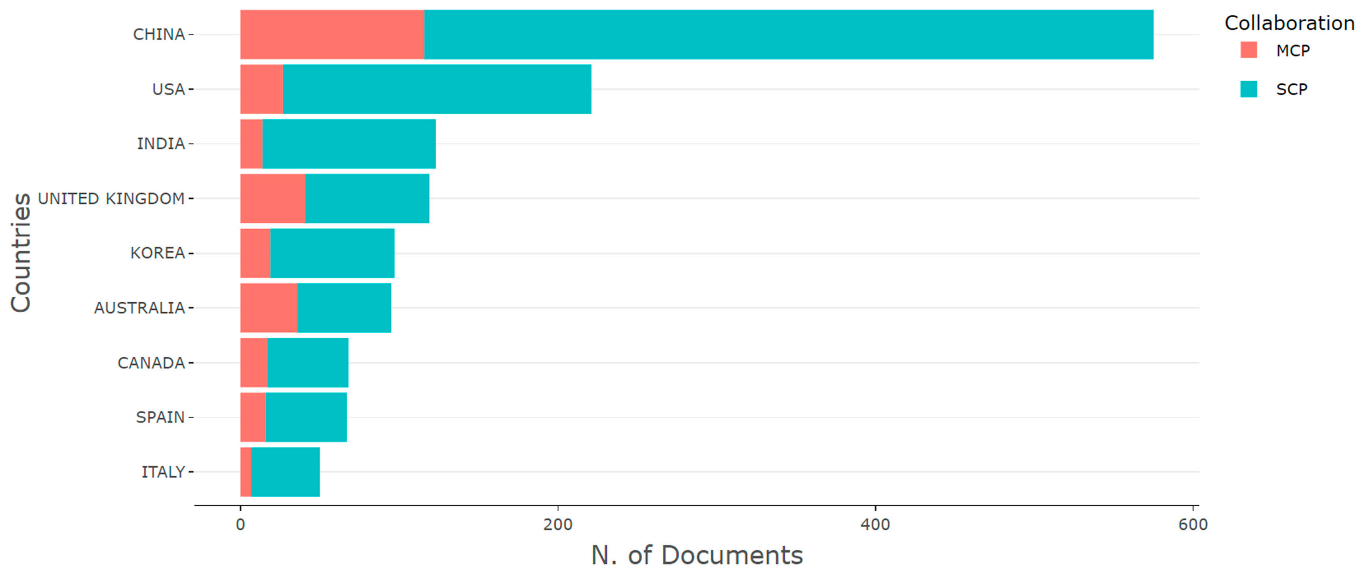

Figure 10. Corresponding author countries (multiple-country and single-country publications) in smart grid research.

The country-wise scientific production of the research articles on smart grids is presented in Figure 11. The top 10 countries are included in the figure. From this tree plot, it is confirmed that China has the highest production of research articles (1423). The second highest number of research articles is produced by the USA (RQ8). The box that has a larger area represents the highest production of the research articles and the box that has a smaller area represents the least production of the research articles on smart grids.

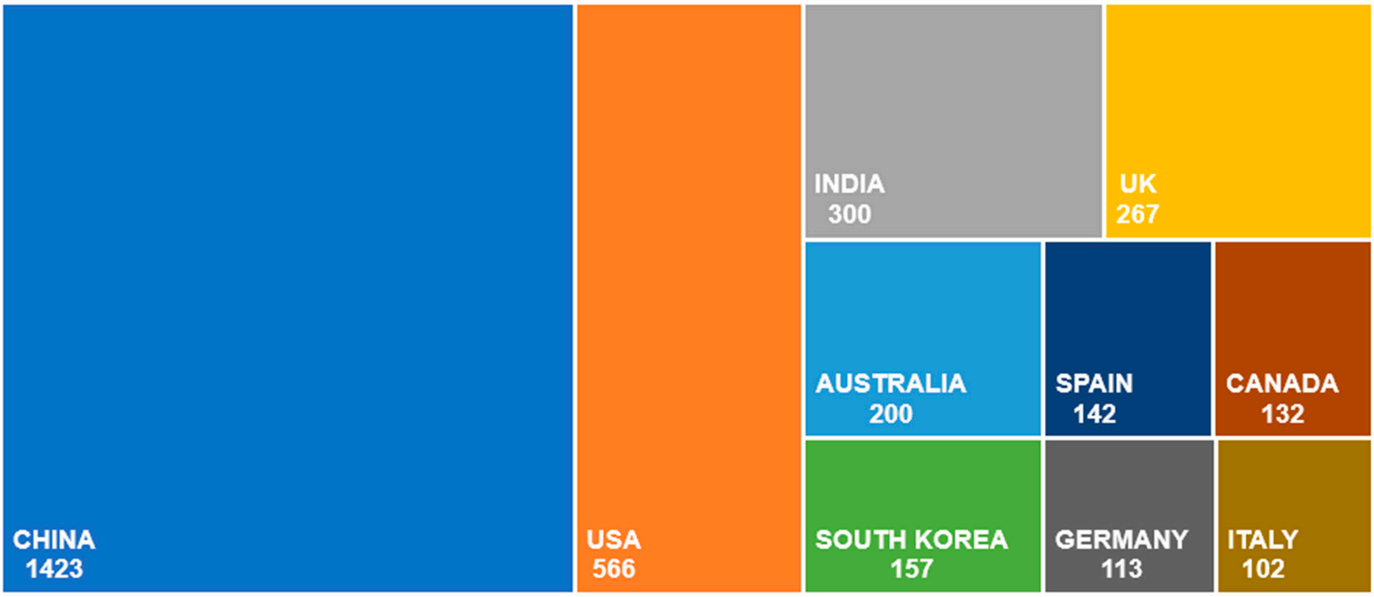

Figure 11. Country-wise scientific production in smart grid research.

The top 10 countries that have the most cited research articles are presented in Figure 12. In this figure, the citation count is on the x-axis and the countries' details are on the y-axis. Further, it is noticed that China has the highest number of citations (3020) among all countries producing smart grid research work. Australia is the second country that has the highest number of citations after China (RQ9).

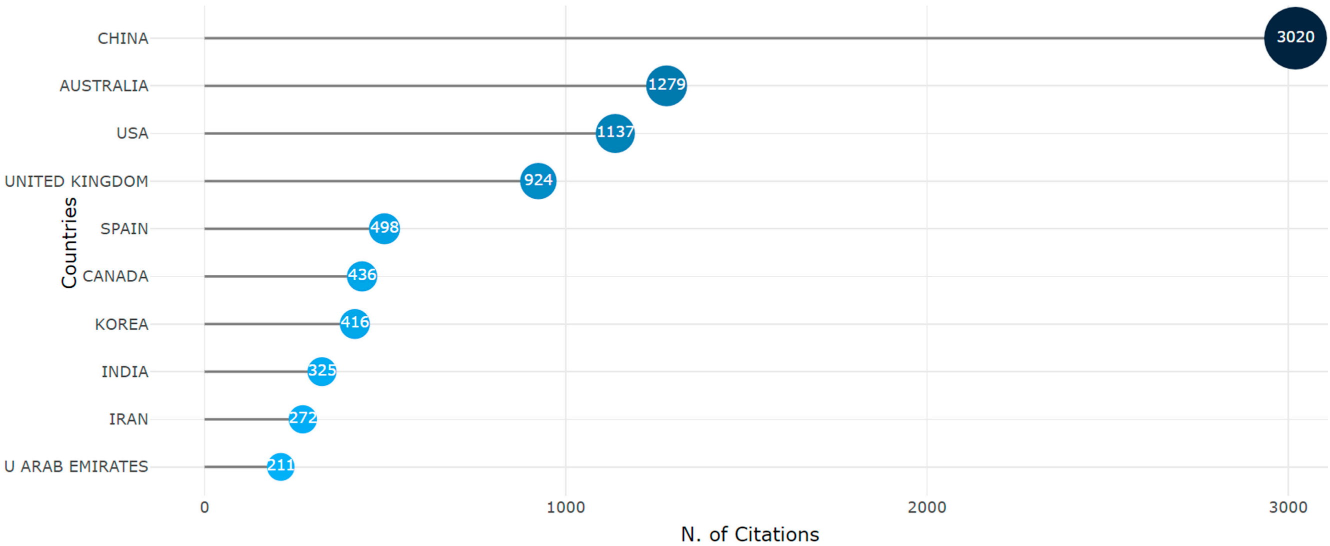

Figure 12. Most cited countries in smart grid research.

A network analysis of the countries that have collaborated to do research on smart grid areas is shown in Figure 13. The majority of research collaboration comes from China with various countries. It is also observed that some countries such as India have very little collaboration on smart grid research (RQ10).

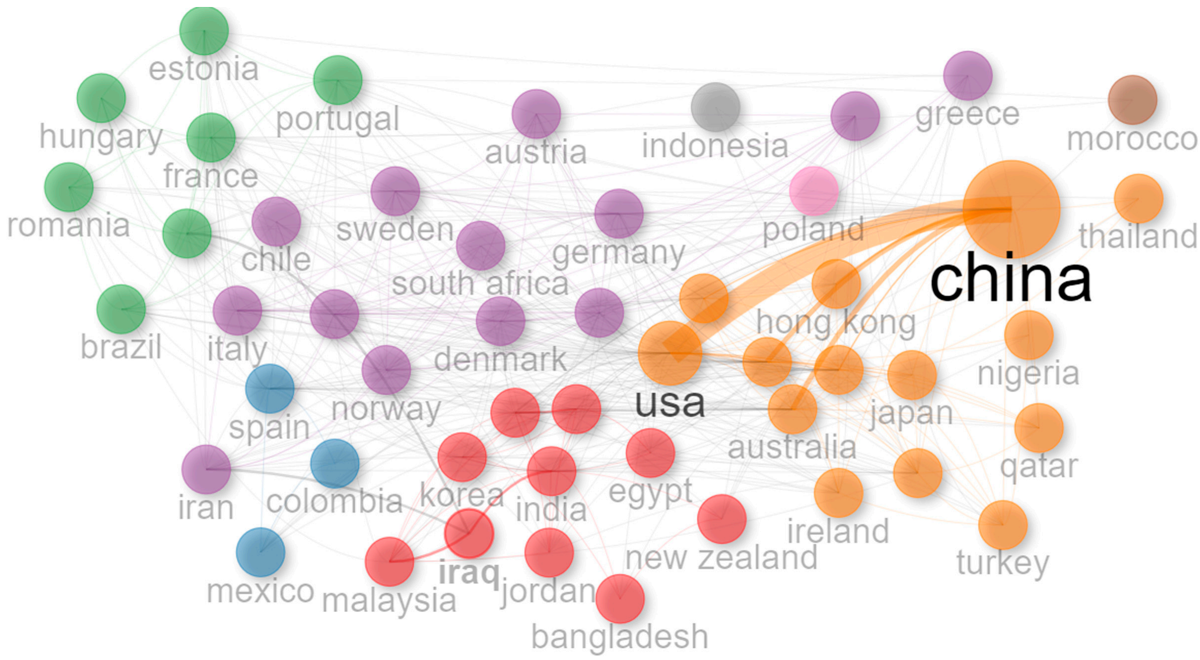

Figure 13. Country collaboration network in smart grid research.

The top 10 documents that have the highest global citations on the research work related to smart grids are shown in Figure 14. From this, it is revealed that the documents from Tsinghua University published by *IEEE Transactions on Smart Grid* make up the highest number of most-cited articles (57) on smart grid research work. North China Electric Power University is in the second position with 44 articles published on smart grid research work (RQ11).

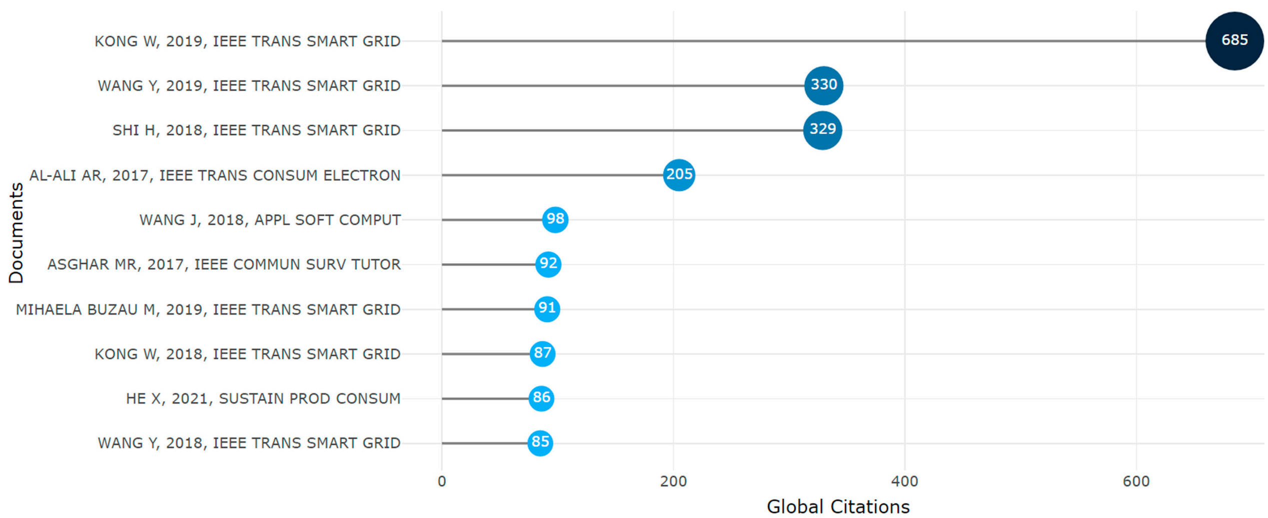

Figure 14. Most cited global documents in smart grid-related research.

The research in smart grid literature on the relation between author (left), author country (middle), and author keyword (right) is shown in Figure 15. The analysis established which smart grid-related keywords have been used most frequently by different authors from different countries. The study of the top authors, countries, and keywords indicated that there are keywords, i.e., "smart grid", "machine learning", "smart meter(s)", "deep learning", "energy consumption" and "energy efficiency", and the authors Wang Y., Zhang X., Li Y., Li J., Wang X., et al., mainly used these keywords, and published their articles in the countries China, USA, and India (RQ12).

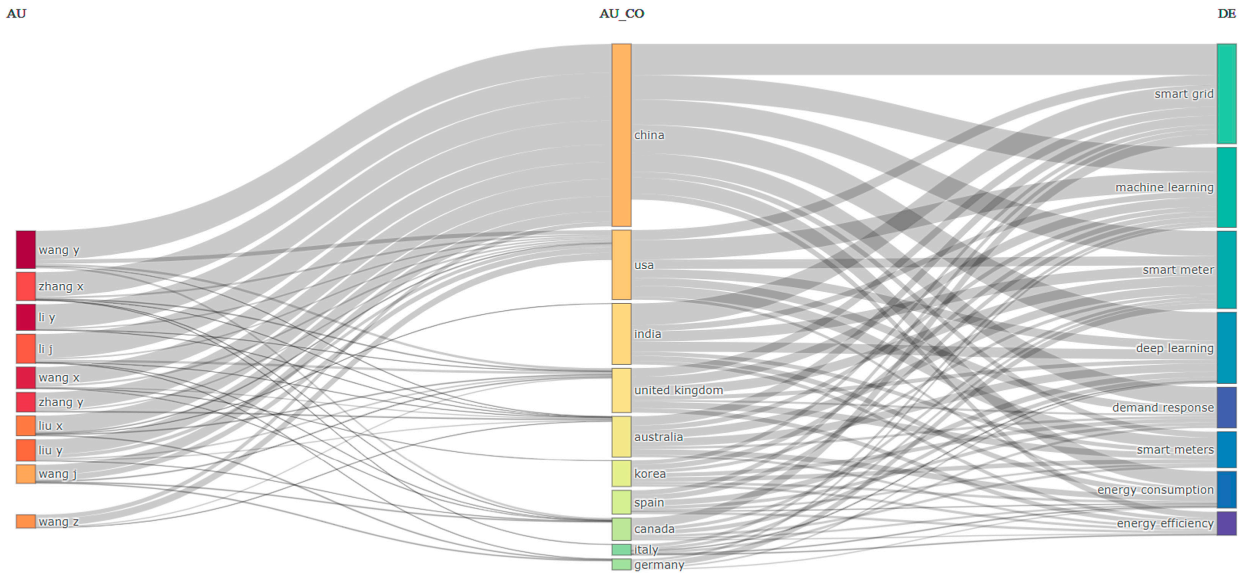

Figure 15. Relation between author, country, and keyword.

Based on Callon's two measures—centrality and density—research themes are mapped with four quadrants called niche themes, motor themes, basic themes, and emerging or declining themes as shown in Figure 16. From this, it is identified that the motor themes (upper-right) quadrant includes themes such as smart grid, smart meter(s), demand response, and clustering. These themes are well developed and vital in the smart grid research field. Themes in the niche (upper-left) quadrant are COVID-19, simulation, climate change, cluster analysis, and residential buildings, and are of marginal importance. Themes in the lower-left quadrant are emerging or declining themes. Further, it is evident that themes such as deep learning, energy consumption, non-intrusive load monitoring, smart metering, and time series are emerging themes in this field. In the lower-right quadrant, machine learning, energy efficiency, the Internet of Things, anomaly detection, and big data are identified as basic themes in the smart grid research area (RQ13).

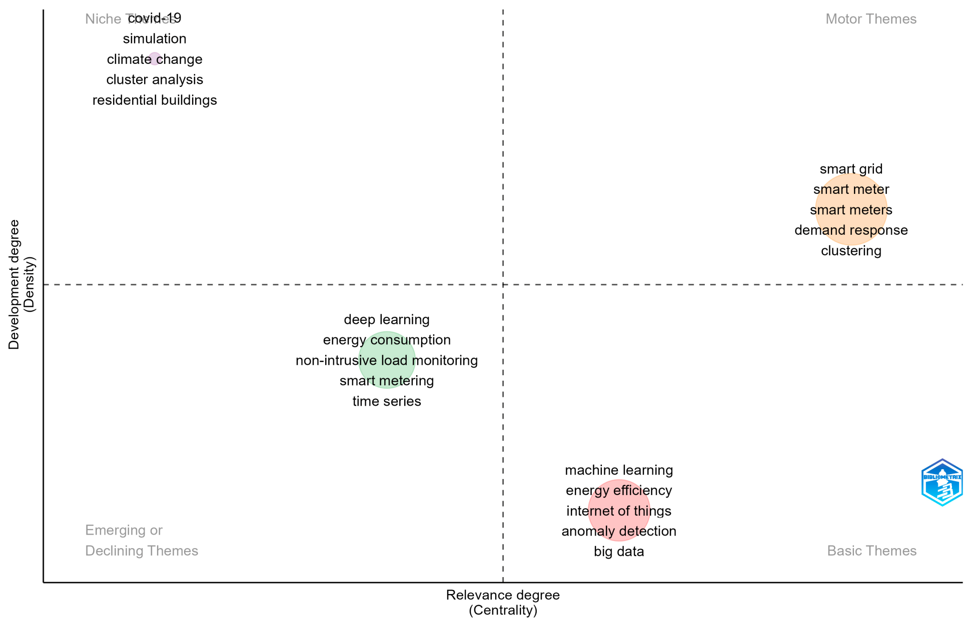

Figure 16. Themes in smart grid research.

The factor analysis, in other words the topic dendrogram, is shown in Figure 17. In this figure, twenty topics are considered and all the topics are clustered with the appropriate topic. These clusters show the relativeness between the topics, which is useful for understanding the topic's importance and collaboration (RQ14). The data points of the topics can be seen on the x-axis to make the clusters, and the distance between clusters can be seen on the y-axis. The point to be noted concerning the factorial analysis is that the number of topics can be increased as per the requirement, but here a few topics are demonstrated for understanding purposes.

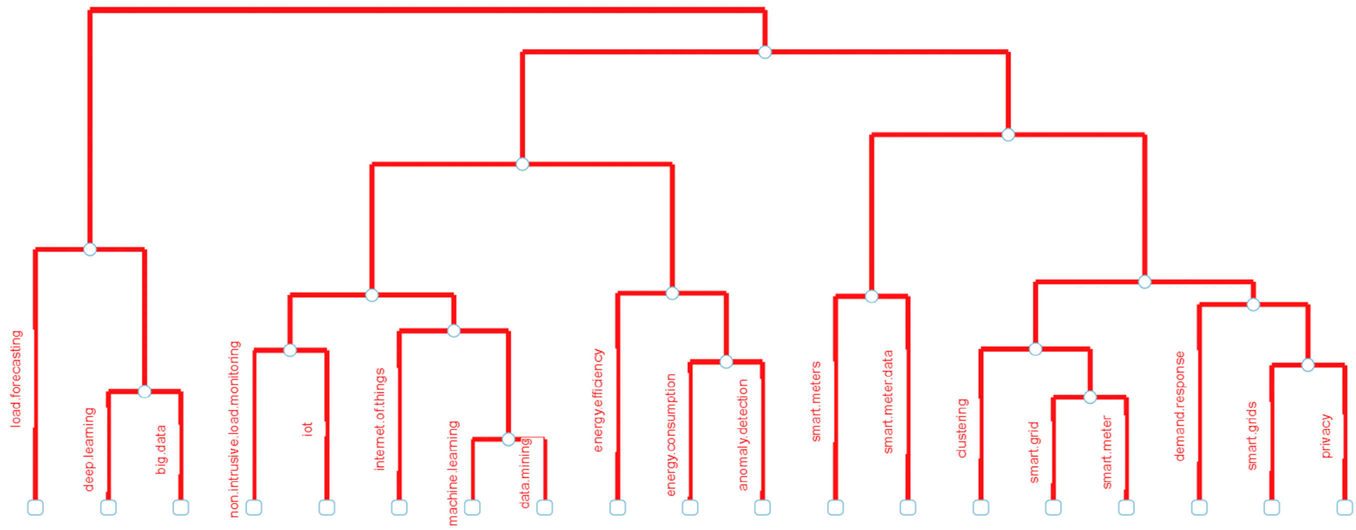

Figure 17. Clustering of relevant topics.

The topic-wise title count is given in Table 3. From this table, it is perceived that the highest count (190) is identified with the keyword "Energy Consumption" and the next highest count (107) is identified with the keywords "Smart Meter Readings | Smart Meter Data" in the titles. Further, the total of topic-wise titles with various keywords is identified as 828 in the considered bibliometric data.

Table 3. Topic-wise titles count.

Topics	Titles Count
Energy Consumption Readings | Energy Consumption Data	26
Power Consumption Readings | Power Consumption Data	12
Smart Meter Readings | Smart Meter Data	107
Smart Home Data	10
Smart Building Data	1
Smart Grid Data	4
Big Data | Data Analytics | Big Data Analytics | Data Analysis	69
Machine Learning	92
Data Issues | Data Anomalies | Abnormal | Abnormalities | Abnormal Behavior | Abnormal Behavior	19
Energy Consumption Behavior | Energy Consumption Behavior | Consumer Behavior | Customer Behavior | Consumer Behavior | Customer Behavior	1
Energy Consumption	190
Forecasting Energy Consumption	2
Energy Sharing | Energy-Sharing	1
Appliance Scheduling	1
Load Scheduling	4
Load Forecasting	106
Load Profiling	5
Internet of Things | IoT | IoT	48
Non-Intrusive Load Monitoring | NILM	42

Table 3. *Cont.*

Topics	Titles Count
Smart Home Technologies	1
Communication	31
Electricity Theft	39
Renewable Energy	17
Total Count	828

4. Conclusions

The presented comprehensive bibliometric analysis has provided key information that is beneficial for future researchers of the smart grid domain. From the results and analysis, it is found that all the RQs are successfully solved and obtained precise results. The summary of these key findings in various aspects is given as follows.

- Various themes/topics namely smart meter(s), demand response, clustering, residential buildings, machine learning, energy efficiency, Internet of Things, anomaly detection, big-data analytics, deep learning, energy consumption, and non-intrusive load monitoring are identified as key topics in smart grids research. It is also found that there is a strong connection between the keywords "smart grid", "smart meter", and "machine learning". This implies that the selection of research topics as a combination of these keywords can lead to successful work. Further, the highest topic-wise title count (190) is identified with the keyword "energy consumption" and the next highest count (107) is identified with the keywords "smart meter readings" and "smart meter data" in the titles.
- There is a gradual increment in the production of articles from 2017 to 2022. However, from the year 2021, there is a drastic change in the annual production with the highest production of articles (1150) found in the year 2021 and the next highest production of articles (925) found in 2022. This showcases the recent growing importance of smart grid research. Further, most of these research works are published in journals namely *Energies* and *IEEE Transactions on Smart Grid* with the numbers of documents being 132 and 102, respectively.
- The most relevant authors identified from the analysis are Wang Y and Li Y. Similarly, the affiliations "Tsinghua University" and "North China Electric Power University" are identified as the most impactful affiliations with the number of articles 57 and 44, respectively.
- This analysis reveals that China and the USA have occupied the top two positions with the production of articles, the numbers being 1423 and 566, respectively. Moreover, the highest number of single-country publications and the highest number of multiple-country collaborative publications on smart grids are from China. The second-highest number of single-country publications are from the USA. The second-highest number of multiple-country collaborative publications are from the United Kingdom. Moreover, the top two positions concerned with having the most citations are occupied by China (3020) and Australia (1279), respectively.

Thus, in summary, conducting bibliometric analysis on smart grids provides a systematic and data-driven approach to understanding the current state of research, and identifying key concepts and research trends. It plays a crucial role in advancing knowledge, guiding research efforts, and supporting evidence-based decision-making in the field of smart grids.

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