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Blockchain in Smart Grids: A Bibliometric Analysis and Scientific Mapping Study

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Abstract: To achieve sustainability and fulfill sustainable development goals, the digitalization of the power sector is vital. This study aims to examine how blockchain can be integrated into and enrich smart grids. In total, 10 research questions are explored. Scopus and Web of Science (WoS) were used to identify documents related to the topic. The study involves the analysis of 1041 scientific documents over the period 2015–2022. The related studies are analyzed from different dimensions including descriptive statistics, identification of the most common keywords and most widely used outlets, examination of the annual scientific production, the analysis of the most impactful and productive authors, countries, and affiliations. The advancement of the research focus and the most popular topics are also examined. Additionally, the results are analyzed, the main findings are discussed, open issues and challenges are presented, and suggestions for new research directions are provided. Based on the results, it was evident that blockchain plays a vital role in securing smart grids and realizing power sector digitalization, as well as in achieving sustainability and successfully meeting sustainable development goals.

Keywords: blockchain; smart grid; power grid; power sector; sustainability; renewable energy resources; sustainable development goals; SDG; energy; review

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1. Introduction

The application of renewable energy resources, the drastic technological advancements, the constantly increasing electrical energy demands, and the growing power infrastructure intricacy have rendered the reliability and stability of power systems more difficult to ensure [1–3]. Additionally, as the number of interconnected devices increase, it is harder to effectively manage them in a centralized grid system [4] which, in turn, leads to availability, confidentiality, integrity, and accountability issues [5,6]. These facts, in combination with the global energy consumption and demand increase, have led to worldwide concerns about energy sustainability and environmental preservation [1,7]. Hence, the need for the modernization of the existing power sector and for new approaches to more effectively produce, manage, distribute, and consume energy while being more eco-friendly, sustainable, secure, and reliable is increasing [8–12].

Existing power grids support a unidirectional power flow and one-way communication between centralized generators and consumers using an interconnected and large-scale network [13,14] and manage power generation, transmission, distribution, and control through an electromechanical hierarchical structure [15,16]. While information and communication technologies (ICT) are presently employed in current power grids to more efficiently process energy from various sources and make them greener to achieve a more sustainable and eco-friendly society [7,17,18], there is a clear need for more decentralized, intelligent, and autonomous smart grids to be adopted and integrated in the power sector to address the demands of modern society [4,19,20].

In an attempt to enhance sustainability, traditional power grids are being transformed into smart grids, which incorporate information and communication technology to integrate renewable resources and green energy more effectively and to ensure the provision of energy at any place and time through a decentralized network, in order to create an eco-friendlier and more effective intelligent grid [4,21]. Despite the fact that there are various definitions of smart grids in the literature, they all share some common aspects and elements. More specifically, smart grids are a future vision towards a more sustainable energy infrastructure that uses power grids which give priority to adaptability, efficiency, resilience, cleanliness, and eco-friendliness and are supported by intelligent systems to actively, autonomously, and pervasively manage, control, and monitor resources and systems [15,20,22–26]. These self-sufficient systems [27] utilize heterogeneous data and a variety of data sources [28], focus on both consumers and prosumers [1], capitalize on renewable resources [7], enable a more effective delivery of energy and exchange of information [22,24,29], and operate in a more responsive, organic, and collaborative manner [7]. Thus, smart grids can enhance energy production, transmission, distribution, management, and consumption [30–32] and improve the effectiveness, performance, security, reliability, and availability of the power sector [33,34]. Realizing smart grids necessitates the employment and integration of distributed, interoperable, and automated systems within the energy network that leverage computational intelligence, environmental status and changes, and data to autonomously make decisions, monitor, adjust, and self-heal in real time [15,16,26,30,35,36]. Table 1 compares and summarizes the characteristics of conventional power grids and smart grids.

Table 1. Summary and comparison of the characteristics of smart grids and conventional power grids adapted from [7,11,37,38].

Smart Grids/Intelligent Grids	Traditional Power Grids/Conventional Power Grids
Digitized/Digitalization	Mechanically operated/Mechanization
Distributed power generation	Centralized power generation
Two-way real time communication/Bi-directional	One-way communication/Unilateral
Many sensors throughout	Small number of sensors
Dispersed network/Dispersed connected	Radial network/Radially connected
Fast response to actions and emergencies	Slow response to actions and emergencies
Automated recovery	Manual recovery
Automated control/Pervasive control	Manual control/Limited control
Many monitoring capabilities/Highly automatic monitoring	Fewer monitoring capabilities/Manual monitoring
More prone to security and privacy issues and concerns	Fewer security and privacy issues and concerns
Flexible and adaptive	Inflexible and static
High data use	Less data use
Many user choices	Fewer user choices

The power sector is a complex system in which several technological applications are used. Artificial intelligence [17] and the Internet of Things (IoT) [39] are two of the enabling technologies for smart energy grids which can offer solution in various domains. However, there are several security issues and challenges that must be addressed in the power network. To ensure the effectiveness of the network, it is essential to secure its processes and transactions throughout its value chain. Blockchain constitutes a novel technology which can be applied in and transform various domains [40]. Blockchain technology can greatly enhance the digitalization of the power sector and contribute to the improvement of smart grids [41]. Blockchain is an immutable and distributed digital ledger technology which enables decentralized transactions to occur in a secure, tamper-proof, traceable, and transparent way without requiring any intermediaries [42,43]. Instead, the transactions, which are stored in a chain of interconnected blocks using digital signatures and cryptographic means, are verified and validated by the distributed and decentralized network [44–46]. Hence, decentralization, anonymity, transparency, auditability, immutability, and persistence can be mentioned as the main characteristics and features of blockchain technology [42,46,47]. In the context of energy transactions, smart contracts are a use case in which blockchain can offer significant benefits, such as transparent, secure, and immutable energy transactions [48–50]. Besides the adoption of blockchain technology, it is important to adopt and apply appropriate energy trading strategies, approaches, and platforms [51–53]. As the power sector and especially smart grids become more advanced and complex, it is becoming clear that blockchain can play a crucial role in overcoming the limitations of the conventional power production and distribution infrastructure [54].

Even though the studies regarding using blockchain in smart grids are constantly increasing, there has been no study that explores how the specific topic has formed and evolved throughout the years. Therefore, to bridge the gap in the existing literature, this study aims to examine the role of blockchain in smart grids, how its employment and integration have developed, and what the main research areas and directions on the topic have been throughout the years using a bibliometric analysis and scientific mapping analysis. To aid the study, the following research questions (RQ) were set to be explored:

- RQ1: What descriptive statistics characterize the studies of the collection?
- RQ2: How are the studies characterized in terms of their scientific production?
- RQ3: Which outlets are most commonly used and are the most impactful?
- RQ4: Which authors have been the most prolific and impactful contributors to this topic?
- RQ5: Which affiliations stand out as the most impactful and relevant ones on this topic?
- RQ6: Which countries have carried out the most impactful and pertinent studies?
- RQ7: Which documents have been the most impactful ones on the development of this topic?
- RQ8: Which are the most common keywords and how are they connected to other factors?
- RQ9: Which were the most popular topics and themes examined in the literature?
- RQ10: How has the primary research focus on the topic evolved throughout the years?

2. Method

As this study analyzes the evolution of a certain topic in the literature, a bibliometric analysis and scientific mapping study was selected as the research methodology [55]. Hence, as this is a bibliometric analysis study, the instructions, guidelines, and techniques described in [56] were followed and the methodological approach presented in [57] was adopted. Particularly, a topic query was used to identify and retrieve documents related to the topic. Although there are several scientific databases, Scopus and Web of Science (WoS) were selected, due to them meeting the essential requirements to be used in a bibliometric and scientific mapping study [56,58], as well as due to their high relevancy, accuracy, and impact [59,60]. Another reason for opting for these databases was their ability to be used in combination in "Bibliometrix", which is an open-source R package for bibliometric analysis [57] and was the main tool used in this study to analyze and visualize the data. It is worth noting that all types of documents were searched from all available categories throughout the years. The topic query that was used to search the Scopus and WoS databases was: ("blockchain" OR "block-chain") AND ("smart grid" OR "intelligent grid" OR "smart power grid" OR "intelligent power grid" OR "smart electric* grid" OR "intelligent electric grid*"). From Scopus, 982 related documents were retrieved, while, from WoS, 606 documents were identified. After removing the duplicate documents (547), in total 1041 scientific documents remained and were included in the bibliometric and scientific mapping analysis. The resulting analysis and visualization are separated into the following subsections:

- Main information;
- Citations;
- Sources;
- Authors;
- Countries;
- Documents.

Tables, figures, and diagrams are used to present the results. The research process is depicted in Figure 1. In particular, as the first step, the topic, keywords, and databases were selected, as the second step, the related documents were identified and retrieved, the data were exported and pre-processed, and finally imported to Bibliometrix. The third step involved the bibliometric analysis and scientific mapping of the collection of documents on this topic and the fourth step consisted of the analysis of the results and the formulation of conclusions.

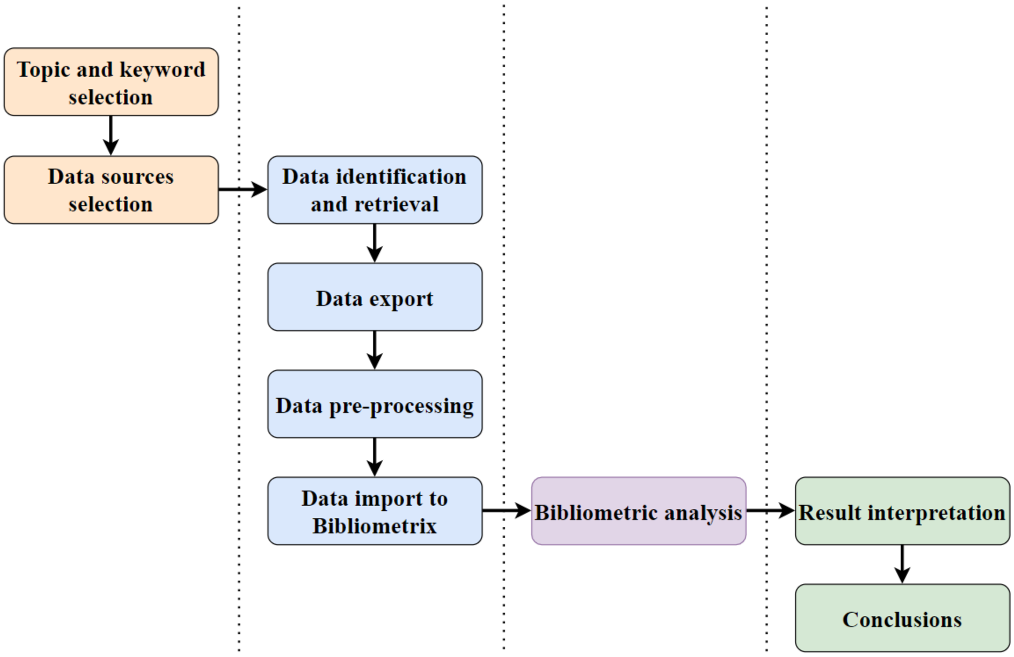


Figure 1. Research process.

3. Result Analysis

This section presents and goes over the results of the bibliometric and scientific mapping analysis. Particularly, it showcases the main information and the analysis of citations, sources, authors, countries, and documents.

3.1. Main Information

The articles contained in this collection were published from 2015 to 2022. Although no date limitation was set, the most recent related article was published in 2015. A total of 2672 authors, from 53 countries and from 1289 affiliations, contributed 1041 scientific documents in 519 scientific outlets to examine the role and use of blockchain within smart grids. The documents have an average age of 2.51 years, an average citation of 18.75 per document, and a significant positive annual growth rate of 127.97%. Throughout the scientific documents, 35,460 different references are used. There are 119 single authored documents and on average 3.95 authors collaborate in each one. Despite this fact, the international collaboration rate is really low (2.79%). The majority of scientific documents were published as conference papers (424), followed by journal articles (383). Table 2 displays the main information of the documents, including each item description and its corresponding result (RQ1).

Table 2. Main information.

Description	Results	Description	Results	Description	Results
Timespan	2015:2022	AUTHORS		DOCUMENT TYPES	
Sources (journals, books, etc.)	519	Authors	2672	article	383
Documents	1041	Authors of single-authored docs	37	article; book chapter	1

Table 2. *Cont.*

Description	Results	Description	Results	Description	Results
Annual growth rate %	127.97	AUTHORS COLLABORATION		article; early access	3
Document average age	2.51	Single-authored docs	119	book	4
Average citations per doc	18.75	Co-authors per doc	3.95	book chapter	50
References	35,460	International co-authorships %	2.786	conference paper	424
DOCUMENT CONTENTS				conference review	81
Keywords plus (ID)	4032			editorial	2
Author's keywords (DE)	1967			editorial material	1
				proceedings paper	17
				retracted	1
				review	73
				short survey	1

3.2. Citations

The significance of this topic and the need for a bibliometric study can be further justified based on the age of the current documents, as well as the extremely large positive annual growth rate which leads to the annual increase in the publication of related documents. Hence, as expected, most documents were published in 2021 and 2022. Figure 2 presents the annual scientific production of the related documents. Based on the results, the annual scientific production and the number of published documents on this topic is constantly increasing. Along with the increasing publication of related studies, the average number of citations that the documents of this collection received is high and increasing. Figure 3 displays the average document citations per year. According to the findings, documents that were published in 2017 and 2018 have the largest number of citations, although it is worth mentioning that most of the documents have been published in the last five years. Figure 4 presents the co-citation network of the documents examined in which two main clusters can be observed (RQ2).

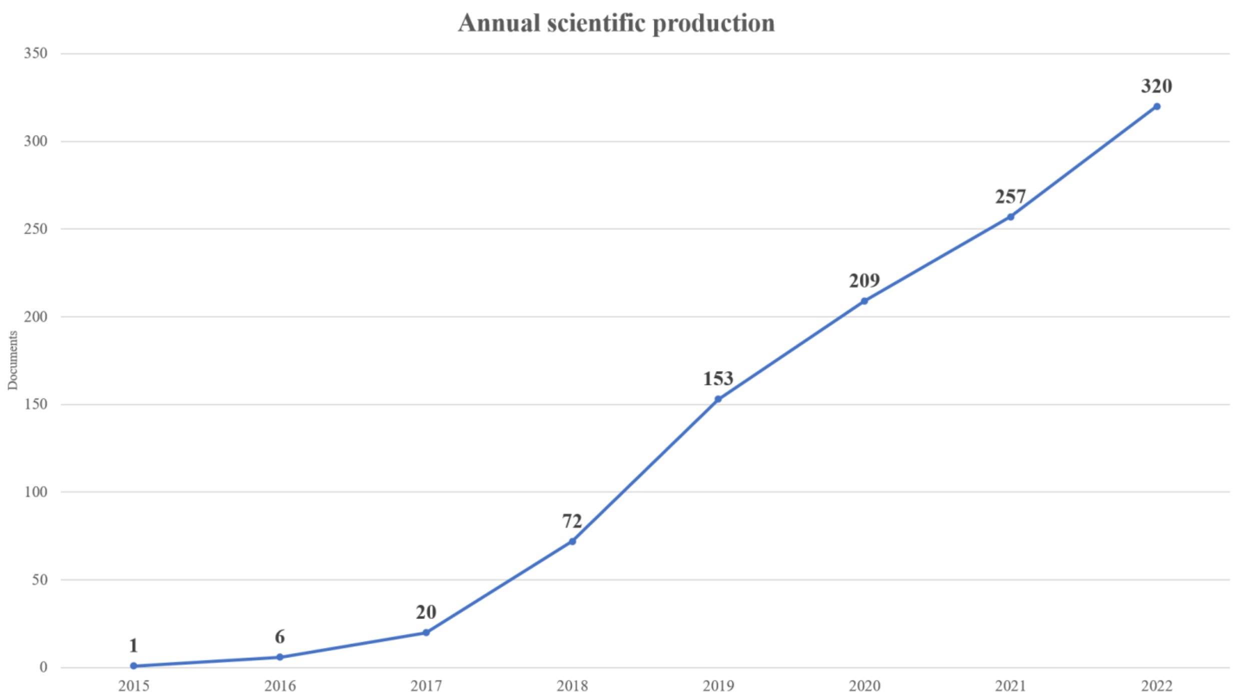


Figure 2. Annual scientific production.

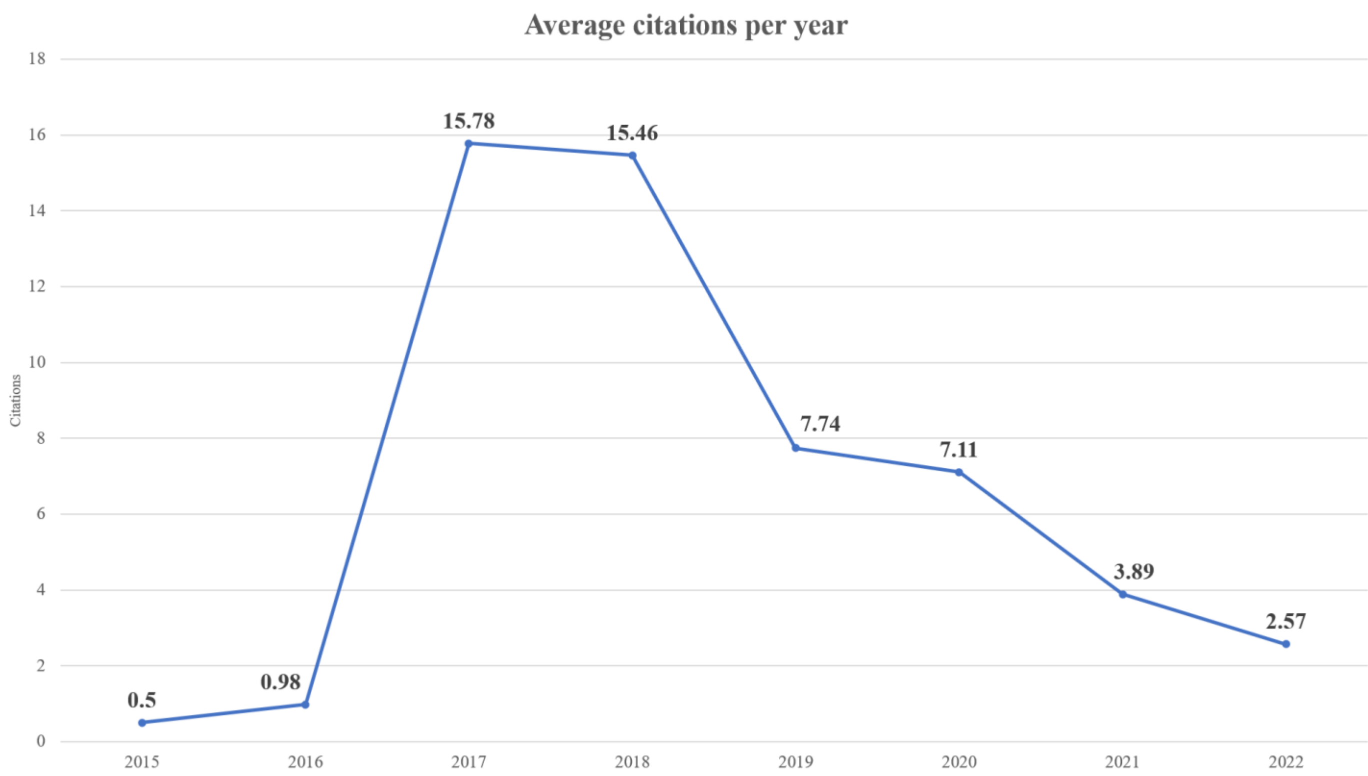


Figure 3. Average citation per year.

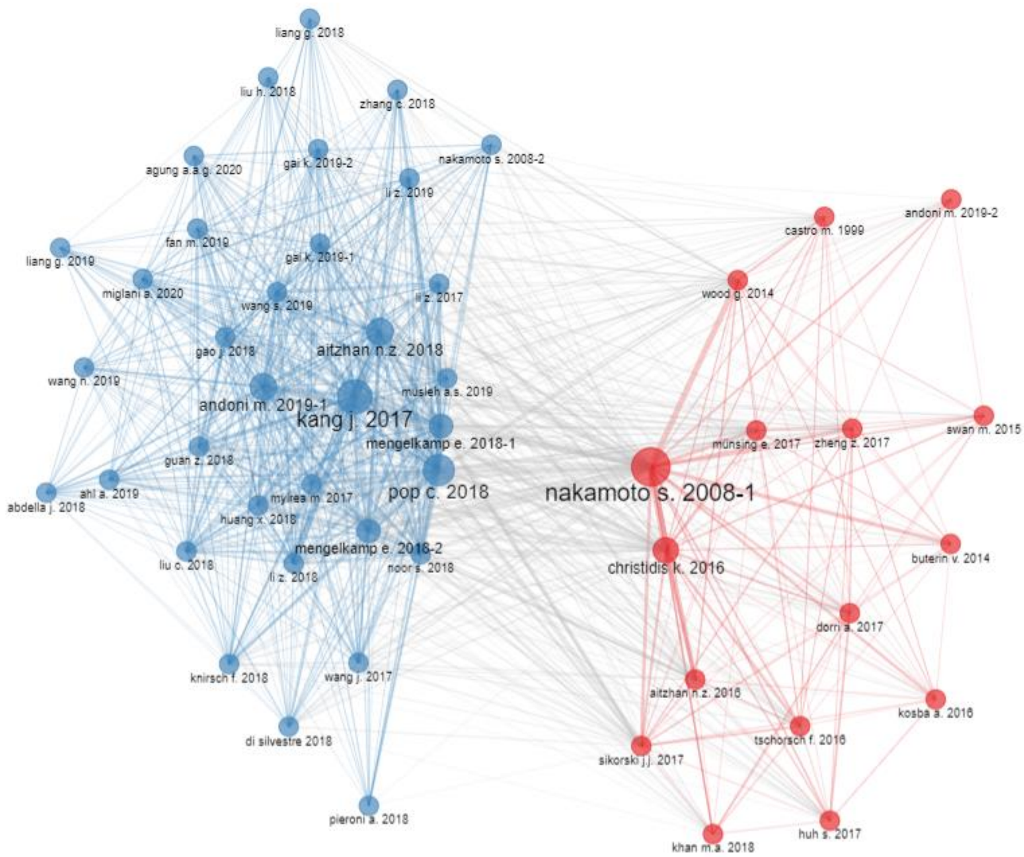


Figure 4. Co-citation network of documents.

3.3. Sources

A total of 519 different scientific outlets were used to publish scientific documents on the topic explored from 2015 to 2022. The breadth and applicability of the given research area can be further justified based on the variety of highly impactful sources used, such as journals, conferences, and book series, as presented in Figure 5, which depicts the top 15 sources according to the number of published documents related to the topic. Three clusters emerged when clustering the sources following Bradford's law. Specifically, cluster 1 comprised 26 different sources and 360 published documents, cluster 2 comprised 150 sources and 352 published documents, and cluster 3 comprised 343 sources and 343 published documents. It is worth noting that cluster 1 has the sources with the most published documents. Following Bradford's law and using the rank, frequency, number of documents, and cluster, Table 3 presents the top 10 sources of cluster 1. The scientific production of annually published documents over the period examined of the top 10 sources, according to Bradford's law, is presented in Figure 6. The H-index and the total number of citations can also be used to evaluate the impact of a scientific source. Thus, Tables 4 and 5 present the top 10 sources using the h-index, g-index, m-index, the number of citations received, the total number of published documents on the topic, and the date of the first published document on this topic. *IEEE Access*, *Energies*, *IEEE Transactions on Industrial Informatics*, *Applied Energy*, and *IEEE Internet of Things Journal* were the top five most impactful sources, according to h-index. According to the total number of citations received, *IEEE Access*, *Applied Energy*, *IEEE Transactions on Industrial Informatics*, *IEEE Communications Surveys and Tutorials*, and *IEEE Internet of Things Journal* were the top five most impactful sources (RQ3).

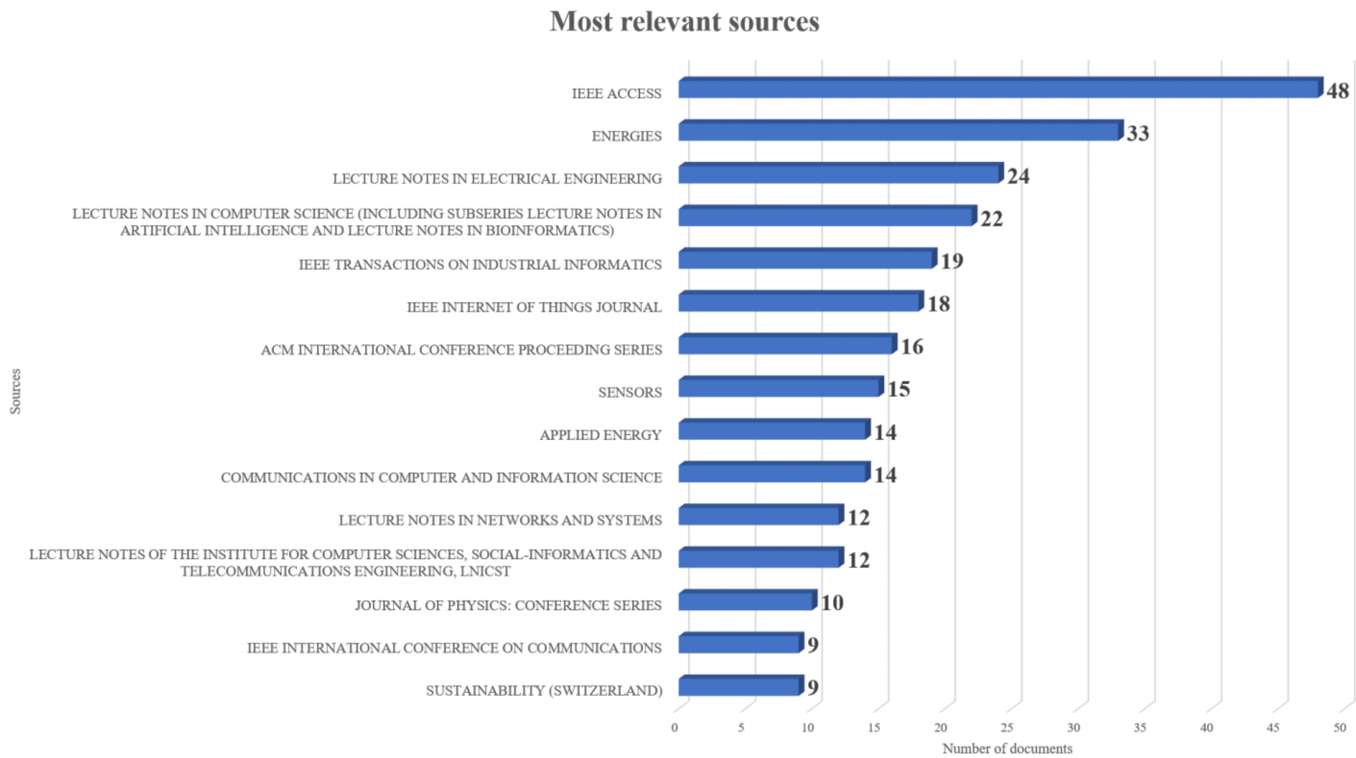


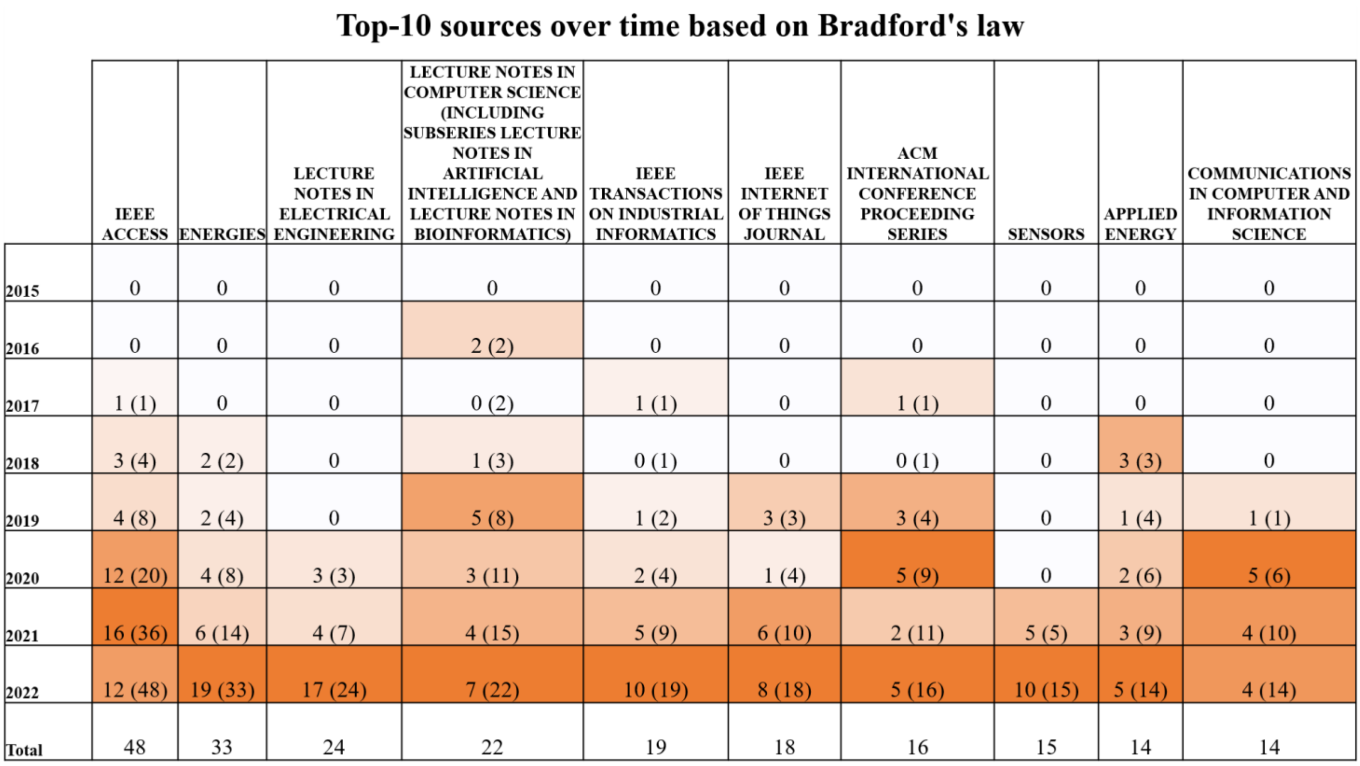
Figure 5. Sources with the most related documents published.

Table 3. Source clustering through Bradford's law.

Source	Rank	Freq	cumFreq	Cluster
IEEE Access	1	48	48	Cluster 1
Energies	2	33	81	Cluster 1

Table 3. *Cont.*

Source	Rank	Freq	cumFreq	Cluster
Lecture Notes in Electrical Engineering	3	24	105	Cluster 1
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	4	22	127	Cluster 1
IEEE Transactions on Industrial Informatics	5	19	146	Cluster 1
IEEE Internet of Things Journal	6	18	164	Cluster 1
ACM International Conference Proceeding Series	7	16	180	Cluster 1
Sensors	8	15	195	Cluster 1
Applied Energy	9	14	209	Cluster 1
Communications in Computer and Information Science	10	14	223	Cluster 1


Top-10 sources over time based on Bradford's law

	IEEE ACCESS	ENERGIES	LECTURE NOTES IN ELECTRICAL ENGINEERING	LECTURE NOTES IN COMPUTER SCIENCE (INCLUDING SUBSERIES LECTURE NOTES IN ARTIFICIAL INTELLIGENCE AND LECTURE NOTES IN BIOINFORMATICS)	IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS	IEEE INTERNET OF THINGS JOURNAL	ACM INTERNATIONAL CONFERENCE PROCEEDING SERIES	SENSORS	APPLIED ENERGY	COMMUNICATIONS IN COMPUTER AND INFORMATION SCIENCE
2015	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	2 (2)	0	0	0	0	0	0
2017	1 (1)	0	0	0 (2)	1 (1)	0	1 (1)	0	0	0
2018	3 (4)	2 (2)	0	1 (3)	0 (1)	0	0 (1)	0	3 (3)	0
2019	4 (8)	2 (4)	0	5 (8)	1 (2)	3 (3)	3 (4)	0	1 (4)	1 (1)
2020	12 (20)	4 (8)	3 (3)	3 (11)	2 (4)	1 (4)	5 (9)	0	2 (6)	5 (6)
2021	16 (36)	6 (14)	4 (7)	4 (15)	5 (9)	6 (10)	2 (11)	5 (5)	3 (9)	4 (10)
2022	12 (48)	19 (33)	17 (24)	7 (22)	10 (19)	8 (18)	5 (16)	10 (15)	5 (14)	4 (14)
Total	48	33	24	22	19	18	16	15	14	14

Figure 6. Top 10 sources over time, based on Bradford's law.

Table 4. The top 10 most impactful sources according to their h-index.

Source	h_index	g_index	m_index	TC	NP	PY_start
IEEE Access	20	41	2.857	1690	48	2017
Energies	10	25	1.667	633	33	2018
IEEE Transactions on Industrial Informatics	10	19	1.429	1485	19	2017
Applied Energy	9	14	1.5	1505	14	2018
IEEE Internet of Things Journal	9	18	1.8	874	18	2019
Sensors	8	8	1.333	745	8	2018
IEEE International Conference on Communications	6	9	1	288	9	2018
IEEE Transactions on Systems, Man, and Cybernetics: Systems	6	6	1.2	451	6	2019
IEEE Transactions on Smart Grid	5	5	0.833	403	5	2018
International Journal of Electrical Power and Energy Systems	5	6	1.667	118	6	2021

Table 5. The top 10 most impactful sources, based on their total number of citations received (TC).

Source	h_index	g_index	m_index	TC	NP	PY_start
IEEE Access	20	41	2.857	1690	48	2017
Applied Energy	9	14	1.5	1505	14	2018
IEEE Transactions on Industrial Informatics	10	19	1.429	1485	19	2017
IEEE Communications Surveys and Tutorials	4	4	0.8	927	4	2019
IEEE Internet of Things Journal	9	18	1.8	874	18	2019
Sensors	8	8	1.333	745	8	2018
IEEE Transactions on Dependable and Secure Computing	2	2	0.333	728	2	2018
Energies	10	25	1.667	633	33	2018
Computer Science—Research and Development	2	2	0.333	619	2	2018
Journal of Network and Computer Applications	3	3	0.75	464	3	2020

3.4. Authors

Due to the significance and applicability of the topic in various domains, a total of 2672 authors from different countries and affiliations contributed to the documents of the collection analyzed, which examines the use of blockchain in smart grids. Table 6 displays the most productive authors, according to their number of published documents on this topic. Figure 7 depicts their publication production over time. The most productive authors started publishing documents on this topic around the period of 2018–2019. Kumar, N., Tanwar, S., Zhang, X., and Wang, H. were the four authors that published the most documents. Based on Figure 8 and following Lotka's law, it can be inferred that the vast majority of authors have written a single document (76.6%) on this topic and only a marginal number of authors have contributed nine or more studies (RQ4).

Table 6. Top authors according to their number of published documents.

Authors	Documents	Documents Fractionalized
Kumar, N.	25	6.56
Tanwar, S.	23	6.13
Zhang, X.	20	5.34
Wang, H.	17	4.77
Li, Y.	16	3.85
Wang, Y.	16	3.51
Kumari, A.	15	4.51
Zhang, Y.	13	2.55
Chen, Y.	12	4.27
Javaid, N.	12	2.45
Liu, C.	12	2.58

Of the 2672 authors that conducted studies on this topic, the most impactful authors can be identified based on their h-index or the total number of citations that they have received. Therefore, Table 7 takes the author's h-index into account to explore the authors with the most significant studies, while Table 8 uses the author's total number of citations received to identify the most impactful ones. Therefore, the top four most impactful authors were Kumar, N., Tanwar, S., Zhang, X., and Kumari A., according to their h-index, while Zhang, Y., Mengelkamp, E., Winhardt, C., and Kumar, N. were the top four most impactful authors, according to their total number of citations (RQ4).

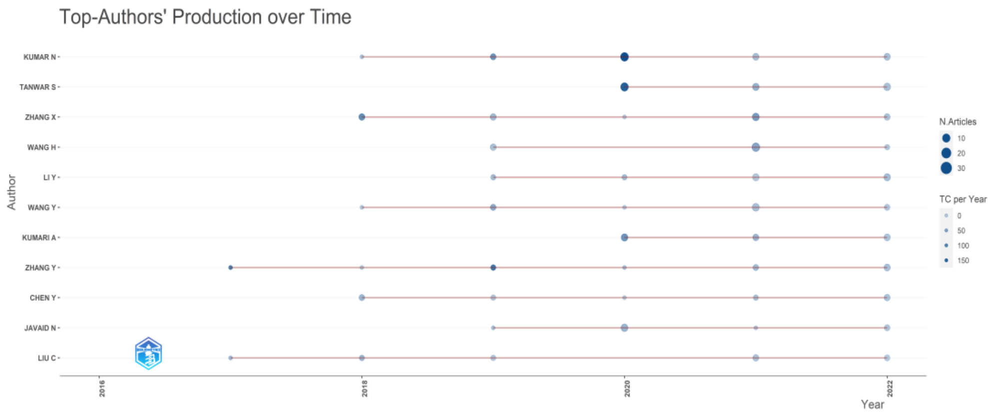


Figure 7. The production of the top 10 authors over time based on the number of published documents.

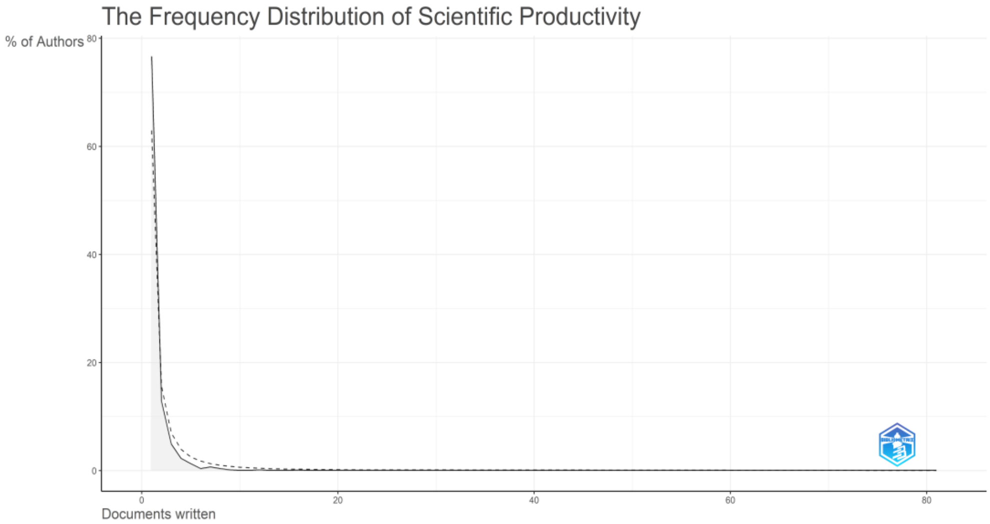


Figure 8. The overall productivity of the authors through Lotka's law.

Table 7. Most impactful authors based on their h-index on this topic.

Author	h_index	g_index	m_index	TC	NP	PY_start
Kumar, N.	14	25	2.333	1182	25	2018
Tanwar, S.	10	23	2.5	728	23	2020
Zhang, X.	9	20	1.5	822	20	2018
Kumari, A.	8	15	2	393	15	2020
Zhang, Y.	8	13	1.143	1475	13	2017
Chen, Y.	7	12	1.167	219	12	2018
Wu, L.	7	7	1.167	425	7	2018
Chai, K.	6	6	1	193	6	2018
Chen, J.	6	8	1.5	461	8	2020
Du, X.	6	7	1	337	7	2018

On average, 3.95 authors were involved in each scientific document. In Figure 9, the authors' collaboration network is displayed, in which six clusters are observed. Each cluster represents the groups and authors who work collaboratively in examining this topic. A total of five prominent authors can be observed in the authors' co-citation network presented in Figure 10.

Table 8. The most impactful authors, based on their total number of citations on this topic.

Author	h_index	g_index	m_index	TC	NP	PY_start
Zhang, Y.	8	13	1.143	1475	13	2017
Mengelkamp, E.	3	3	0.5	1373	3	2018
Weinhardt, C.	3	3	0.5	1373	3	2018
Kumar, N.	14	25	2.333	1182	25	2018
Kessler, S.	2	2	0.333	892	2	2018
Orsini, L.	2	2	0.333	892	2	2018
Gärttner, J.	1	1	0.167	873	1	2018
Rock, K.	1	1	0.167	873	1	2018
Zhang, X.	9	20	1.5	822	20	2018
Huang, X.	3	5	0.429	769	5	2017

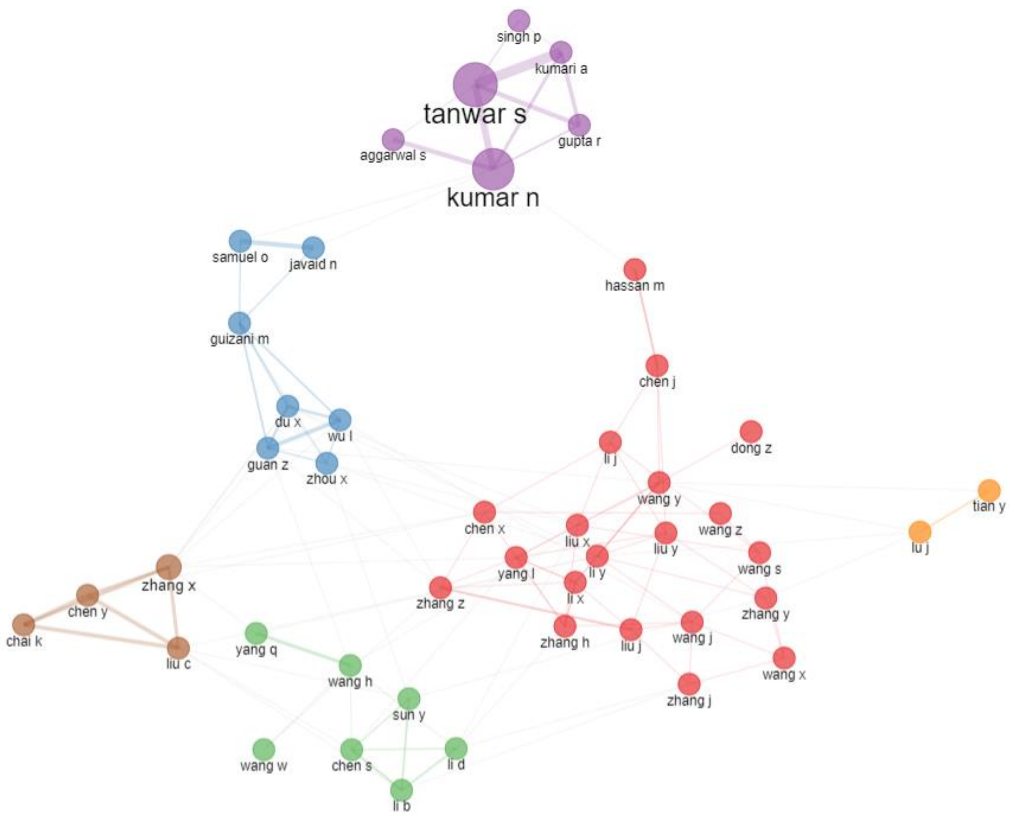


Figure 9. Collaboration network of authors.

In total, 1289 affiliations were identified in the collection. According to the total number of related documents published on this topic, the most prolific affiliations are presented in Figure 11. It is worth noting that each of the top affiliations had at least 11 related documents published. Figure 12 displays their production over time; that is, the number of documents published in each year and the total number of published documents. In Figure 13, the affiliation collaboration network is presented. A total of seven clusters have emerged, which highlights the topic's interdisciplinary nature and broadness. North China Electric Power University, Nirma University, King Saud University, Thapar Institute of Engineering and Technology, Nanyang Technological university, and COMSATS University Islamabad were the affiliations that had the most published documents on the topic (RQ5).

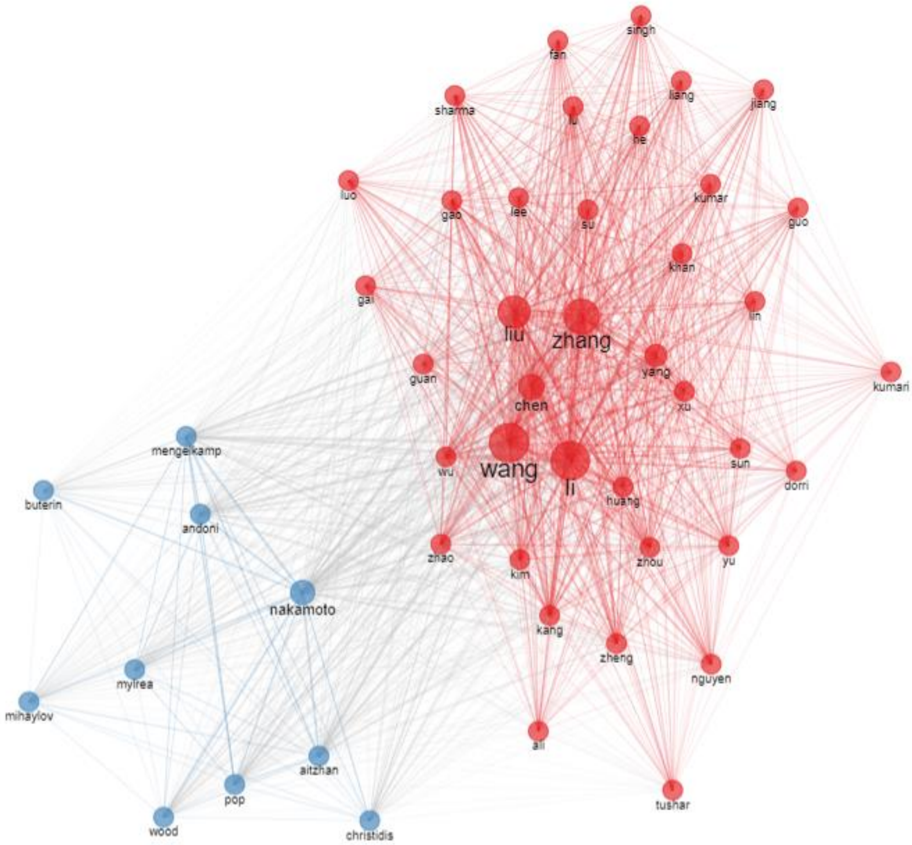


Figure 10. Co-citation network of authors.

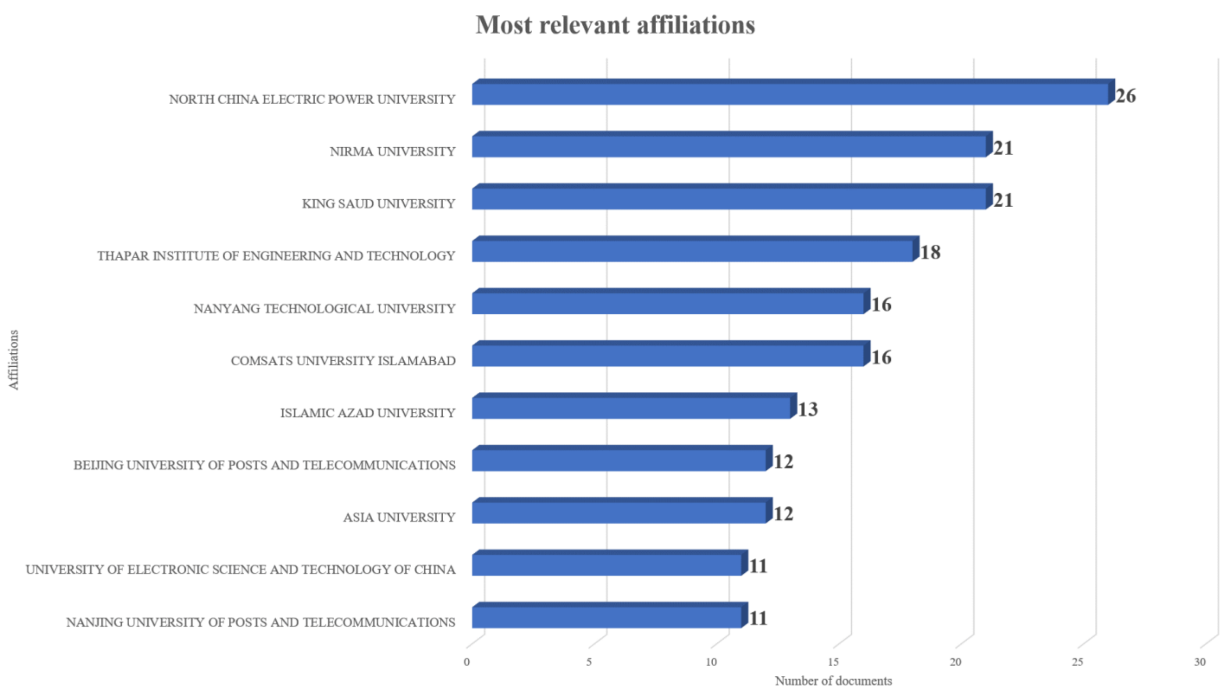


Figure 11. Most relevant affiliations, based on the number of documents published.

Most relevant affiliations' production over time

	NORTH CHINA ELECTRIC POWER UNIVERSITY	NANJING UNIVERSITY OF POSTS AND TELECOMMUNICATIONS	NANYANG TECHNOLOGICAL UNIVERSITY	THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY	UNIVERSITY OF ELECTRONIC SCIENCE AND TECHNOLOGY OF CHINA	BEIJING UNIVERSITY OF POSTS AND TELECOMMUNICATIONS	COMSATS UNIVERSITY ISLAMABAD	ISLAMIC AZAD UNIVERSITY	KING SAUD UNIVERSITY	ASIA UNIVERSITY	NIRMA UNIVERSITY
2015	0	0	0	0	0	0	0	0	0	0	0
2016	0	0	0	0	0	0	0	0	0	0	0
2017	3 (3)	0	0	0	0	0	0	0	0	0	0
2018	0 (3)	1 (1)	2 (2)	1 (1)	4 (4)	0	0	0	0	0	0
2019	1 (4)	2 (3)	0 (2)	2 (3)	2 (6)	4 (4)	2 (2)	3 (3)	1 (1)	0	0
2020	5 (9)	0 (3)	3 (5)	5 (8)	1 (7)	2 (6)	9 (11)	5 (8)	9 (10)	6 (6)	9 (9)
2021	7 (16)	5 (8)	5 (10)	6 (14)	1 (8)	4 (10)	2 (13)	3 (11)	5 (15)	1 (7)	5 (14)
2022	10 (26)	3 (11)	6 (16)	4 (18)	3 (11)	2 (12)	3 (16)	2 (13)	6 (21)	5 (12)	7 (21)
Total	26	11	16	18	11	12	16	13	21	12	21

Figure 12. Most relevant affiliations, based on their scientific production over time.

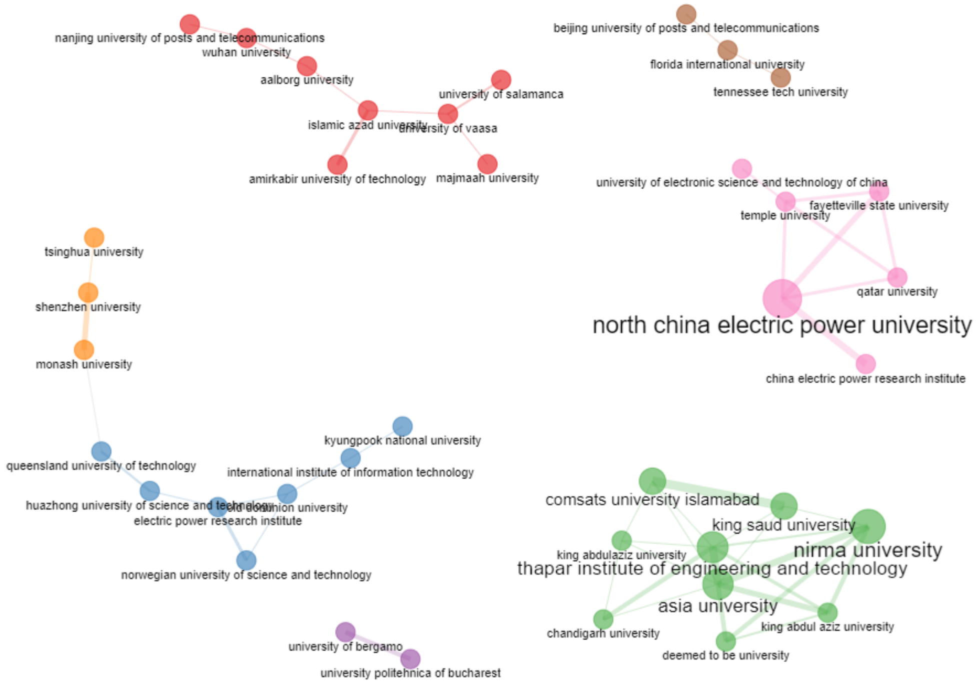


Figure 13. Affiliation collaboration network.

3.5. Countries

China, Germany, the United States of America, Australia, India, and Canada were the countries that received the most citations. As can be seen in Figure 14, which depicts the top 10 most cited countries, there is a significant difference even between the top countries, based on their total number of citations received. Figure 15 presents the top 10 countries with most publications, according to the corresponding author's country. Once again, there is a clear difference in the number of citations, even among the top counties. Furthermore, Figure 16 takes the nationality of all authors into account and presents the scientific production of each country in a world map, which further highlights the importance of the topic, as it is being examined worldwide. China, India, Korea, the United States of America, and Australia were the countries that published the most. Figure 17 presents the annual scientific production of the top 10 countries, according to the number of documents published throughout the years. Figures 18 and 19 present the country collaboration network. There is a clear need to further promote and encourage international collaboration, as the international co-authorship rate is low (2.79%) and the clusters of collaboration among countries are limited (RQ6).

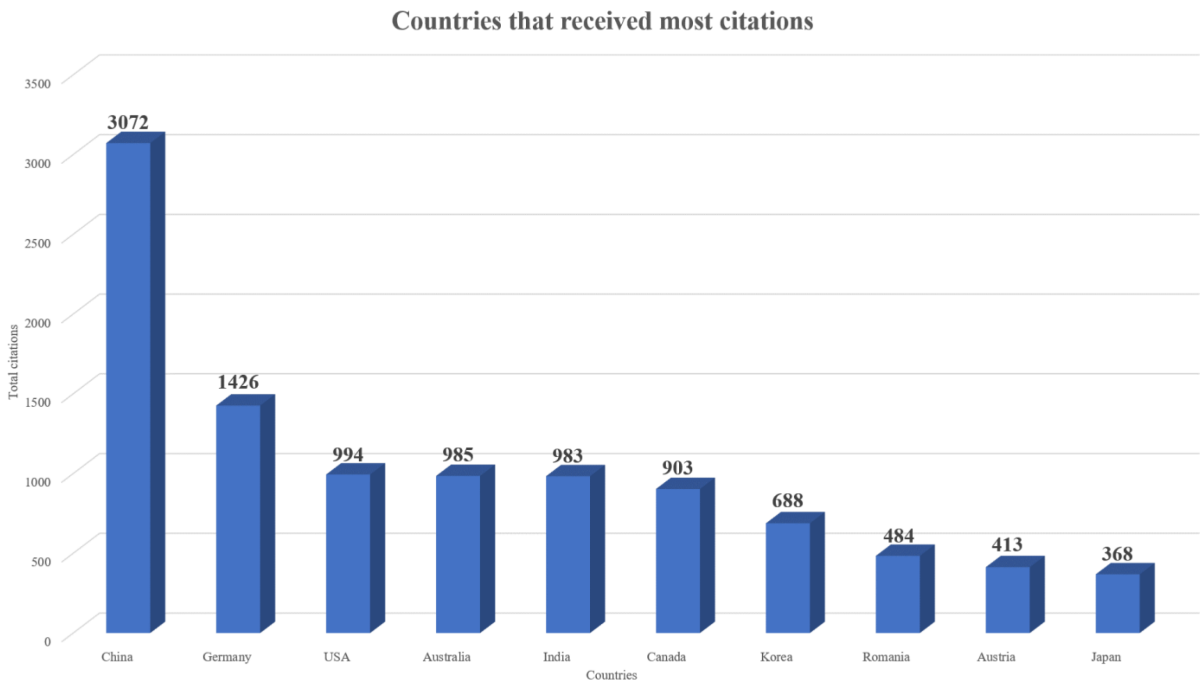


Figure 14. Top 10 countries based on the number of citations received.

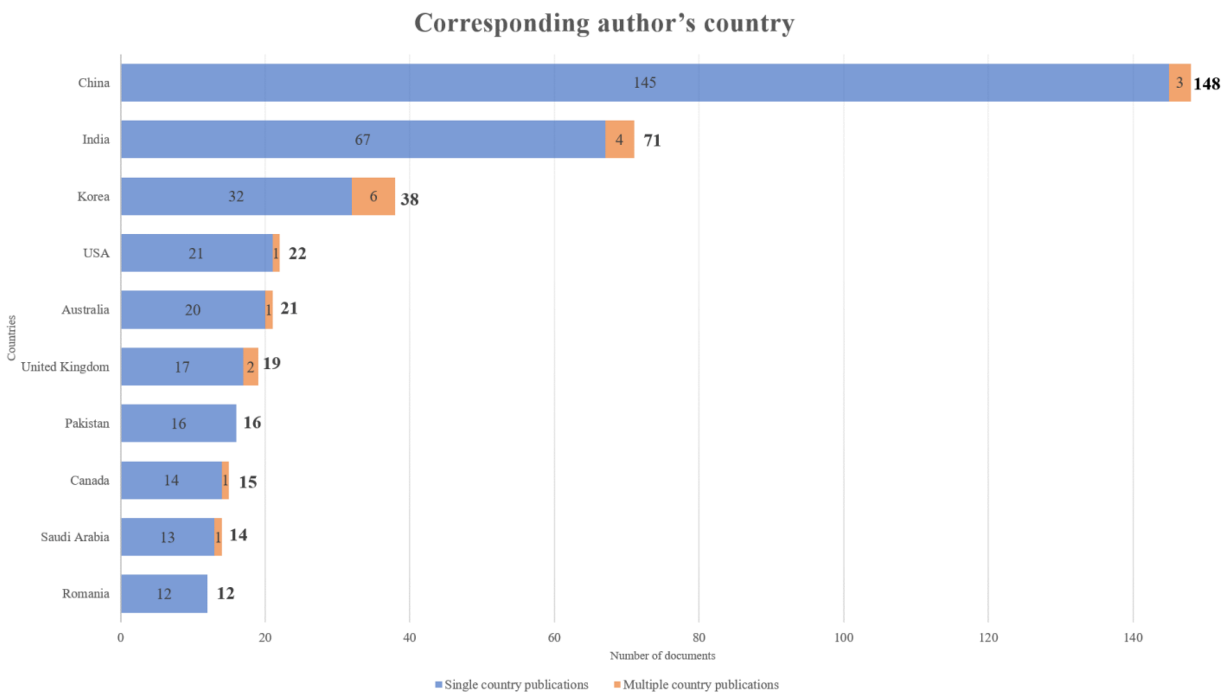


Figure 15. Top 10 countries according to the scientific production of the corresponding authors.

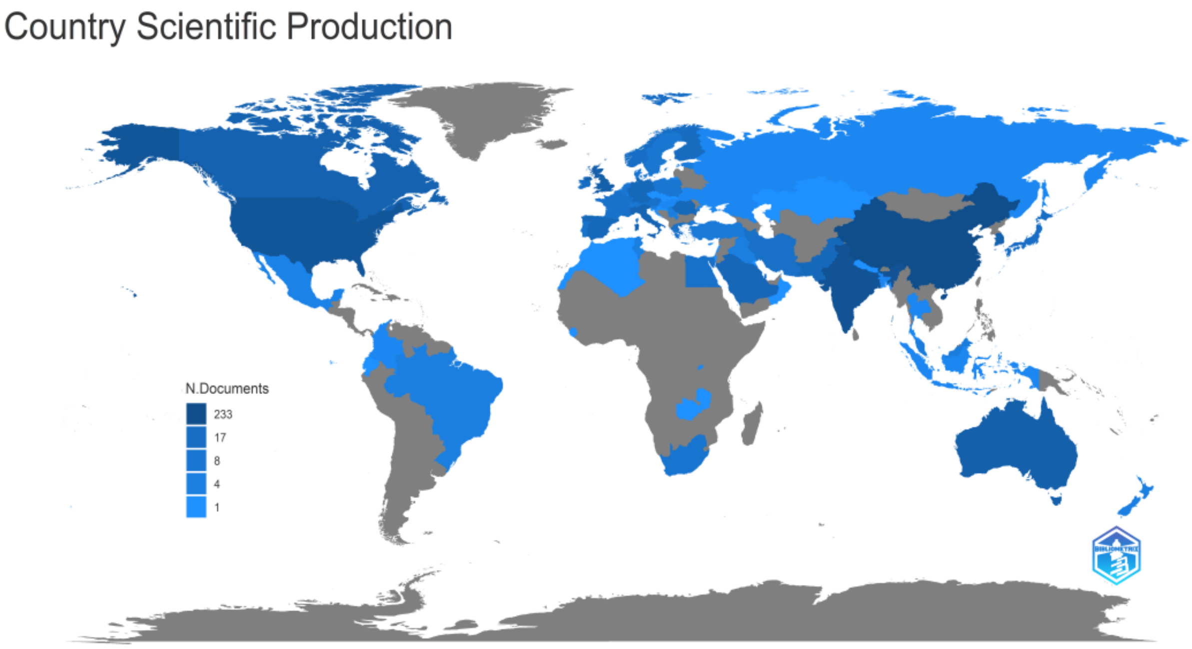


Figure 16. Country collaboration map.

Top-10 countries that published the most over time

	China	India	USA	United Kingdom	Australia	Korea	Canada	Italy	Saudi Arabia	Romania
2015	0	0	0	1 (1)	0	0	0	0	0	0
2016	0	0	0	3 (4)	0	1 (1)	0	0	0	0
2017	5 (5)	0	3 (3)	0 (4)	2 (2)	0 (1)	1 (1)	3 (3)	0	1 (1)
2018	8 (13)	2 (2)	17 (20)	4 (8)	2 (4)	6 (7)	0 (1)	3 (6)	0	1 (2)
2019	16 (29)	17 (19)	23 (43)	9 (17)	9 (13)	6 (13)	5 (6)	7 (13)	0	5 (7)
2020	31 (60)	18 (37)	21 (64)	6 (23)	6 (19)	7 (20)	5 (11)	8 (21)	6 (6)	8 (15)
2021	82 (142)	43 (80)	18 (82)	12 (35)	20 (39)	16 (36)	10 (21)	2 (23)	11 (17)	5 (20)
2022	85 (227)	65 (145)	29 (111)	19 (54)	9 (48)	10 (46)	17 (38)	10 (33)	11 (28)	6 (26)
Total	227	145	111	54	48	46	38	33	28	26

Figure 17. Scientific production, over time, of the top 10 countries that published the most.

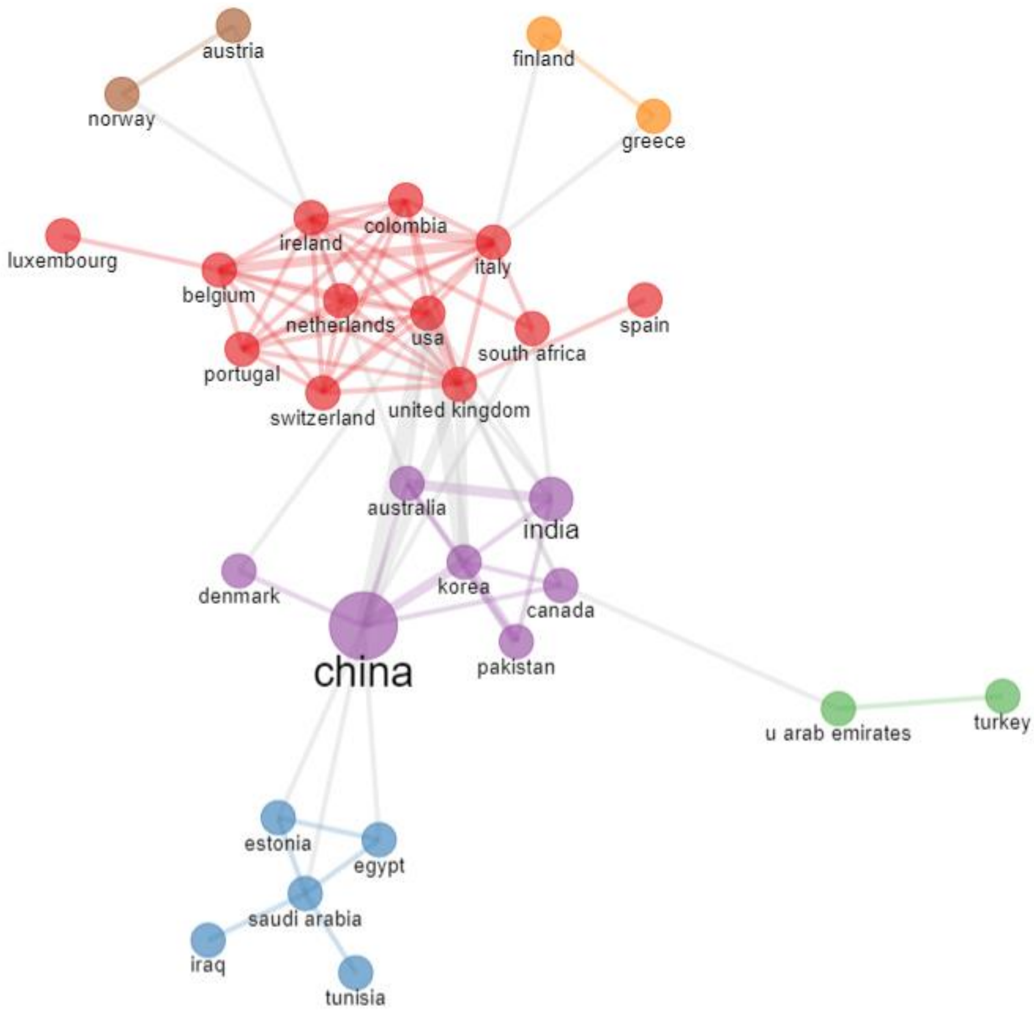


Figure 18. Collaboration network of countries.

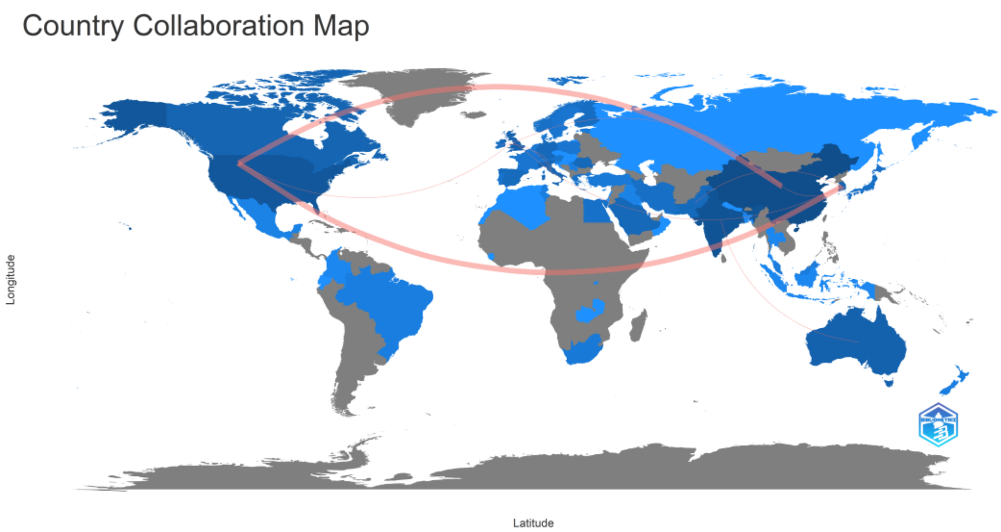


Figure 19. Collaboration map of countries.

3.6. Documents

In total, 1041 studies were conducted, regarding the role and integration of blockchain in smart grids. The top 10 most frequently cited documents are presented in Table 9 and their total number of citations, annual citations, and normalized total number of citations are also described. Figure 20 depicts the reference publication year spectroscopy, which further justifies the impact of these publications. According solely to the total number of citations, the studies of Mengelkamp et al. [61], Kang et al. [62], Aitzhan et al. [63], Mengelkamp et al. [64], and Pop et al. [65] were the top five most impactful ones (RQ7).

Table 9. The top 10 documents based on the total number of citations they received.

Reference	Document	Total Citations	TC per Year	Normalized TC
[61]	Mengelkamp, E., 2018, *Applied Energy*	873	145.5	11.29
[62]	Kang, J., 2017, *IEEE Transactions on Industrial Informatics*	759	108.43	8.01
[63]	Aaitzhan, N.Z., 2018, *IEEE Transactions on Dependable and Secure Computing*	721	120.17	9.32
[64]	Mengelkamp, E., 2018, *Computer Science—Research and Development*	488	81.33	6.31
[65]	Pop, C., 2018, *Sensors*	390	65	5.04
[66]	Yang, R., 2019, *IEEE Communications Surveys and Tutorials*	336	67.2	10.85
[67]	Gai, K., 2019, *IEEE Transactions on Industrial Informatics*	332	66.4	10.72
[68]	Xie, J., 2019, *IEEE Communications Surveys and Tutorials*	314	62.8	10.14
[69]	Banerjee, M., 2018, *Digital Communications and Networks*	309	51.5	4
[70]	Sengupta, J., 2020, *Journal of Network and Computer Applications*	300	75	14.07

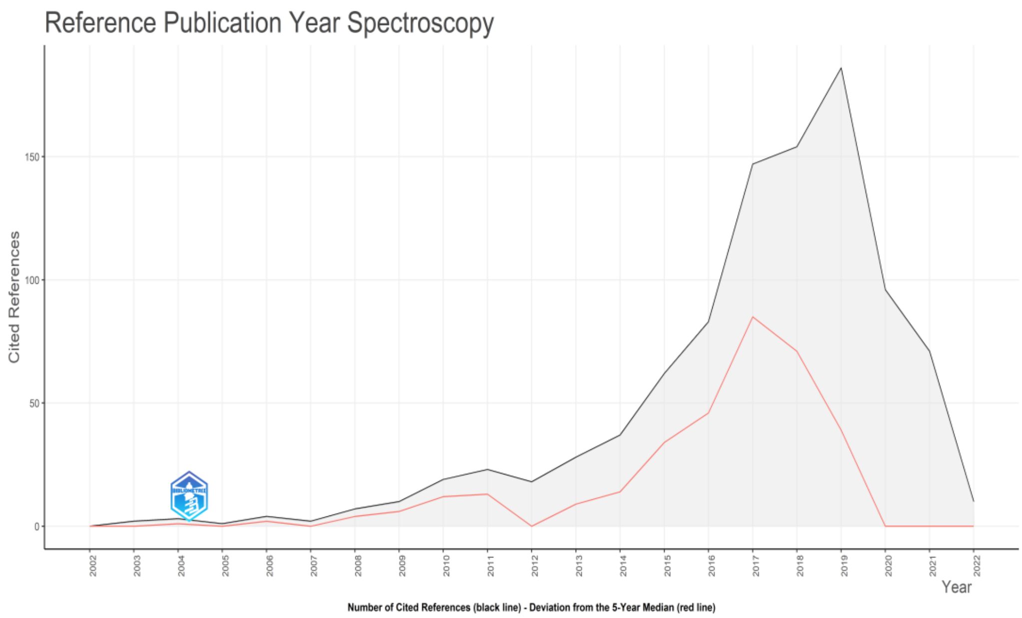


Figure 20. Spectroscopy of reference publication year.

Both the keywords of the author's keywords and keywords plus categories were used in this analysis as they can both satisfactorily display a document knowledge structure [71]. The data deriving from Scopus and WoS was another determining factor for this decision. Hence, the most frequent authors' keywords are displayed in Figure 21 and the most frequent keywords plus used are depicted in Figure 22. The top five authors' keywords were blockchain, smart grid, smart contract, Internet of Things, and security, while the most common keywords plus were blockchain, smart grid, electric power transmission networks, power markets, and Internet of Things. Four main clusters of keywords used within the documents emerged in the co-occurrence network of keywords plus, as can be observed in Figure 23. After having explored the countries, sources, and keywords of the scientific documents of this collection, the relationship of the top 10 most productive countries, most frequent keywords, and most commonly used sources is presented through a three-field plot in Figure 24, using authors' keywords, and in Figure 25 using keywords plus. The interrelationship among the variables is evident in both figures (RQ8).

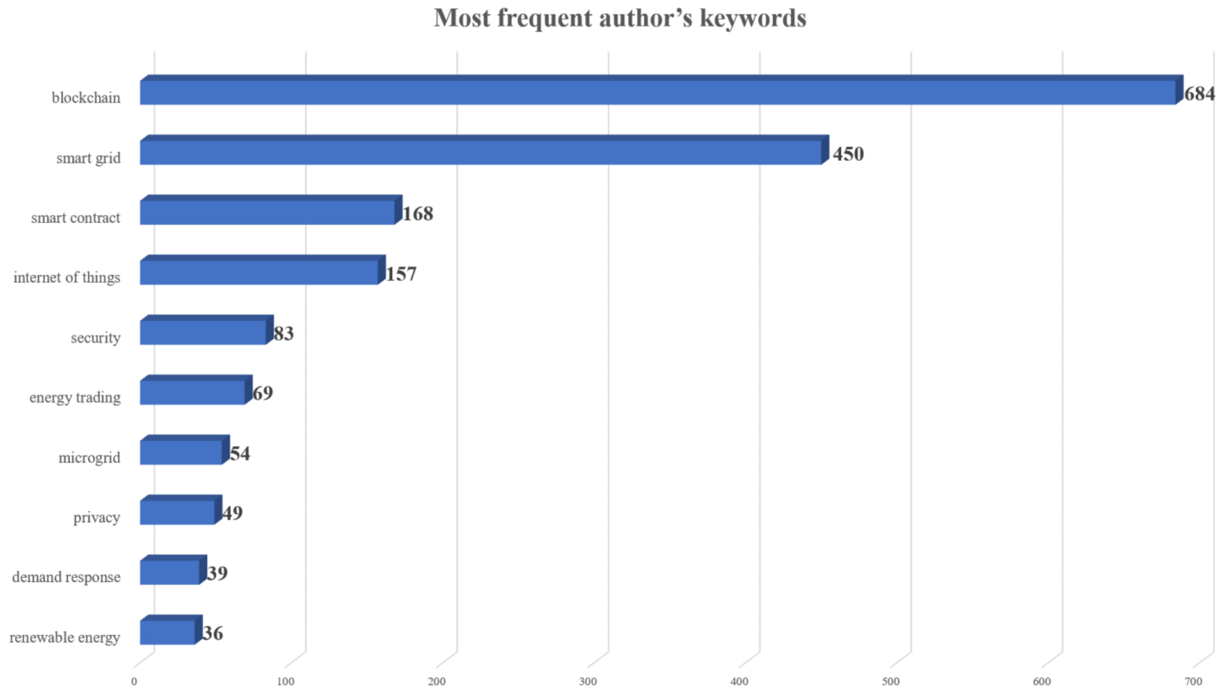


Figure 21. Most frequently used author's keywords.

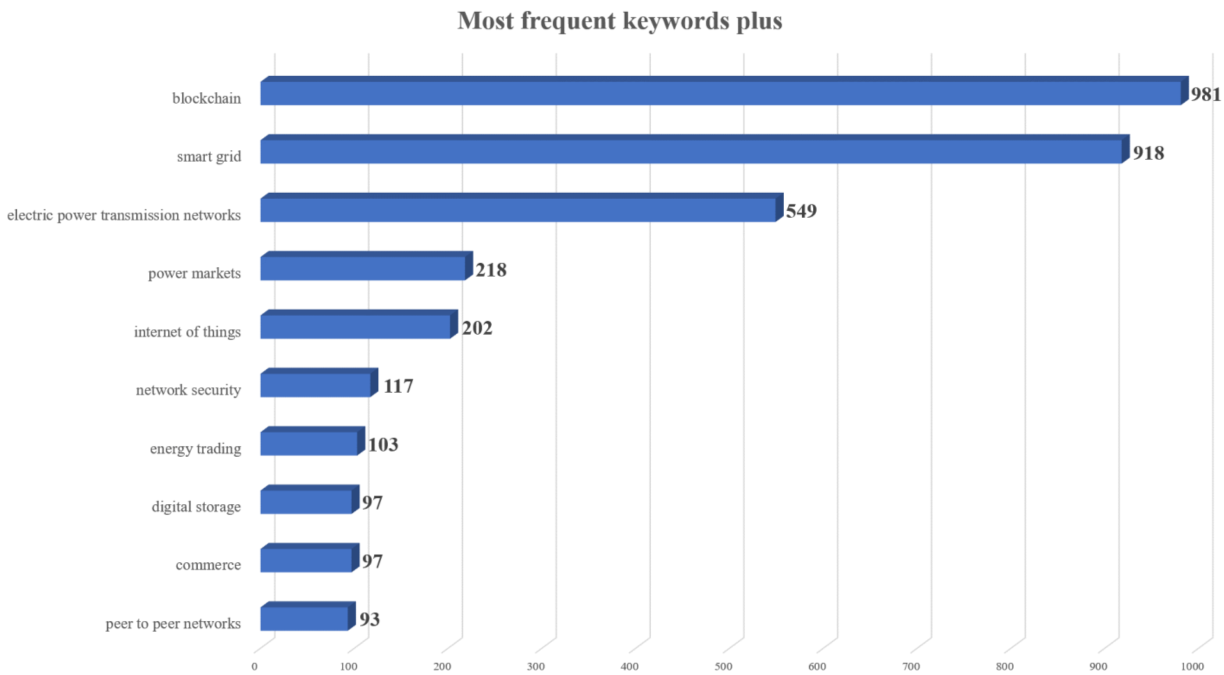


Figure 22. Most frequently used keywords plus.

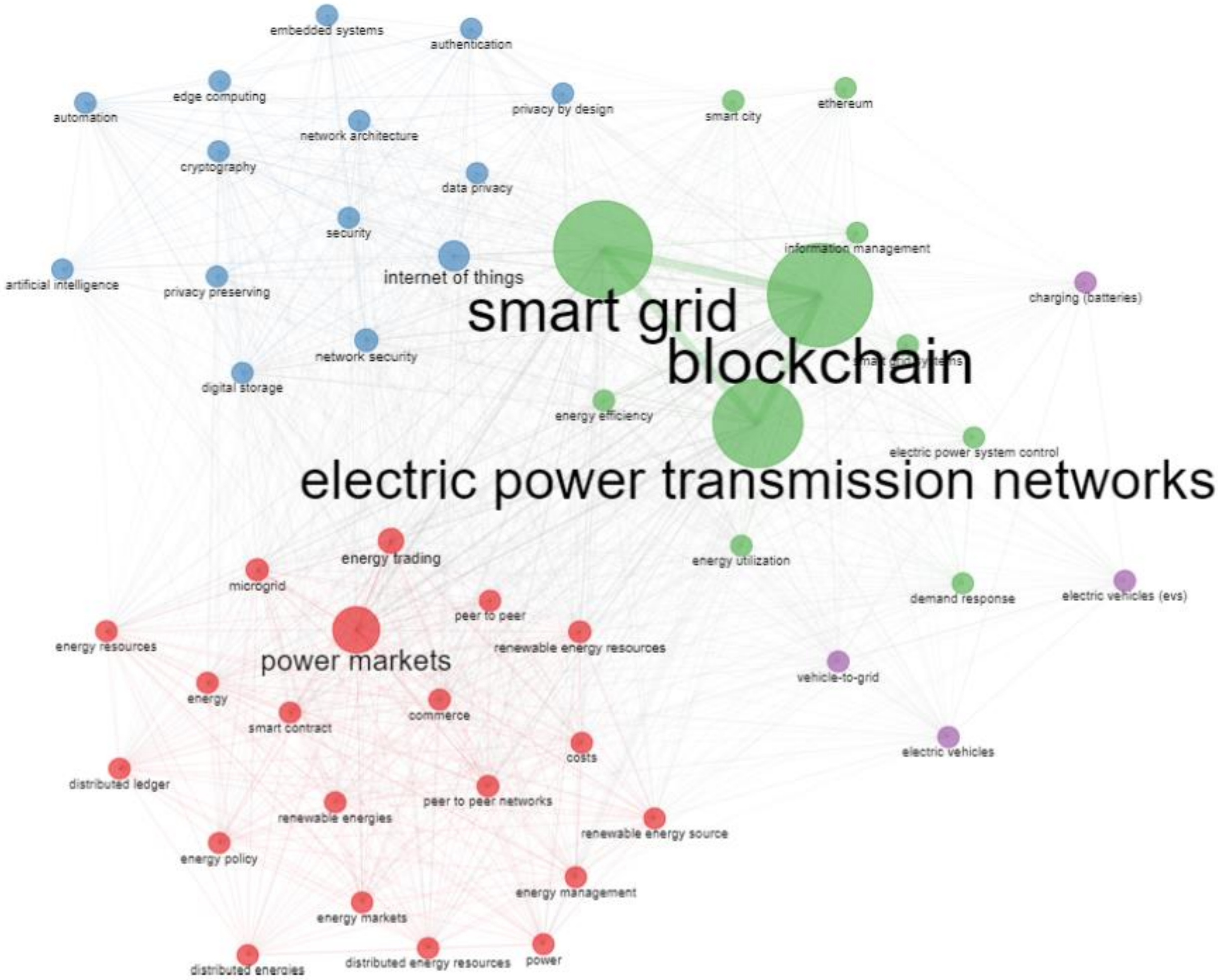


Figure 23. Keywords co-occurrence network.

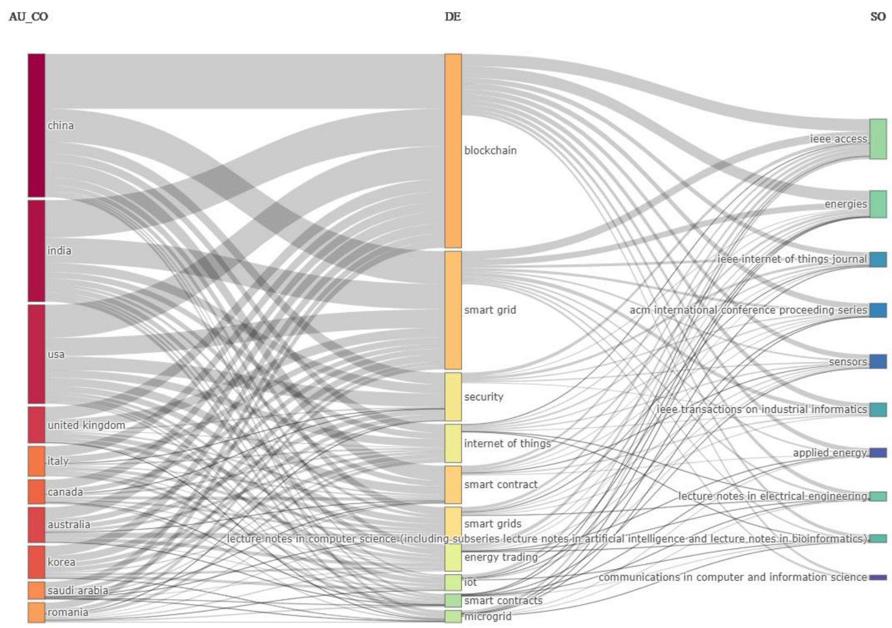


Figure 24. Relationship between the top 10 countries, author’s keywords, and sources.

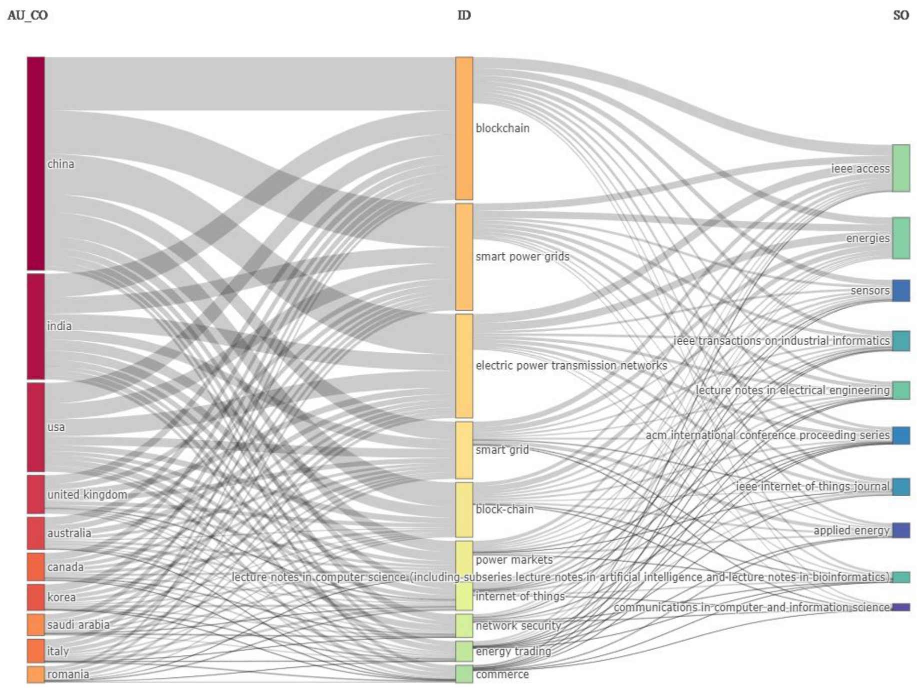


Figure 25. The relationship among the top 10 countries, keywords plus, and sources.

The keywords were also used to explore the topic's trends, evolution, and focus, which can be seen in Figure 26, which uses author's keywords, and in Figure 27, which uses keywords plus. Although the time period of the topic is short, the transition of focus from security and resilience concerns to smart contracts, the Internet of Things and blockchain solutions, as well as the use of machine learning, authentication mechanisms, and fog computing in the context of smart grids, indicates the need for research into intelligent, secure, and autonomous systems in the power sector, to optimize its operation and enrich the use of renewable energy resources. To cluster the documents, document coupling was used, with the document references as a measurement unit and the document global citation score as the impact measure. The three clusters of documents that emerged are presented in Figures 28 and 29 (RQ9).

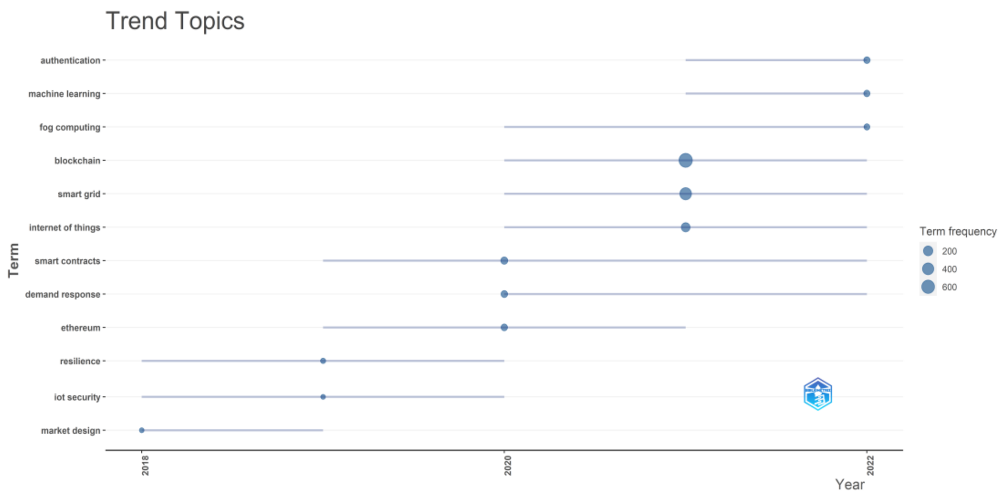


Figure 26. Topic trends according to authors' keywords.

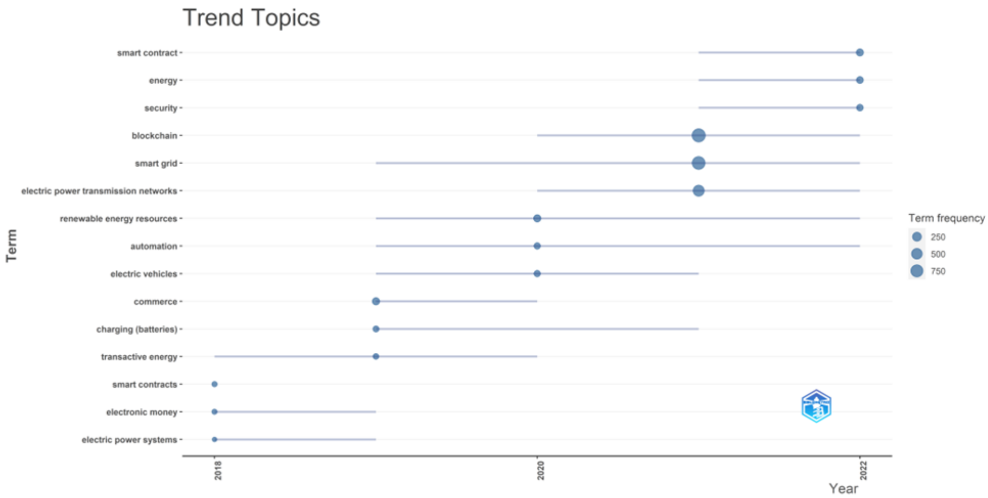


Figure 27. Topic trends according to keywords plus.

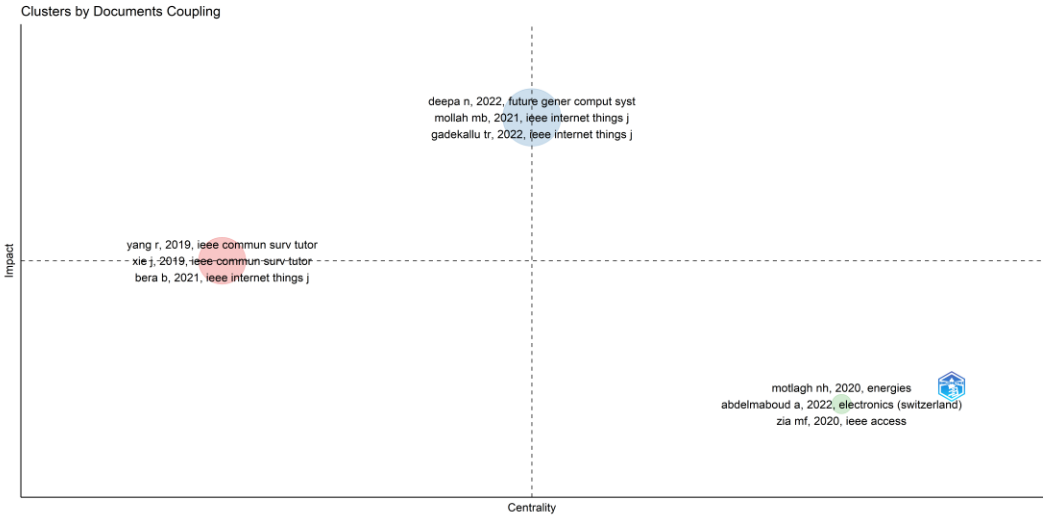


Figure 28. Document clusters map.

Following a factorial analysis based on the keywords used, a conceptual structure map of the topics that emerged is displayed in Figure 30, while a dendrogram of the clustered keywords of each topic and their direct relation is presented in Figure 31. Based on the two clusters that emerged, it can be inferred that the use of blockchain in smart grids is focused mainly on the power sector, but there is also a more specific use case for electric and autonomous vehicles. Moreover, through the clustering of the related keywords, the different themes of the specific domain are shown in Figures 32 and 33. Particularly, as these figures showcase, the motor theme of the topic was related to blockchain, smart grids, microgrids, power markets, and the electric power transmission network. The emerging or declining themes that arose were related to the Internet of Things, network security, cryptography, digital storage, and information management. Finally, Figure 34 displays the thematic evolution of the use of blockchain in smart grids, which is split into two phases: 2015–2019 and 2020–2022. Based on the results, it can be inferred that, at the beginning of the research on this topic, particular emphasis was put on specific technologies and areas, but, in recent years, the focus has been on how these technologies can interact and support each other and how they can be integrated into the power sector, with an emphasis on the Internet of Things and blockchain (RQ10).

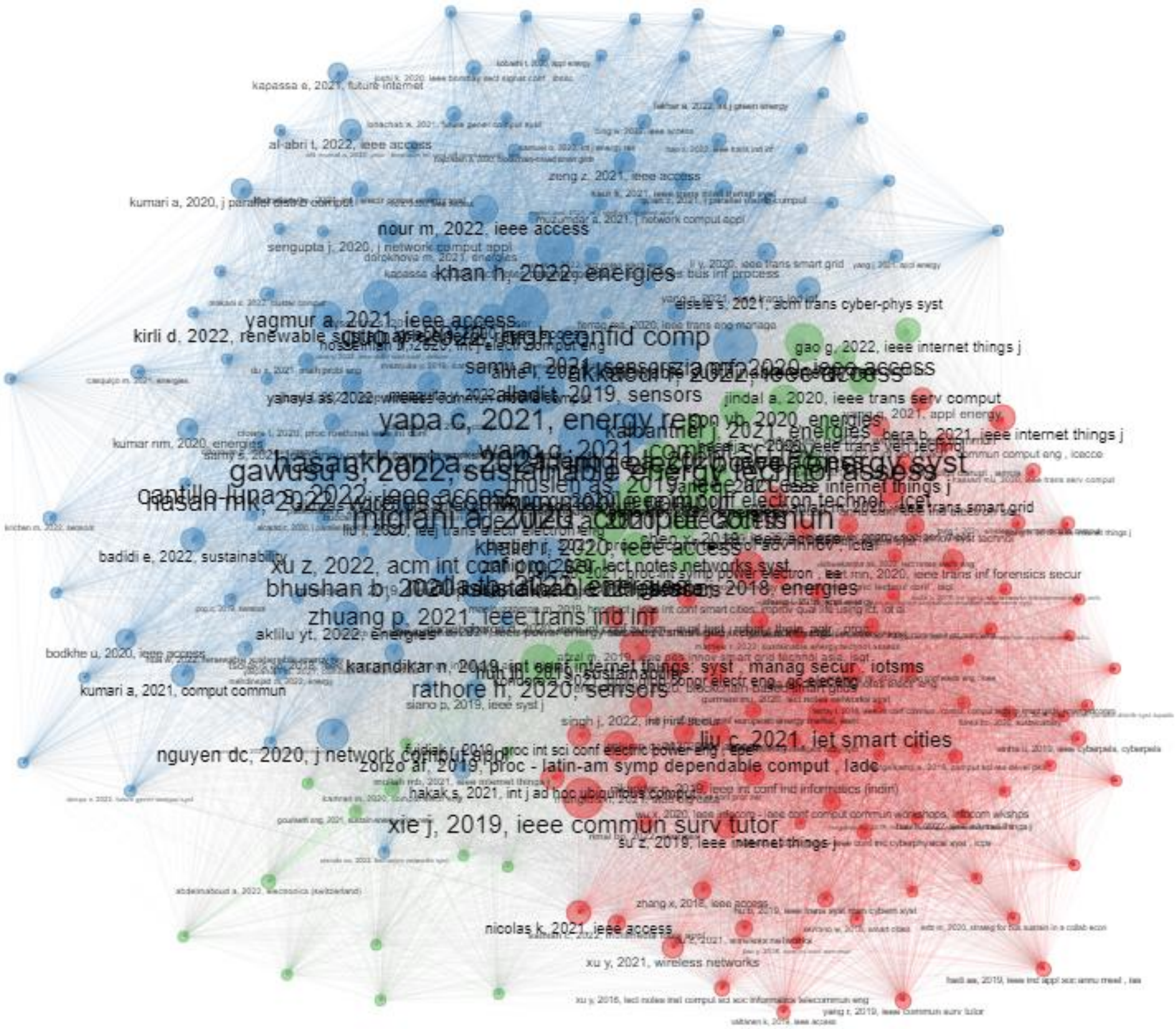


Figure 29. Document clusters network.

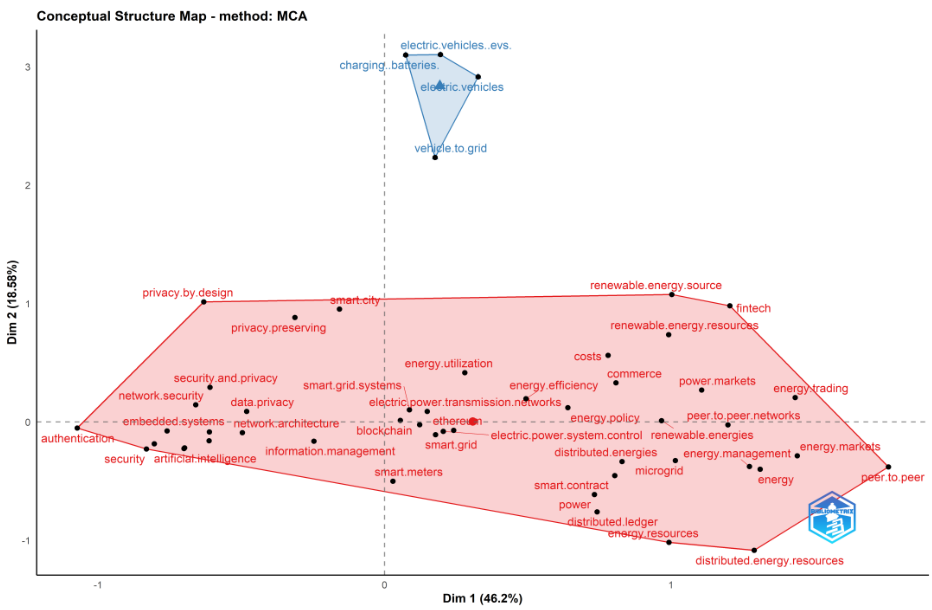


Figure 30. Topic conceptual structure map.

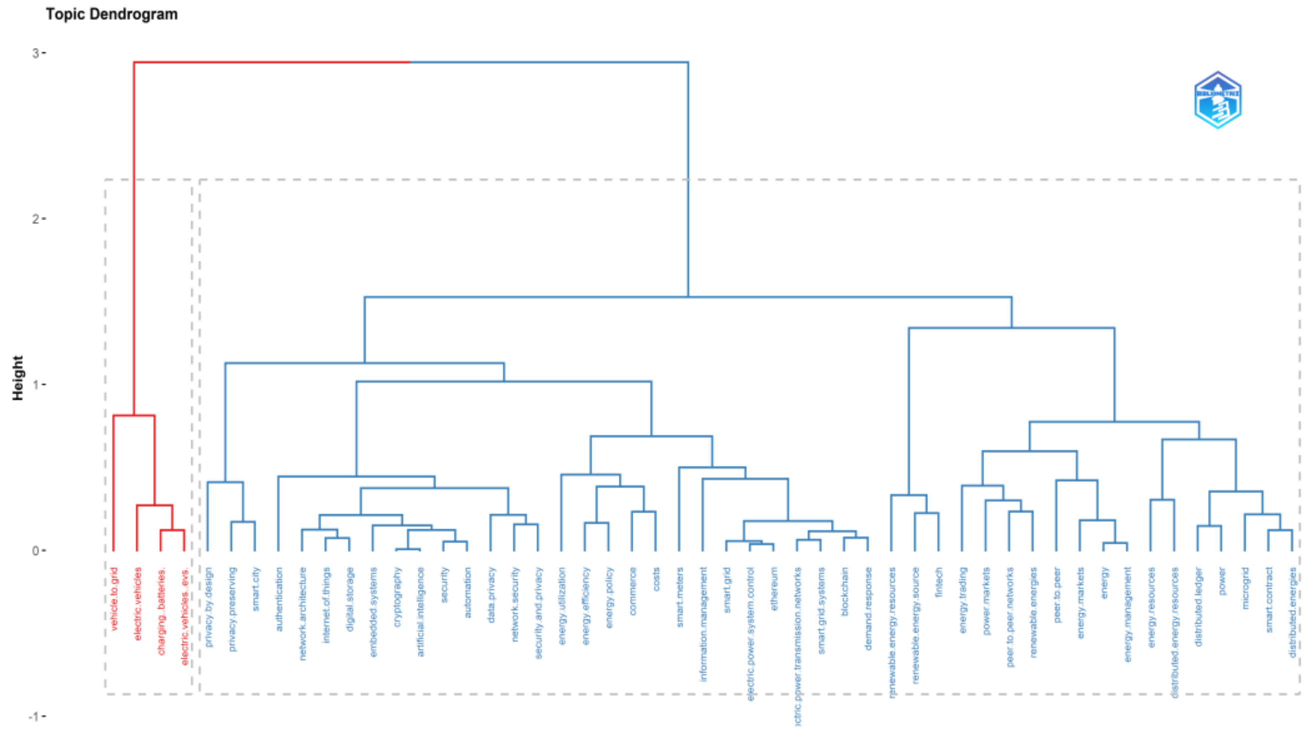


Figure 31. Topic dendrogram.

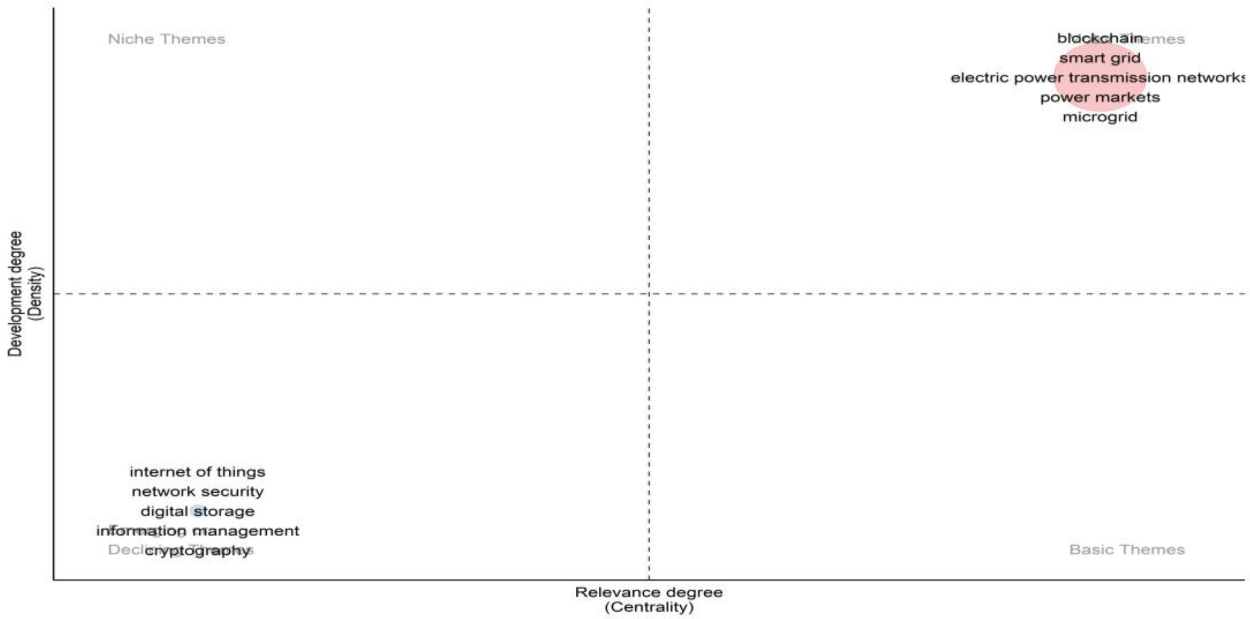


Figure 32. Topic thematic map.

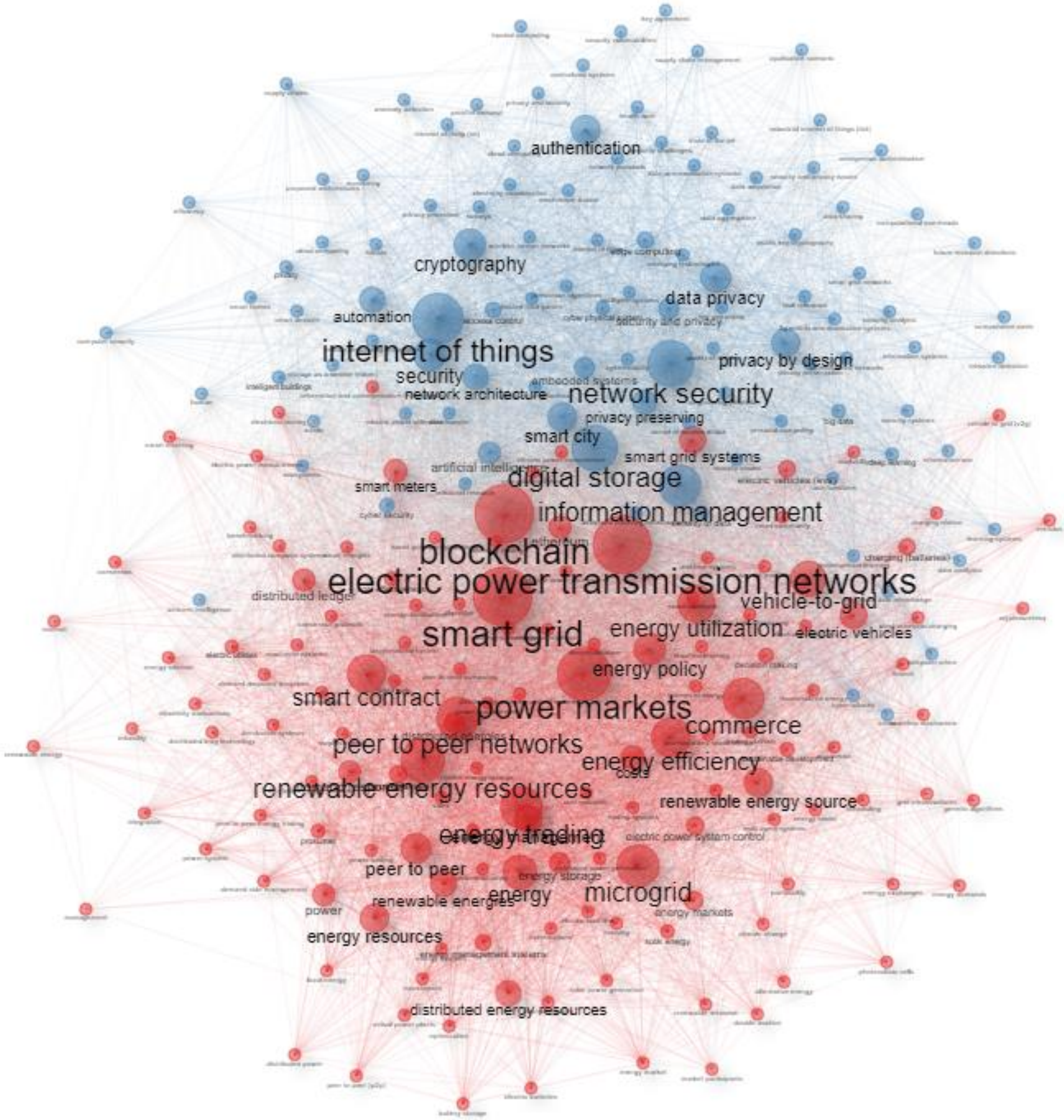


Figure 33. Topic thematic network.

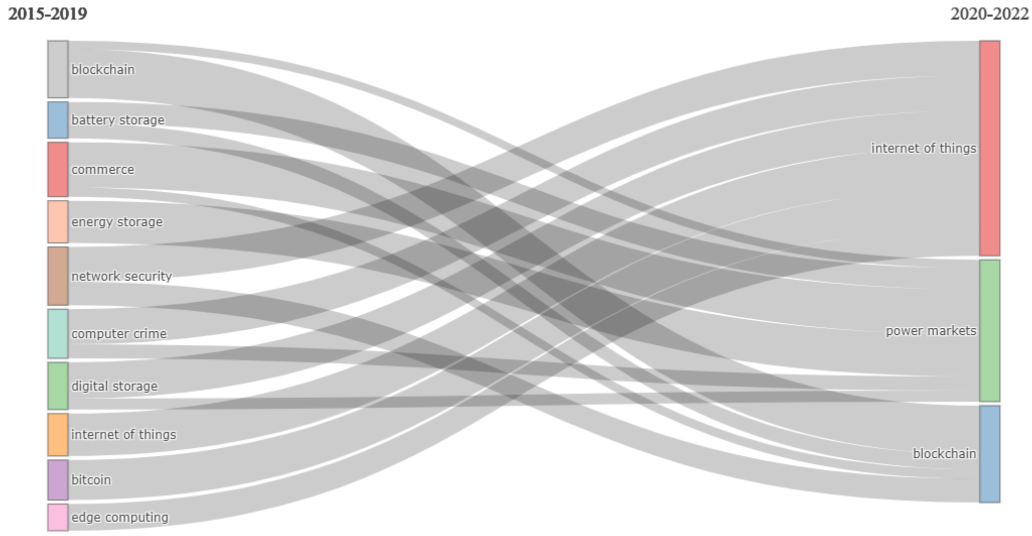


Figure 34. Topic thematic evolution based on two time periods.

4. Discussion

To achieve the sustainable development goals and to fully realize sustainability, the power sector's digital transformation is imminent. As blockchain can be used throughout the value chain of the power sector, its use in smart grids is gaining ground. Through its immutable transactions, blockchain can ensure that every transaction between generators and consumers, as well as among consumers, will be executed and, additionally, it supports the maintenance of a transaction history which, in turn, facilitates auditing and dispute solving [2]. Through its embedded protection mechanisms, blockchain can enrich the cybersecurity, reliability, and trustworthiness of smart grids [3–5,21,63]. Hence, blockchain can enable secure, reliable, tamper-proof, and efficient peer-to-peer energy trading, data aggregation, control, monitoring, and diagnosis [72,73], which, in turn, allow for flexible and real-time adjustments and management of all processes [65] and the optimization of power generation, transmission, distribution, and consumption [1,74]. Moreover, the decentralized nature of blockchain and it not requiring a central intermediary positively influences both consumers and prosumers and, thus, supports the transition to a more sustainable electricity market, the management of renewable resources, the reduction in costs, and the creation of eco-friendly energy infrastructure [3,61,62,64,75]. To fully integrate blockchain in smart grids and reap its benefits, there are limitations, open issues, as well as technical, external, inter-organizational, and intra-organizational barriers that must be addressed and overcome [42]. Security and privacy, interoperability, energy production and consumption, renewable resources use and management, process optimization, regulations and laws, costs and risks, scalability, and decentralization are some of the areas that need to be further examined [21,46,64,72,75].

This study followed a bibliometric and scientific mapping approach to explore and analyze the adoption and integration of blockchain technology in smart grids and the evolution of the topic throughout the years. Therefore, without setting any search limitations, a total of 1041 scientific documents were retrieved from Scopus and WoS. However, using only two databases to identify and retrieve the related documents is a limitation of this study. The analytical procedure encompassed examining the descriptive statistics and annual scientific production of the documents in the collection, identifying the most prolific and impactful authors, countries, and affiliations, and exploring the most impactful documents and sources. In addition, the analysis involved the examination of the most common keywords, their relation to other factors, and the thematic evolution of the use of blockchain in smart grids. The advancement of the research focus and directions as well as the most popular topics over the years were also examined.

Summing up the analysis results, on a yearly basis since 2015 there has been a growing interest in using blockchain technology in smart grids. The document annual growth rate is 127.9%, the document average age is 2.51 years, and the average number of citations that each document received is 18.75 citations. This fact highlights the novelty and significance of this field of study. Although most documents were published as conference papers (424), there are also many journal articles (383). Of the 1041 scientific documents, 922 were co-authored and 119 single-authored. Despite this fact and the average co-authors per document being 3.95, the international co-authorship rate was exceptionally low (2.79%). Following Bradford's law, the outlets used were clustered into three groups. A total of 519 different outlets were used. Based on the total number of citations and their h-index, the most impactful outlets were *IEEE Access*, *Energies*, *IEEE Transactions on Industrial Informatics*, *Applied Energy*, and *IEEE Internet of Things Journal*, and *IEEE Communications Surveys and Tutorials*. In total, 2672 authors from around the world contributed with their studies to this field. Most authors contributed a single document (76.6%), with only a marginal number of authors having contributed nine or more studies. The four authors that published the most documents on this topic were Kumar, N., Tanwar, S., Zhang, X., and Wang, H. When taking the authors' number of total citations received into account, Zhang, Y., Mengelkamp, E., Winhardt, C., and Kumar, N. were the four most impactful authors. When taking the authors' h-index into consideration, the most impactful ones were Kumar, N., Tanwar, S., Zhang, X., and Kumari, A. Of the 1289 different affiliations identified in this dataset, the affiliations whose authors published the most on this topic were North China Electric Power University, Nirma University, King Saud University, Thapar Institute of Engineering and Technology, Nanyang Technological university, and COMSATS University Islamabad. Based on the documents examined, authors from 53 countries contributed to this topic, with China, Germany, the United States of America, Australia, India, and Canada being the ones that received the most citations. According to the total number of citations, the countries that published most documents were China, India, Korea, the United States of America, and Australia. Based solely on the total number of citations, it can be inferred that of all the studies examined, the studies of Mengelkamp et al. [61], Kang et al. [62], Aitzhan et al. [63], Mengelkamp et al. [64], and Pop et al. [65] were the most impactful. Blockchain, smart grid, smart contract, Internet of Things, and security were the most common authors' keywords while blockchain, smart grid, electric power transmission networks, power markets, and Internet of Things were the most common keywords plus. The motor theme of the topic that emerged was related to blockchain, smart grids, microgrids, power markets, and the electric power transmission network, while, from the clusters that arose, it can be inferred that, besides the focus on using blockchain in smart grids within the power sector, additional focus is given on its use in electric and autonomous vehicles. Moreover, the trend topics depicted the shift of focus to the Internet of Things, smart contracts, blockchain, and intelligent solutions and the increased use of machine learning, artificial intelligence, authentication mechanisms, autonomous systems, and fog computing. Hence, it can be inferred that the current focus is on optimizing the production, transmission, distribution, and consumption within the power sector through autonomous, intelligent, and secure systems and processes and on analyzing how new technologies can interact and support each other to realize the digitalization of the power sector.

5. Conclusions

Examining the role and use of blockchain in smart grids and the development of the topic throughout the years was the main goal of this study. Specifically, this study involved an extensive bibliometric analysis and scientific mapping of 1041 scientific documents, which derived from the Scopus and WoS databases from 2015 to 2022, and explored 10 research questions. The data analysis used descriptive statistics and encompassed the identification of the annual scientific production, the most prolific and impactful authors, countries, and affiliations, the most impactful documents and sources, and the most common keywords. Moreover, the study also examined the advancement of the research focus, the most popular topics, the research directions, and the thematic evolution of the topic during this period. The outcomes and findings of this study contribute to bridging the existing gap in the literature, concerning the adoption and integration of blockchain in smart grids and the power sector in general.

The results of this study highlight the important role of blockchain in securing smart grids and realizing power sector digitalization, as well as in successfully meeting sustainable development goals and achieving sustainability. This study hopes to pave the way for new lines of work to be developed.

In the context of sustainability, future studies should further examine how blockchain can be integrated into different domains to ensure the achievement of sustainable development goals. Critical infrastructure plays a vital role in ensuring sustainability. There is a clear need for more empirical studies that integrate blockchain technology in smart grids and in critical infrastructure to be conducted. Finally, commonly accepted and used models, standards, frameworks, and metrics should be developed.

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Conflicts of Interest: The author declares no conflicts of interest.

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