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Artificial intelligence in smart grids: A bibliometric analysis and scientific mapping study

Georgios Lampropoulos [a, b, *]

[a] *Department of Information and Electronic Engineering, International Hellenic University*
14th km Thessaloniki - N. Moudania National Road, Thermi, GR 57001, Greece
[b] *School of Humanities, Hellenic Open University*
18 Aristotelous St, Patras, GR 26335, Greece

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Abstract

The realization of sustainable development and sustainable development goals achievement are essential. Hence, the power sector digitalization is imminent. This bibliometric and mapping study aims to explore the use of artificial intelligence in smart grids and how the topic has evolved over the years. In total, ten research questions are set to be explored. The analysis includes 1,926 articles that were identified and retrieved from Scopus and Web of Science (WoS) over the period 2005 to 2022. The analysis includes the descriptive statistics of the related studies and the annual scientific production, the identification of the most relevant and impactful authors, articles, outlets, affiliations, and countries, and the examination of the most commonly used keywords. The most popular topics and the advancement of the research focus are also explored. The study examines the results, discusses the main findings, presents open issues, and suggests new research directions. The significant role of artificial intelligence in the realization of smart grids and the digitalization of the power sector to enable sustainable development and the achievement of sustainable development goals was evident.

Keywords: artificial intelligence; smart grid; power sector; renewable energy resources; sustainable development.

I. Introduction

The increase in electricity consumption and demand is a global phenomenon that has led to worldwide concerns regarding environmental preservation and energy sustainability [1][2]. Problems arise in the increasing power grid complexity and in the production, management, distribution, and consumption of electrical energy while simultaneously, the need for more reliable, secure, efficient, affordable, sustainable, and environmentally friendly methods and approaches increases [3][4][5]. As the power industry has electricity grids at its core, the transformation, and modernization of existing power grids have been widely researched, and technological innovations have been experienced [6]. Conventional power grids are capable of generating, transmitting, distributing, and controlling electricity through an electromechanical hierarchical structure [7]. Despite this fact, they transfer electric energy to consumers in a unidirectional power flow that derives from large-scale centralized generators through an interconnected network that supports one-way communication [8]. Hence, although Information and Communication Technologies (ICT) have been implemented in the context of power grids to make them greener [1], process energy from multiple sources [9], and build smart cities [10] as well as create a sustainable and eco-friendly society, it is important to modernize and transform current centralized power grids into intelligent, automated, and decentralized smart grids [11][12][13].

Although there is no commonly accepted definition regarding smart grids, there are common aspects and elements in the definitions provided in the literature [1][14][15]. Particularly, smart grids constitute a vision of the future of cleaner, more adaptive, resilient, eco-friendly, and effective

* Corresponding Author. +30-2310-013075
E-mail address: lamprop.geo@gmail.com

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electrical grids, which are pervasively and actively controlled, managed, and monitored by highly intelligent systems [7][14][16]. The transition to smart grids entails the use of automated, interoperable, and distributed digital systems and energy networks that capitalize on computational intelligence to self-heal, monitor, and automatically and autonomously make decisions and cognitive adjustments based on data and previous and current environmental changes in the grid in real-time [7][15][17]. Hence, the functionality that smart grids provide can also improve the efficiency and effectiveness of the existing infrastructure [1][13].

More specifically, smart grids constitute self-sufficient systems [18] that put emphasis on both prosumers and consumers to generate and distribute energy [2], use heterogeneous data and various data sources [19], enable renewable energy resources to be integrated into the grid [1], and can dynamically respond to various conditions and events and address issues that appear throughout the network and grid [7]. Smart grids are characterized as the next-generation power grid and are radically different from traditional grids as they capitalize on ICT to enable bidirectional and more efficient electricity delivery and information exchange [16][20] and facilitate and improve energy generation, transmission, distribution, and control [21]. Moreover, they can function in a more organic, responsive, and collaborative manner in comparison to conventional grids [1]. Therefore, they have the potential to increase overall efficiency, performance, availability, security, and reliability [22]. The main differences between traditional grids and smart grids are summarized in Table 1 [1][6][14][23].

The use of several technologies to support and enrich smart grids is being explored in the literature. Among these technologies, artificial intelligence is regarded as one of the most popular, as it has the potential to greatly affect the power sector. Artificial intelligence refers to the capability of computers, systems, and machines to acquire reasoning abilities, communicate, and interact with their environment by simulating human intelligence and mimicking human actions [24][25]. Artificial intelligence can improve machine-to-machine communication and human-computer interaction [26] through the development of intelligent and autonomous decision-making systems that have human characteristics, cognitive functions, and rational capabilities [27]. More specifically, artificial intelligence can be implemented throughout its value chain [28], improve power system productivity and operation, reduce costs [29], overcome the limits of the current power production and distribution systems, and lead to sustainable economic growth [30]. The beneficial role of artificial intelligence in smart grids is amplified by the increasing complexity of the power infrastructure and the exponentially increasing volume of data [31].

Despite the number of studies on this topic continuing to increase, there has not been a study that explores how the use of artificial intelligence in smart grids has developed over the years and what the main research directions and areas are. Consequently, to address this gap in the literature, the aim of this study is to analyze through bibliometric analysis and scientific mapping how the research regarding the adoption and implementation of artificial intelligence in smart grids has evolved. To guide this study, the following research questions (RQ) were set:

- RQ1: What are the descriptive statistics of the related studies?
- RQ2: What are the characteristics (annual growth, average citations, and co-citation network) of the annual scientific production of studies?
- RQ3: Which are the most relevant and impactful outlets?
- RQ4: Which authors have published the most on this topic and were the most impactful?
- RQ5: Which are the most relevant and most impactful affiliations?
- RQ6: Which countries conducted the most relevant and impactful studies?
- RQ7: Which were the most impactful articles?
- RQ8: Which keywords are mostly used, and how are they related to other factors (e.g., countries, sources, etc.)?
- RQ9: Which were the most popular topics explored?
- RQ10: How the main research focus on this topic evolved over the years?

Table 1.
Comparison between traditional/conventional power grids and smart/intelligent grids adapted from [1][6][14][23]

Traditional/Conventional grid	Smart/Intelligent grid
Mechanically operated / mechanization	Digitized/digitalization
One-way communication / unilateral	Two-way real-time communication / bi-directional
Centralized power generation	Distributed power generation
Radial network / radially connected	Dispersed network / dispersed connected
A small number of sensors	Many sensors throughout
Fewer monitoring capabilities / manual monitoring	Many monitoring capabilities / highly automatic monitoring
Manual control / limited control	Automated control / pervasive control
Manual recovery	Automated recovery
Fewer security and privacy issues and concerns	More prone to security and privacy issues and concerns
Slow response to actions and emergencies	Fast response to actions and emergencies
Fewer data use	High data use
Fewer user choices	Many user choices
Inflexible and static	Flexible and adaptive

II. Materials and Methods

The bibliometric approach is a fitting research methodology to analyze how a certain topic has evolved over the years [32]. The current bibliometric study adopted the methodological approach described in [33] and followed the guidelines described in [34]. Taking the essential requirements of a bibliometric study [34][35] and the need for the databases used to be accurate, relevant, and impactful into account, the Scopus and Web of Science (WoS) databases were selected to retrieve the related documents [36]. The tool selected to be used to conduct the analysis and visualization of the data is the open-source R package "Bibliometrics" which can utilize both Scopus and WoS data [33]. The query used was: ("artificial intelligence" OR "ai") AND ("smart grid" OR "intelligent grid" OR "smart power grid" OR "intelligent power grid" OR "smart electric* grid" OR "intelligent electric grid*").

In total, 2,462 related documents were retrieved 1,840 from Scopus and 622 from WoS. After removing the 536 duplicates, the final number of documents included in this analysis was 1,926. The result analysis was grouped into: 1) Main information, 2) Citations, 3) Sources, 4) Authors, 5) Countries, and 6) Documents and represented through tables, diagrams, and figures. Figure 1 presents the process of the research, which involved the stages of i) the initial search for an appropriate topic, keywords, and data sources, ii) the data identification, exportation, preprocessing, and import to Bibliometrix, iii) the conduct of the bibliometric analysis, and iv) the result interpretation and conclusions.

III. Results and Discussions

A. Main information

The main information of the studies included in this bibliometric analysis is presented in Table 2, which showcases the description of each item and its corresponding result. Particularly, 1,926 studies were published in 947 different outlets during the period of 2005-2022. The average age of the documents is 4.89 years, and the annual growth rate is 27.5 %. In total, 61,064 references are used across all studies, which on average, receive 14.3 citations. As a whole, 4,746 authors were involved in these

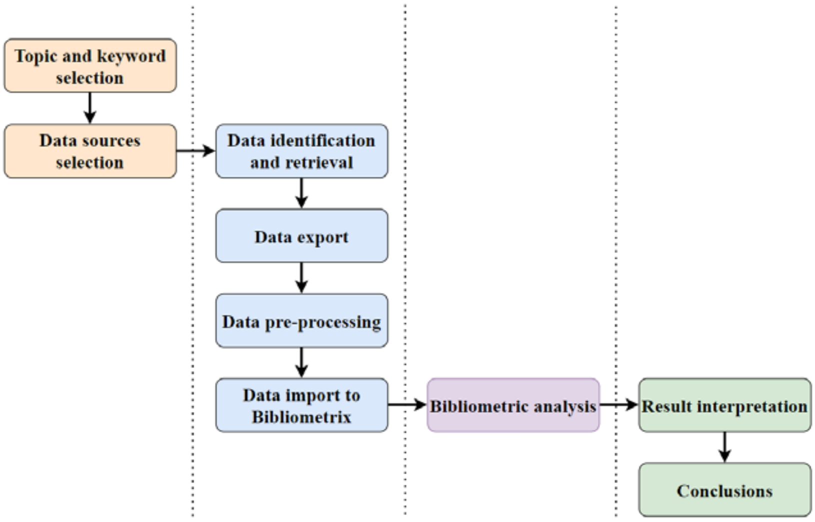

Figure 1. Stages in the research process

Table 2.
The main information of the bibliometric analysis

Description	Results	Description	Results	Description	Results
Timespan	2005-2022	Document contents		Document types	
Sources (journals, books, etc.)	947	Keywords plus (ID)	9,156	Article	534
Documents	1,926	Author's keywords (DE)	4,605	Article; book chapter	1
Annual growth rate %	27.5			Article; early access	2
Document average age	4.89	Authors		Book	13
Average citations per doc	14.3	Authors number	4,746	Book chapter	52
References	61,064	Authors of single-authored docs	106	Conference paper	1,119
		Authors' collaboration		Conference review	55
		Single-authored docs	179	Editorial	7
		Co-authors per Doc	3.7	Editorial material	3
		International co-authorships %	1.558	Note	1
				Proceedings paper	20
				Review	118
				Review; early access	1

studies, with 179 single-authored documents and an average of 3.7 authors per study, while the international co-authorship rate was really low at 1.56 %. Most studies were published as conference papers (1,119), followed by journal articles (534) (RQ1).

B. Citations

As the annual growth rate of the related studies is positive, the total number of articles that are published yearly increases except for the year 2017. Due to this fact, most articles were published during 2021 and 2022. The significance of renewable energy and of creating efficient and effective power grids that utilize artificial intelligence can be a determining factor for this specific increase. The annual scientific production is displayed in Figure 2. Particularly, the X axis refers to the years while the Y axis represents the number of articles. As can be seen, there is a clear increase in the number of articles examining this topic as well as the annual scientific production. On this note, and while taking the average age and citations of the documents into account, it is obvious that the average citations per year increased, as can be seen in Figure 3. Specifically, the X axis refers to the years, while the Y axis represents the number of citations. As can be seen, there has been a clear increase in the number of citations over the years, with the exception of the recent articles of the last five years due to their recency. Finally, the co-citation network of the collection documents is presented in Figure 4, in which nine main clusters of documents can be observed that highlight the interdisciplinary nature, flexibility, and outreach of the topic (RQ2).

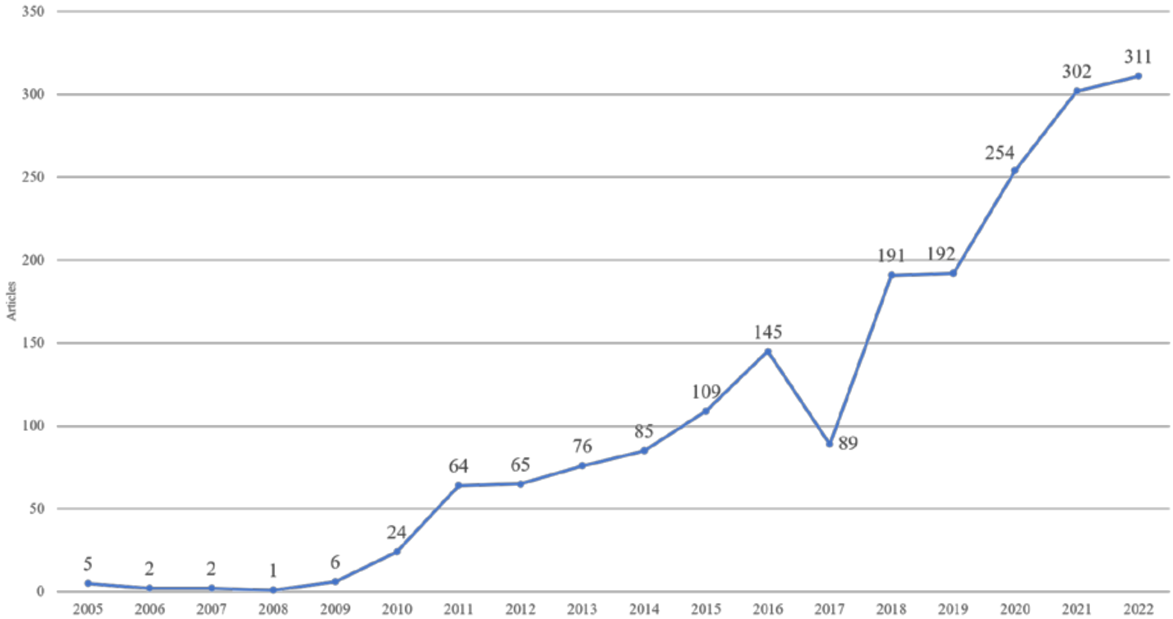

Figure 2. Annual scientific production

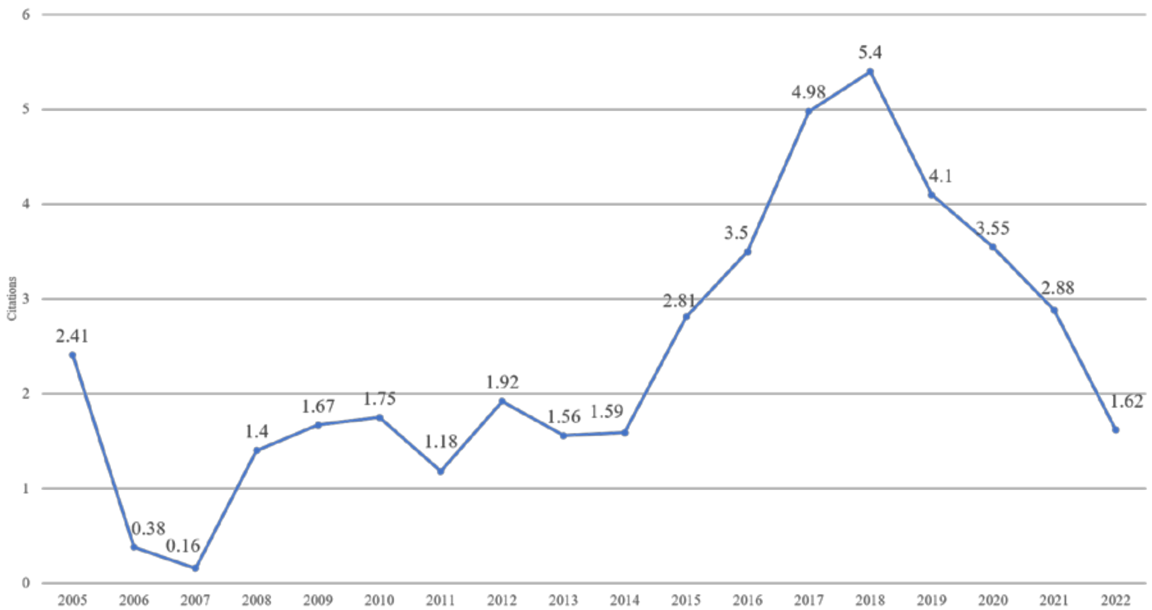

Figure 3. Average citation per year

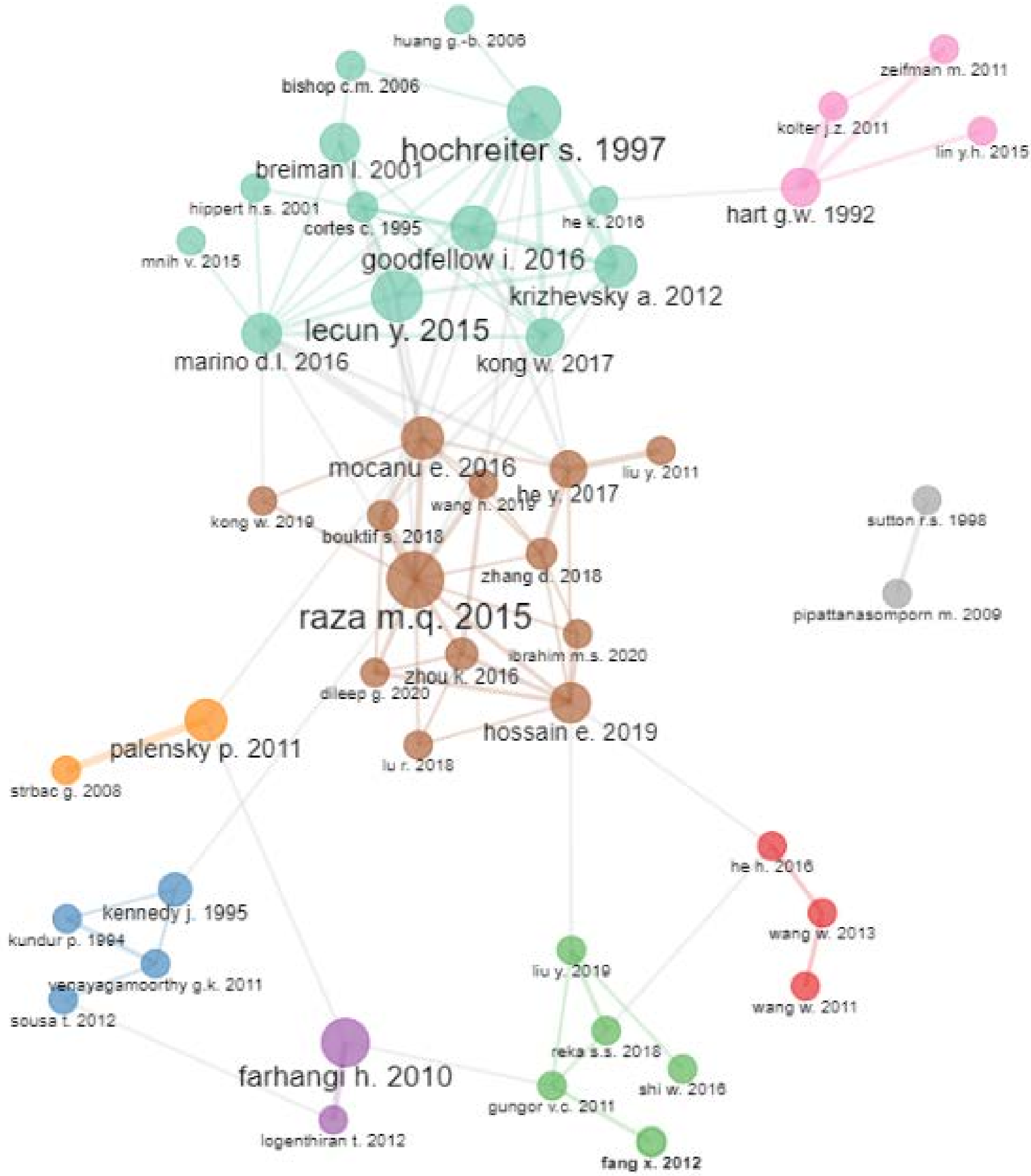

Figure 4. Document co-citation network

C. Sources

Over the time period of 2005-2022, various scientific outlets were used. The top-15 sources out of the 947 different outlets are displayed in Figure 5. Particularly, the X axis refers to the number of documents, while the Y axis represents the sources of the documents. As it can be observed, there is a variety of sources spanning across journals, conferences, and books. The top-5 most relevant sources based on the number of published articles were "Lecture Notes in Computer Science," "Energies," "IEEE Access," "Advances in Intelligent Systems and Computing," and "IEEE Symposium on Computational Intelligence Applications in Smart Grid." The top-4 most impactful outlets based on their h-index and number of total citations (TC) were "IEEE Transactions on Smart Grid," "Energies," "IEEE Access," and "Applied Energy." As a combination of journals, conferences, and book series can be seen across the top outlets, the importance and the breadth of the topic become more evident.

The source clustering following Bradford's law, which shows the quantitative relationship between scientific outlets and articles, revealed three clusters. The first cluster consisted of 40 sources in which 636 articles were published, the second cluster had 273 sources and 651 articles, and the third cluster comprised 633 sources and 633 articles, respectively. The source field was not filled in some articles. Hence, the numbers of the sources and articles do not add up exactly to the initially reported numbers. Figure 6 presents the dynamic of the top ten sources based on Bradford's law. Specifically, it presents the number of documents published in each of the top sources each year, as well as the total number of published documents. Additionally, the color scale showcases the years that had the most published documents in each source.

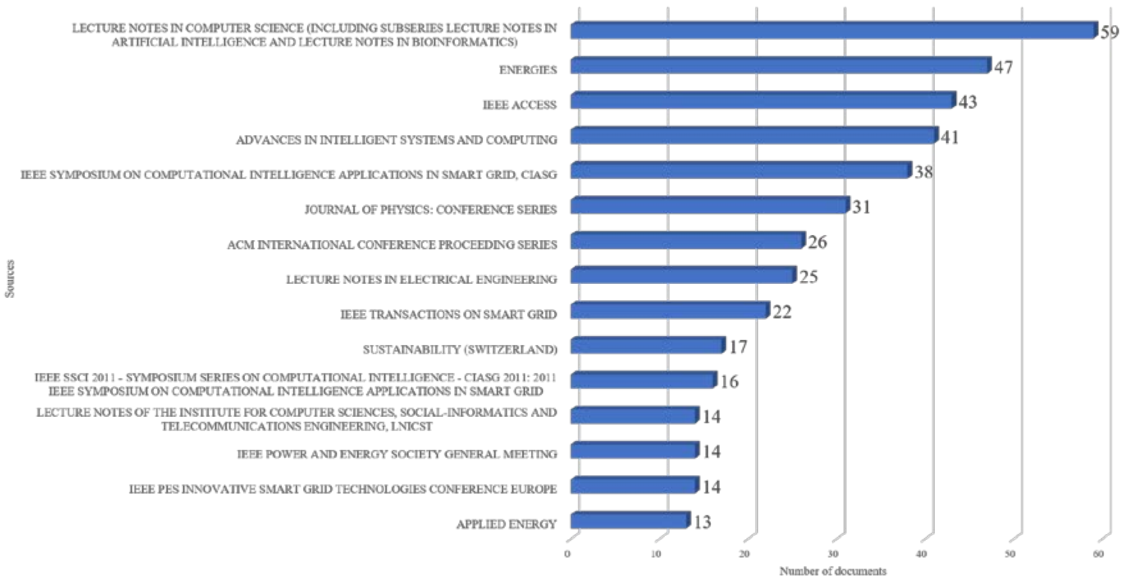

Figure 5. The most relevant sources

	LECTURE NOTES IN COMPUTER SCIENCE (INCLUDING SUBSERIES LECTURE NOTES IN ARTIFICIAL INTELLIGENCE AND LECTURE NOTES IN BIOINFORMATICS)	ENERGIES	IEEE ACCESS	ADVANCES IN INTELLIGENT SYSTEMS AND COMPUTING	IEEE SYMPOSIUM ON COMPUTATIONAL INTELLIGENCE APPLICATIONS IN SMART GRID, CIASG	JOURNAL OF PHYSICS: CONFERENCE SERIES	ACM INTERNATIONAL CONFERENCE PROCEEDING SERIES	LECTURE NOTES IN ELECTRICAL ENGINEERING	IEEE TRANSACTIONS ON SMART GRID	SUSTAINABILITY (SWITZERLAND)
2005	0	0	0	0	0	0	0	0	0	0
2006	1 (1)	0	0	0	0	0	0	0	0	0
2007	0 (1)	0	0	0	0	0	0	0	0	0
2008	0 (1)	0	0	0	0	0	0	0	0	0
2009	0 (1)	0	0	0	0	0	0	0	0	0
2010	2 (3)	0	0	0	0	0	0	0	0	0
2011	2 (5)	0	0	0	0	0	0	0	0	0
2012	4 (9)	0	0	0	0	0	0	0	2 (2)	0
2013	3 (12)	0	0	1 (1)	16 (16)	0	0	0	5 (7)	0
2014	4 (16)	0	0	0 (1)	0 (16)	0	1 (1)	1 (1)	1 (8)	0
2015	5 (21)	0	0	2 (3)	22 (38)	0	0 (1)	0 (1)	2 (10)	0
2016	2 (23)	2 (2)	0	7 (10)	0 (38)	0	1 (2)	0 (1)	2 (12)	0
2017	8 (31)	0 (2)	0	3 (13)	0 (38)	0	2 (4)	0 (1)	2 (14)	0
2018	7 (38)	10 (12)	6 (6)	6 (19)	0 (38)	2 (2)	7 (11)	1 (2)	1 (15)	2 (2)
2019	8 (46)	6 (18)	3 (9)	3 (22)	0 (38)	7 (9)	7 (18)	1 (3)	3 (18)	1 (3)
2020	3 (49)	4 (22)	11 (20)	13 (35)	0 (38)	5 (14)	3 (21)	6 (9)	1 (19)	4 (7)
2021	6 (55)	9 (31)	8 (28)	6 (41)	0 (38)	14 (28)	4 (25)	7 (16)	2 (21)	3 (10)
2022	4 (59)	16 (47)	15 (43)	0 (41)	0 (38)	3 (31)	1 (26)	9 (25)	1 (22)	7 (17)
Total	59	47	43	41	38	31	26	25	22	17

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

Table 3.
Source clustering through Bradford's law

Source	Rank	Freq	cumFreq	Cluster
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	1	59	59	Cluster 1
Energies	2	47	106	Cluster 1
IEEE Access	3	43	149	Cluster 1
Advances in Intelligent Systems and Computing	4	41	190	Cluster 1
IEEE Symposium on Computational Intelligence Applications in Smart Grid (CIASG)	5	38	228	Cluster 1
Journal of Physics: Conference Series	6	31	259	Cluster 1
ACM International Conference Proceeding Series (ICPS)	7	26	285	Cluster 1
Lecture Notes in Electrical Engineering (LNEE)	8	25	310	Cluster 1
IEEE Transactions on Smart Grid	9	22	332	Cluster 1
Sustainability	10	17	349	Cluster 1

Table 3 displays the top ten sources of cluster 1 based on Bradford's law, in which the rank, frequency, number of documents, and cluster are presented. Moreover, Table 4 and Table 5 display the top ten most impactful scientific outlets based on their h-index and total number of citations accordingly. Specifically, Table 4 and Table 5 present the source and its related index, the total number of citations, the number of published documents, and the date of the first related document publication (RQ3).

Table 4.
Top-10 most impactful sources based on their h-index

Source	h_index	g_index	m_index	TC	NP	PY_start
IEEE Transactions on Smart Grid	17	22	1.417	1988	22	2012
Energies	16	32	2	1085	47	2016
IEEE Access	16	33	2.667	1099	43	2018
Applied Energy	13	13	1.083	1047	13	2012
IEEE SSCI 2011: IEEE Symposium Series on Computational Intelligence - CIASG 2011: IEEE Symposium on Computational Intelligence Applications in Smart Grid	9	16	0.692	328	16	2011
International Journal of Electrical Power & Energy Systems	9	12	1.125	448	12	2016
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	9	14	0.5	255	59	2006
IEEE Symposium on Computational Intelligence Applications in Smart Grid (CIASG)	8	15	0.727	259	38	2013
Sustainability	8	13	1.333	173	17	2018
Dianli Xitong Zidonghua / Automation of Electric Power Systems	7	7	0.5	289	7	2010
Energy	7	8	0.778	402	8	2015
IEEE Power & Energy Society (PES) General Meeting (GM)	7	9	0.538	101	14	2011
Renewable and Sustainable Energy Reviews	7	9	0.7	1011	9	2014
Zhongguo Dianji Gongcheng Xuebao / Proceedings of the Chinese Society of Electrical Engineering	7	9	0.583	462	9	2012
Advances in Intelligent Systems and Computing	6	9	0.545	113	41	2013

Table 5.
Top-10 most impactful sources based on their total number of citations (TC)

Source	h_index	g_index	m_index	TC	NP	PY_start
IEEE Transactions on Smart Grid	17	22	1.417	1988	22	2012
IEEE Access	16	33	2.667	1099	43	2018
Energies	16	32	2	1085	47	2016
Applied Energy	13	13	1.083	1047	13	2012
Renewable and Sustainable Energy Reviews	7	9	0.7	1011	9	2014
IEEE Wireless Communications	2	5	0.286	730	5	2017
Energy Conversion and Management	2	2	0.167	569	2	2012
IEEE Transactions on Industrial Informatics	6	8	0.667	554	8	2015
IEEE Transactions on Neural Networks and Learning Systems	2	2	0.25	468	2	2016
Zhongguo Dianji Gongcheng Xuebao / Proceedings of the Chinese Society of Electrical Engineering	7	9	0.583	462	9	2012
International Journal of Electrical Power & Energy Systems	9	12	1.125	448	12	2016
Energy and Buildings	6	7	0.6	433	7	2014
IEEE Transactions on Industrial Electronics	2	2	0.222	420	2	2015
CSEE Journal of Power and Energy Systems	5	6	0.833	410	6	2018
Energy	7	8	0.778	402	8	2015

D. Authors

As the applicability of the topic can be extended to various sectors and include numerous technologies, a number of authors with different backgrounds and expertise have contributed to the exploration of the use of artificial intelligence in smart grids. The top authors based on the number of their published articles are presented in Table 6, which describes the author, the number of documents published on this topic, and the articles fractionalized.

The authors' production over time is displayed in Figure 7. Particularly, the X axis of Figure 7 presents refers to the years while the Y axis represents the authors. It can be said that the top authors, according to the number of documents published, mostly started examining this topic around the period of 2010-2013. The top-5 authors that

Table 6.
Top authors based on the number of their published articles

Authors Name	Articles Number	Articles Fractionalized
Vale Z	35	8.04
Liu Y	28	7.49
Wang Y	27	5.22
Chen Y	23	5.95
Li Y	20	5.53
Zhang J	19	3.72
Zhang X	19	4.4
Wang X	18	4.14
Li J	17	3.4
Soares J	17	3.76
Wang J	17	4.46
Zhang L	17	3.89

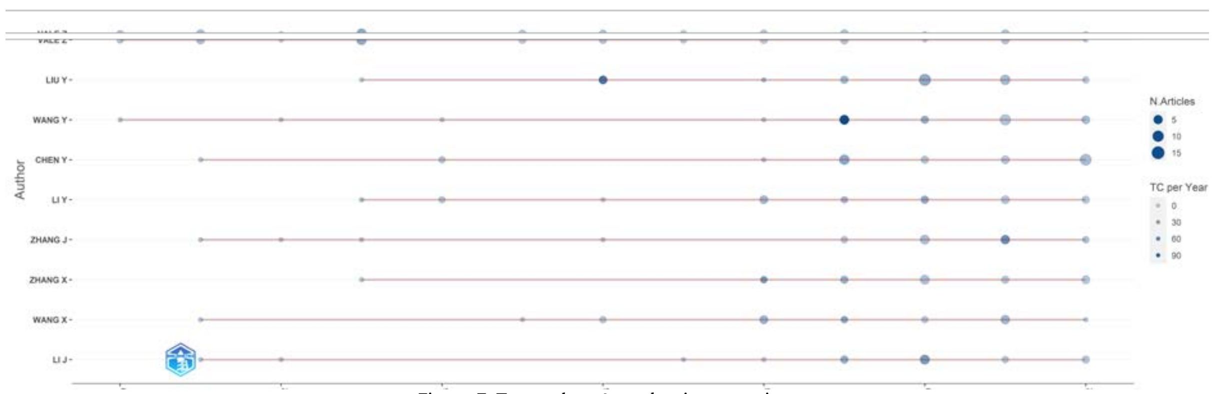

Figure 7. Top authors' production over time

published the most articles were Vale Z., Liu Y., Wang Y., Chen Y., and Lin Y. Additionally, the authors' productivity through Lotka's law can be seen in Figure 8 with the X axis representing the number of documents written while the Y axis referring to the percentage of authors, the overwhelming majority of authors have written either a single article (79 %) or five articles at the most on this topic (RQ4).

The most impactful authors can be seen in Table 7 and Table 8, which showcase the author, the index, the total number of citations, the number of published documents, and the first year that the first document got published. Particularly, in Table 7, the authors are presented according to their h-index of their articles on this topic, while in Table 8, they are displayed based on the total number of citations that

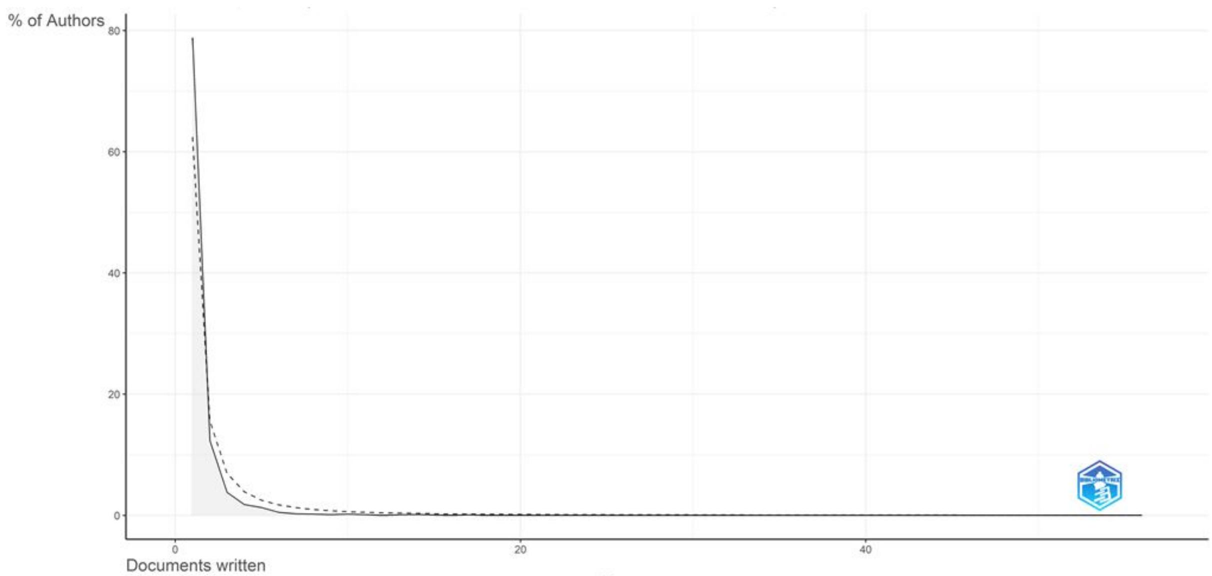

Figure 8. Authors' overall productivity through Lotka's law

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

Author	h_index	g_index	m_index	TC	NP	PY_start
Vale Z	10	24	0.714	621	35	2010
Liu Y	9	23	0.818	571	28	2013
Chen Y	8	14	0.615	219	23	2011
Faria P	8	15	0.571	465	15	2010
Venayagamoorthy G	8	14	0.533	280	14	2009
Zhang D	8	10	1	697	10	2016
Khang S	7	10	0.778	388	10	2015
Li Y	7	18	0.636	349	20	2013
Lin Y	7	16	0.636	314	16	2013
Morais H	7	15	0.5	491	15	2010
Rogers A	7	9	0.538	732	9	2011
Soares J	7	17	0.538	434	17	2011
Wang X	7	18	0.538	344	18	2011
Zhang J	7	15	0.538	236	19	2011

Table 8.
Most impactful authors based on the total number of citations on this topic.

Author	h_index	g_index	m_index	TC	NP	PY_start
Han Z	2	2	0.286	1006	2	2017
Zhang H	4	10	0.5	884	10	2016
Rogers A	7	9	0.538	732	9	2011
Ren Y	2	3	0.154	719	3	2011
Chen K	1	4	0.143	717	4	2017
Hanzo L	1	1	0.143	717	1	2017
Jiang C	1	1	0.143	717	1	2017
Wang Y	6	26	0.429	704	27	2010
Zhang D	8	10	1	697	10	2016
Ramchurn S	5	7	0.385	682	7	2011

their work on this topic has received. The top-5 most impactful authors based on their h-index of their related articles were Vale Z., Liu Y., Chen Y., Faria P., and Venayagamoorthy G. The top-4 authors based on their total number of citations of their related to the topic articles were Han Z., Zhang H., Rogers A., and Ren Y. (RQ4).

An average of 3.7 authors contributed to each document. The collaboration network based on authors is presented in Figure 9. In this figure, four main clusters can be observed, which demonstrate the closest collaborators and the groups of authors mostly exploring this topic. Additionally, Figure 10 depicts the co-citation network of the authors in which five prominent authors can be observed.

The authors, whose studies are included in this collection, are members of 2,132 different affiliations. The most relevant affiliations based on the number of studies that were conducted in them are depicted in Figure 11. Specifically, the X axis of the figure refers to the number of documents, while the Y axis represents the affiliations of the authors. As can be seen, the top affiliations all have at least 12 documents published on this topic. The top-5 affiliations with the highest number of publications were China Electric Power Research Institute, North China Electric Power University, Nanyang Technological University, Zhejiang University, and Carnegie Mellon University.

The affiliations with the highest publication production over time are presented in Figure 12, which specifically presents the number of documents published from each of the top affiliations in each year as well as the total number of published documents. Additionally, the color scale showcases the years that had the most published documents in each source. Finally, the collaboration network based on affiliations is displayed in Figure 13, in which 11 clusters can be observed, a fact that highlights the flexibility, broadness, and interdisciplinary nature of this topic (RQ5).

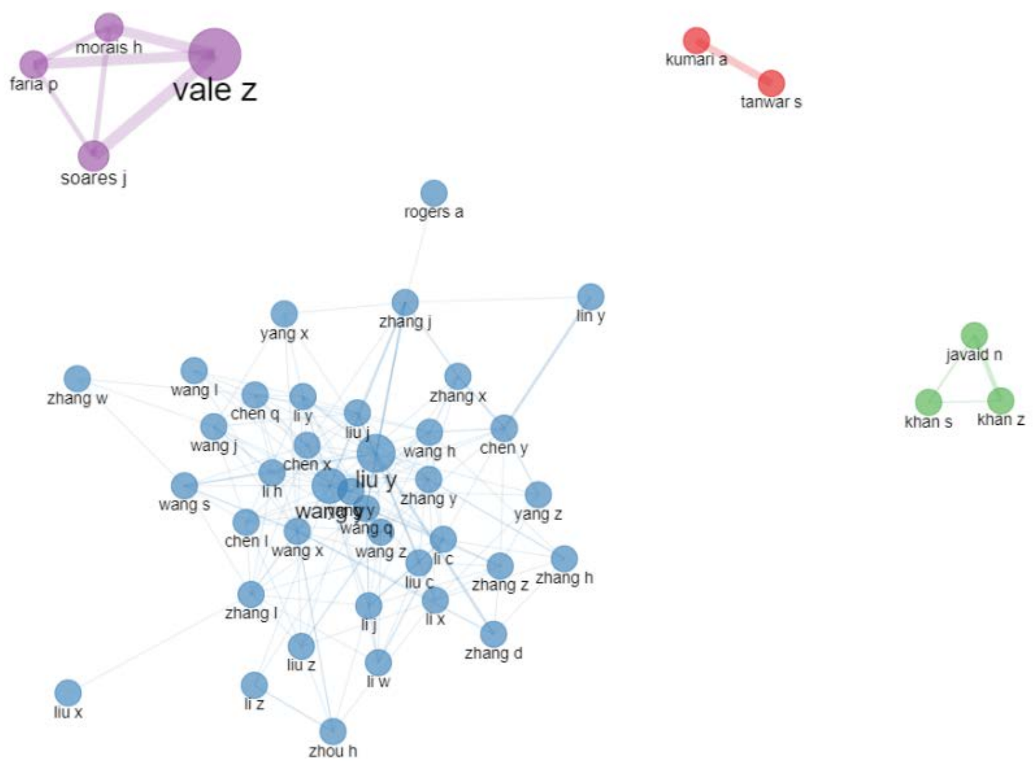

Figure 9. Authors' collaboration network

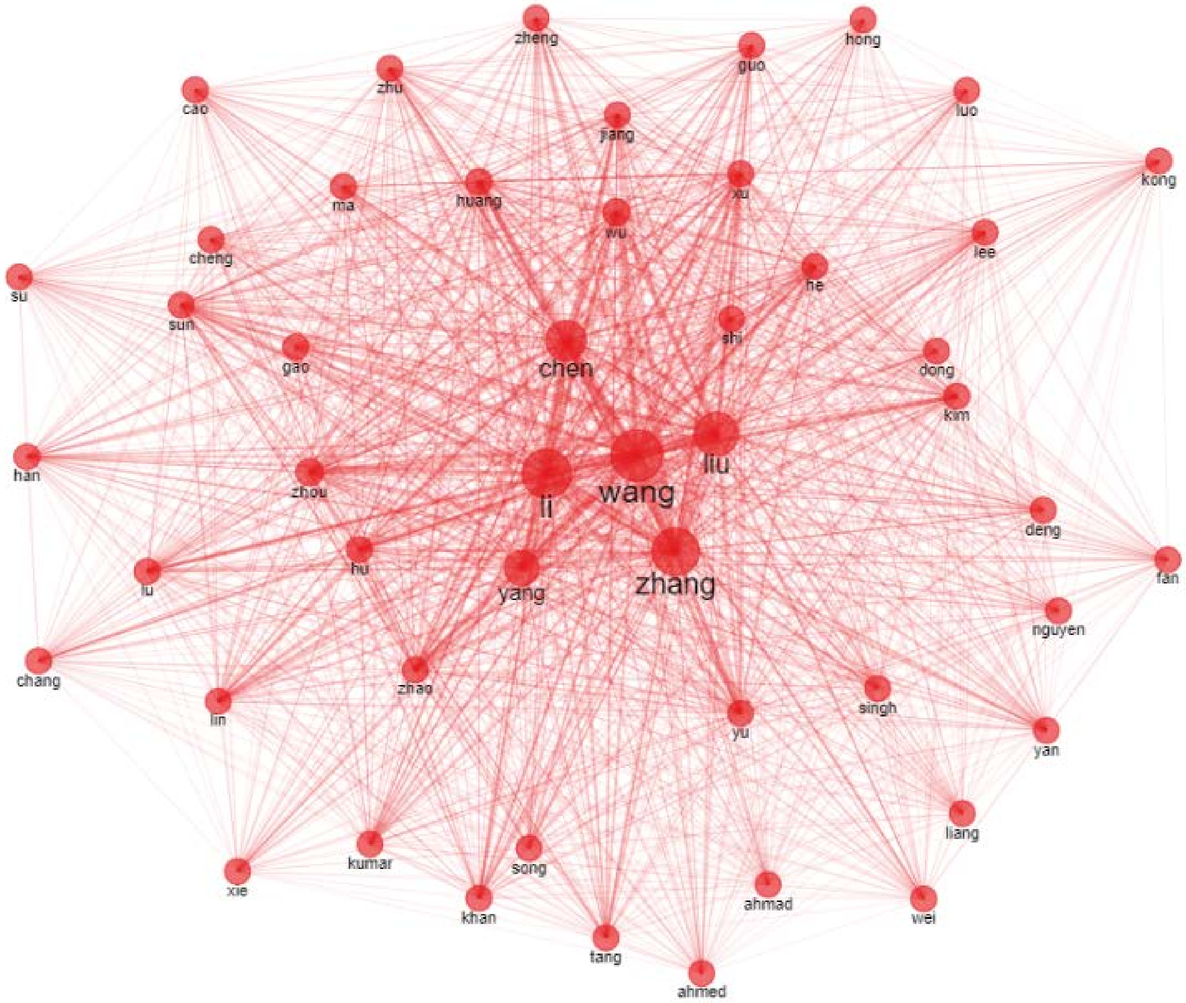

Figure 10. Authors' co-citation network

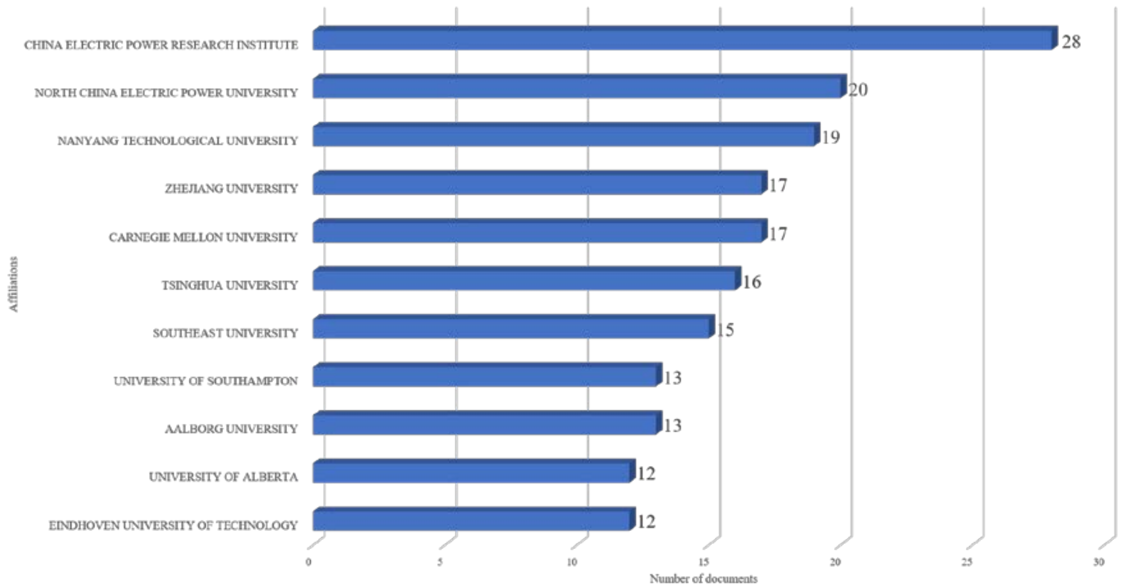

Figure 11. Most relevant affiliations based on the number of studies

E. Countries

Authors from 66 countries published on this topic. China, India, and the United States contributed the most studies. China, the United States, Canada, the United Kingdom, and Korea were the five countries that received the most citations shown in Figure 14. More specifically, the X axis represents the countries, while the Y axis refers to the total number of citations received. It is worth highlighting the drastic changes to the number of citations, even among the top countries, based on the number of

	CHINA ELECTRIC POWER RESEARCH INSTITUTE	NORTH CHINA ELECTRIC POWER UNIVERSITY	NANYANG TECHNOLOGICAL UNIVERSITY	CARNEGIE MELLON UNIVERSITY	ZHEJIANG UNIVERSITY	TSINGHUA UNIVERSITY	SOUTHEAST UNIVERSITY	AALBORG UNIVERSITY	UNIVERSITY OF SOUTHAMPTON	EINDHOVEN UNIVERSITY OF TECHNOLOGY
2005	0	0	0	0	0	0	0	0	0	0
2006	0	0	0	0	0	1 (1)	0	0	0	0
2007	0	0	0	0	0	0 (1)	0	0	0	0
2008	0	0	0	0	0	0 (1)	0	0	0	0
2009	0	0	0	0	0	0 (1)	0	0	0	0
2010	0	0	0	0	2 (2)	0 (1)	0	0	0	0
2011	0	1 (1)	0	4 (4)	1 (3)	0 (1)	0	0	3 (3)	1 (1)
2012	2 (2)	2 (3)	0	2 (6)	0 (3)	0 (1)	1 (1)	1 (1)	3 (6)	0 (1)
2013	0 (2)	0 (3)	1 (1)	3 (9)	0 (3)	0 (1)	1 (2)	0 (1)	0 (6)	2 (3)
2014	2 (4)	2 (5)	0 (1)	2 (11)	0 (3)	0 (1)	3 (5)	0 (1)	1 (7)	0 (3)
2015	0 (4)	0 (5)	1 (2)	2 (11)	0 (3)	0 (1)	0 (5)	2 (3)	1 (8)	0 (3)
2016	0 (4)	1 (6)	2 (4)	2 (13)	0 (3)	1 (2)	1 (6)	0 (3)	3 (11)	1 (4)
2017	2 (6)	2 (8)	3 (7)	3 (16)	0 (3)	2 (4)	0 (6)	0 (3)	2 (13)	1 (5)
2018	2 (8)	2 (8)	2 (9)	1 (17)	2 (5)	4 (8)	2 (8)	2 (5)	0 (13)	1 (6)
2019	4 (12)	4 (12)	0 (9)	0 (17)	3 (8)	1 (9)	1 (9)	0 (5)	0 (13)	3 (9)
2020	6 (18)	3 (15)	2 (11)	0 (17)	3 (11)	2 (11)	1 (10)	1 (6)	0 (13)	1 (10)
2021	9 (27)	2 (17)	4 (15)	0 (17)	3 (14)	4 (15)	2 (13)	5 (11)	0 (13)	1 (11)
2022	1 (28)	3 (20)	4 (19)	0 (17)	3 (17)	1 (16)	2 (15)	2 (13)	0 (13)	1 (12)
Total	28	20	19	17	17	16	15	13	13	12

Figure 12. Most relevant affiliations' production over time

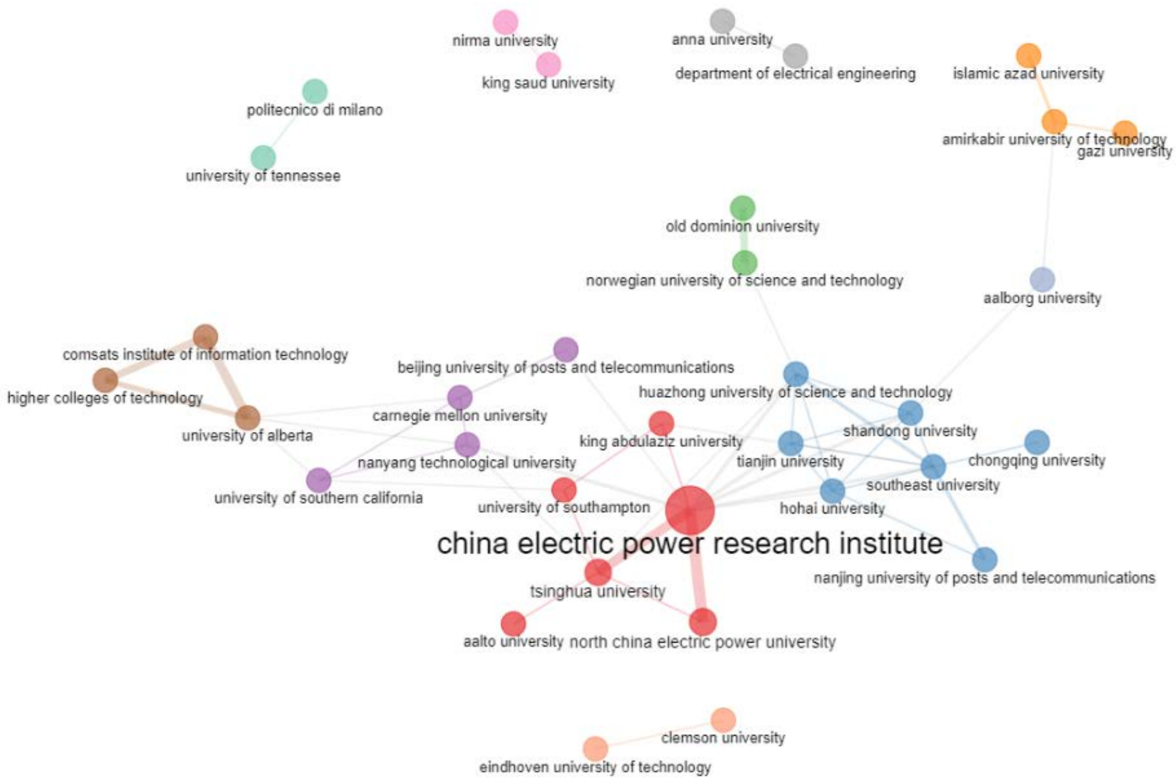

Figure 13. Collaboration network based on affiliations

articles published. The top ten countries that published the most on this topic based on the corresponding author's country are depicted in Figure 15. In this figure, the X axis refers to the number of documents, while the Y axis represents the countries based on the country of the first author in each document published.

The drastic change in the number of citations received is once again obvious, even among the top countries. The overall country's scientific production, when taking all authors' nationalities into consideration, is displayed in Figure 16, which highlights the significance of the topic as authors and groups worldwide explore it. In Figure 17, the production over time of the top-10 countries that contributed the most is presented. In particular, it presents the number of documents published in each of the top countries each year as well as the total number of published documents. Additionally, the color scale showcases the years that had the most published documents in each source. China, the United States, India, Germany, and Italy were the top-5 countries that published most articles.

The collaboration network and map based on countries are displayed in Figure 18 and Figure 19, respectively. The seven clusters and the limited number of lines indicating the collaboration among countries highlight the fact that the promotion of international collaboration should be further encouraged (RQ6).

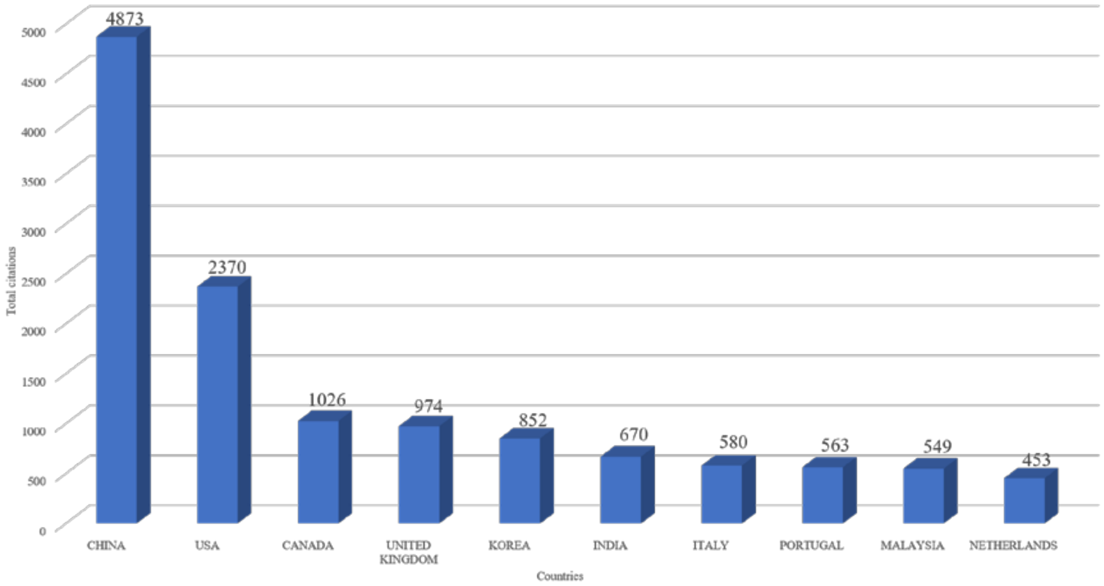

Figure 14. Top-10 countries that received the most citations

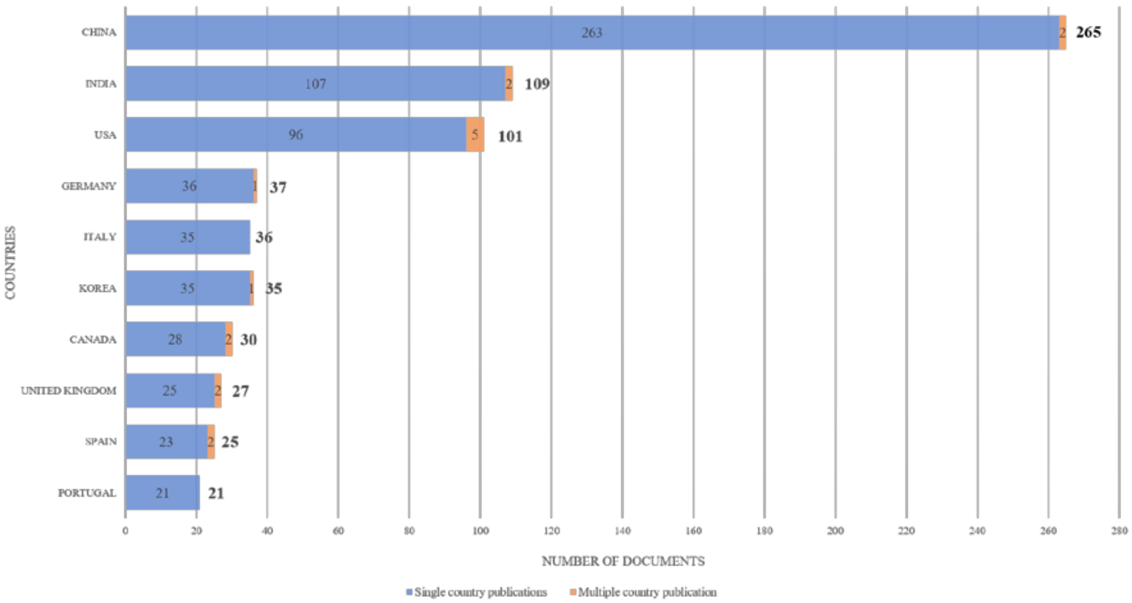

Figure 15. Countries that published the most based on the corresponding author's country

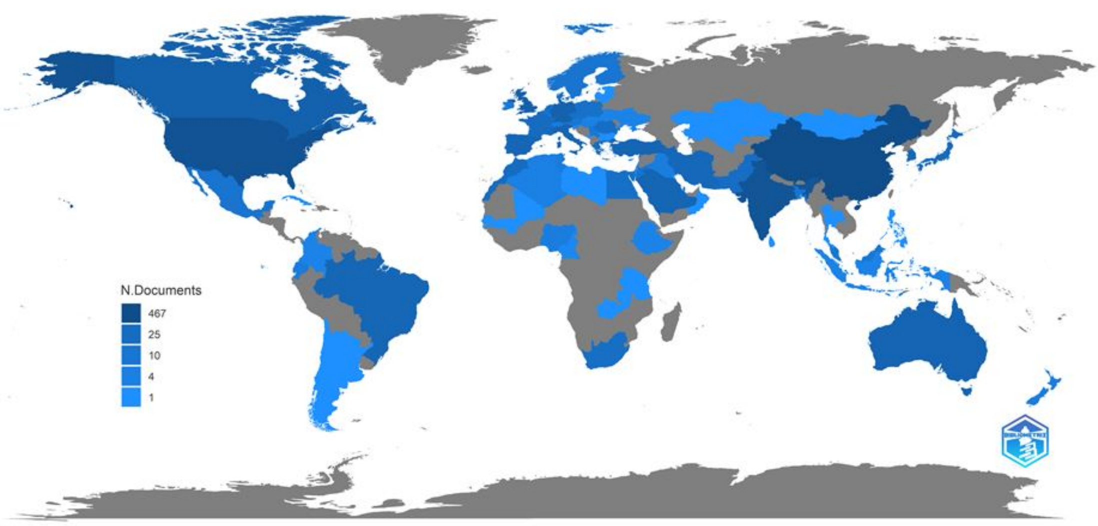

Figure 16. Countries' overall scientific production

	CHINA	USA	INDIA	UNITED KINGDOM	CANADA	GERMANY	AUSTRALIA	ITALY	SAUDI ARABIA	TURKEY
2005	0	2 (2)	0	1 (1)	0	0	0	0	0	0
2006	1 (1)	0 (2)	0	0 (1)	0	0	0	0	0	0
2007	1 (2)	0 (2)	0	0 (1)	0	0	0	0	0	0
2008	0 (2)	0 (2)	0	0 (1)	1 (1)	0	0	0	0	0
2009	0 (2)	3 (5)	0	0 (1)	0 (1)	0	0	1 (1)	0	0
2010	6 (8)	5 (10)	0	1 (2)	1 (2)	1 (1)	1 (1)	3 (4)	0	0
2011	9 (17)	19 (29)	2 (2)	3 (5)	1 (3)	7 (8)	1 (2)	0 (4)	0	0
2012	17 (34)	10 (39)	2 (4)	5 (10)	3 (6)	2 (10)	4 (6)	6 (10)	1 (1)	0
2013	12 (46)	10 (49)	5 (9)	3 (13)	2 (8)	3 (13)	2 (8)	2 (12)	0 (1)	0
2014	12 (58)	11 (60)	13 (22)	1 (14)	6 (14)	3 (16)	0 (8)	2 (14)	0 (1)	1 (1)
2015	4 (62)	18 (78)	9 (31)	8 (22)	4 (18)	4 (20)	3 (11)	3 (17)	3 (4)	3 (4)
2016	21(83)	30 (108)	10 (41)	11 (33)	10 (28)	4 (24)	3 (14)	3 (20)	1 (5)	5 (9)
2017	8 (91)	15 (123)	10 (51)	4 (37)	4 (32)	7 (31)	1 (15)	3 (23)	0 (5)	5 (14)
2018	47 (138)	30 (153)	16 (67)	6 (43)	7 (39)	8 (39)	3 (18)	4 (27)	3 (8)	7 (21)
2019	75 (213)	22 (175)	10 (77)	4 (47)	5 (44)	3 (42)	1 (19)	3 (30)	3 (11)	9 (30)
2020	87 (300)	39 (214)	33 (110)	10 (57)	9 (53)	7 (49)	10 (29)	6 (36)	5 (16)	5 (35)
2021	91 (391)	34 (248)	50 (160)	10 (67)	9 (62)	9 (58)	11 (40)	5 (41)	18 (34)	7 (42)
2022	74 (465)	28 (276)	59 (219)	7 (74)	7 (69)	9 (67)	9 (49)	6 (47)	13 (47)	4 (46)
Total	465	276	219	74	69	67	49	47	47	46

Figure 17. Top-10 countries that published the most over time

Figure 18. Country collaboration network

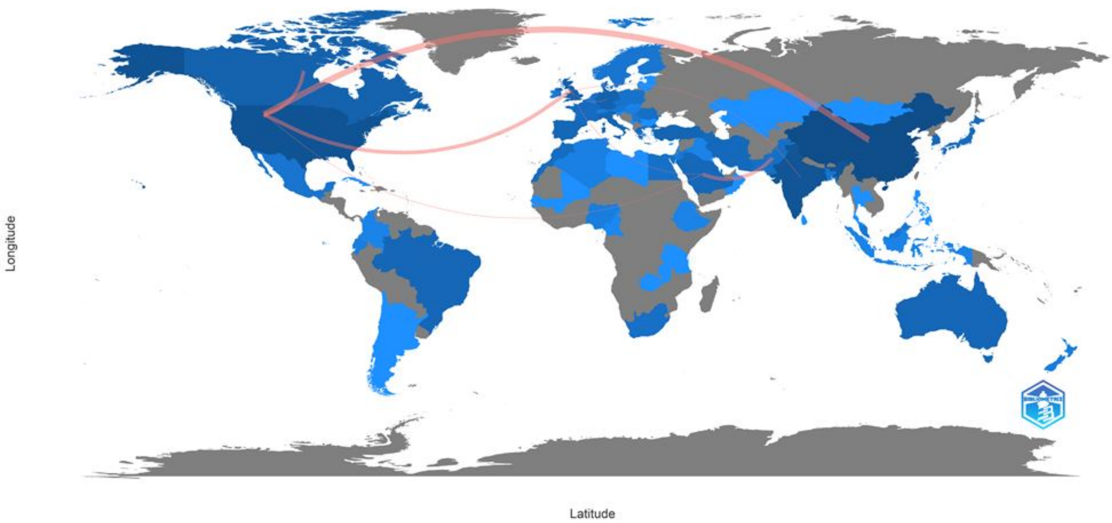

Figure 19. Country collaboration map

F. Documents

Of the 1926 studies included in this bibliometric analysis, the top-10 most cited articles are displayed in Tabel 9 which particularly describes the related publication, the total number of citations it received, the citations per year, and the normalized total number of citations. The significance of these publications can also be viewed in the reference publication year spectroscopy diagram in Figure 20, which presents in its X-axis the years and in the Y-axis the number of cited references. The results of this figure are in line with those of Figure 3. The studies conducted by [20][37][38][39][40] were the top-5 most impactful articles published based on their total number of citations (RQ7) while the studies by [41][42][43][44][45] were having less impactfull

Furthermore, as data from Scopus and WoS was used and both author's keywords and keywords plus can present the knowledge structure of the document [46], both keyword types were used in the analysis. More specifically, Figure 21 presents the most frequently used author's keywords, while Figure 22 depicts the most frequently used keywords plus. Both figures present the frequency in their X-axis and the related keywords in their Y-axis. Based on the results, the diverse nature of the topic is highlighted. Smart grid, artificial intelligence, machine learning, internet of things, and renewable energy were the top-5 most commonly used author's keywords, while smart power grids, artificial intelligence, electric power transmission networks, learning systems, and energy management were the top-5 most commonly used keywords plus. Figure 23 depicts the co-occurrence network of the keywords used in the documents analyzed in which two main clusters of keywords can be seen. Finally, Figure 24 presents the relationship among the top-10 most commonly used author's keywords, most productive countries, and most frequent sources, while Figure 25 presents the same relationship but uses keywords plus. In both figures, the interrelationship among the variables is clearly depicted (RQ8).

Figure 26 displays the topic trends based on the author's keywords, while Figure 27 presents the topic trends according to keywords plus. In both figures, the X axis refers to the years, and the Y axis presents the topic trends based on the related keywords. The evolution of the topic and its main focus can be observed. Although intelligent systems, agents, and decision support systems were the main focus at the beginning, in recent years, the focus has shifted to sustainability, machine learning, deep learning, blockchain, artificial intelligence, and the Internet of Things is profound. When clustering the documents using coupling measured by references and global citation score as the impact measure, a total of seven clusters are created, as can be seen in Figure 28 and Figure 29. In both figures, the seven clusters emerged following documents coupling can be seen (RQ9).

Table 9.
Top-10 most cited documents

Ref.	Paper	Total Citations	TC per Year	Normalized TC
[37]	Jiang C, 2017, IEEE Wireless Communications	717	102.43	24
[38]	Raza MQ, 2015, Renewable and Sustainable Energy Reviews	554	61.56	24.62
[39]	Wang Y, 2019, IEEE Transactions on Smart Grid	545	109.00	33.25
[40]	Sobri S, 2018, Energy Conversion and Management	421	70.17	15.6
[20]	Ramchurn SD, 2012, Communications of the ACM	374	31.17	17.74
[41]	Ozay M, 2016, IEEE Transactions on Neural Networks and Learning Systems	360	45.00	14.68
[42]	Francois-Lavet V, 2018, Foundations and Trends in Machine Learning	351	58.50	13.01
[43]	Alahakoon D, 2016, IEEE Transactions on Industrial Informatics	337	42.13	13.75
[44]	Chemali E, 2018, IEEE Transactions on Industrial Electronics	322	53.67	11.94
[45]	Zhou X, 2018, Zhongguo Dianji Gongcheng Xuebao	311	51.83	11.53

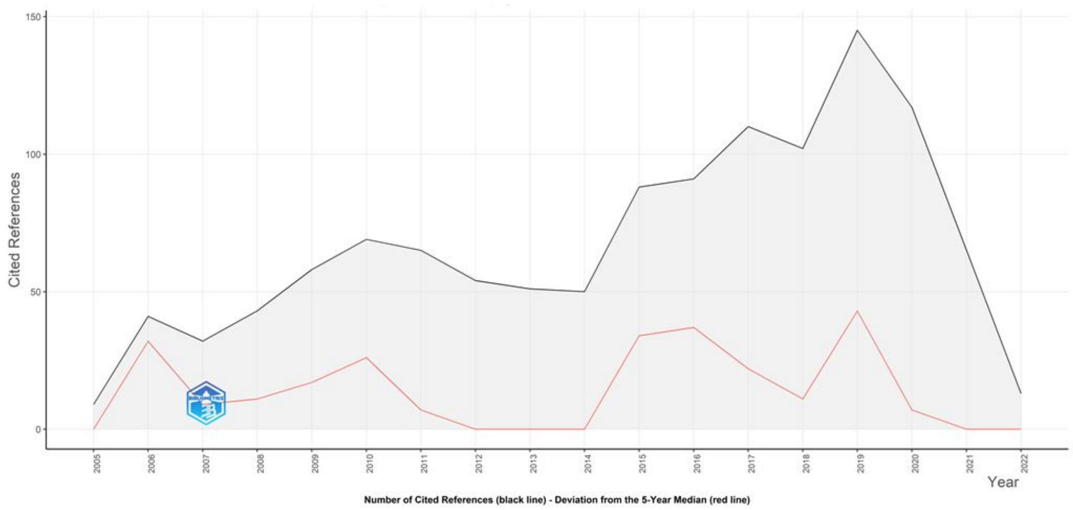

Figure 20. Reference publication year spectroscopy

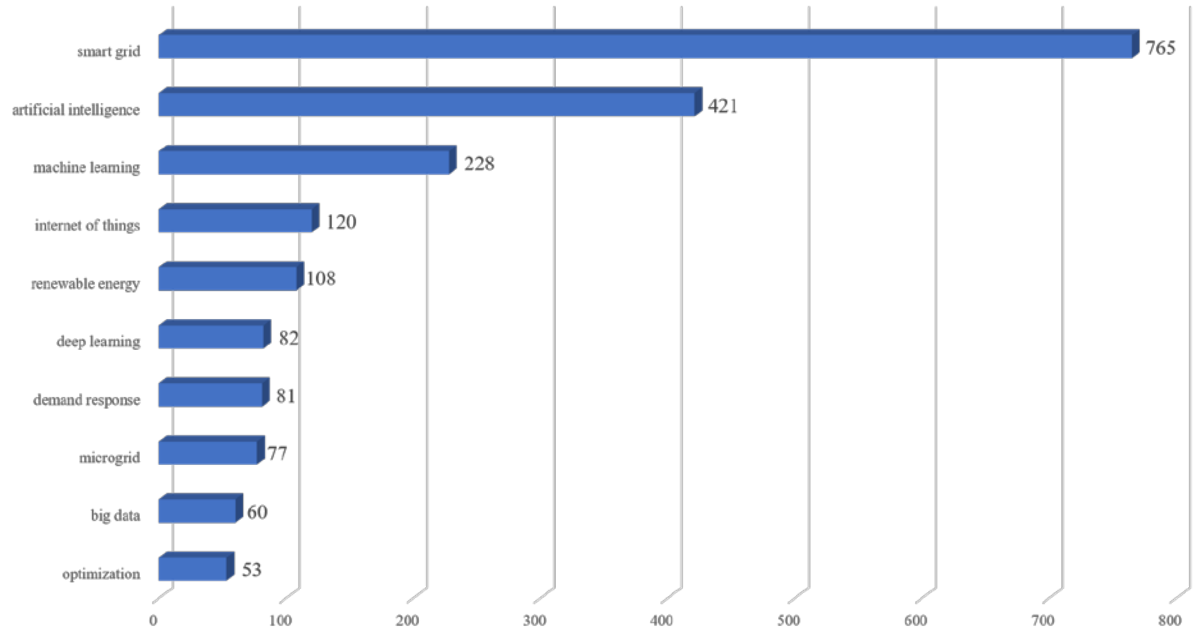

Figure 21. Most frequent author's keywords

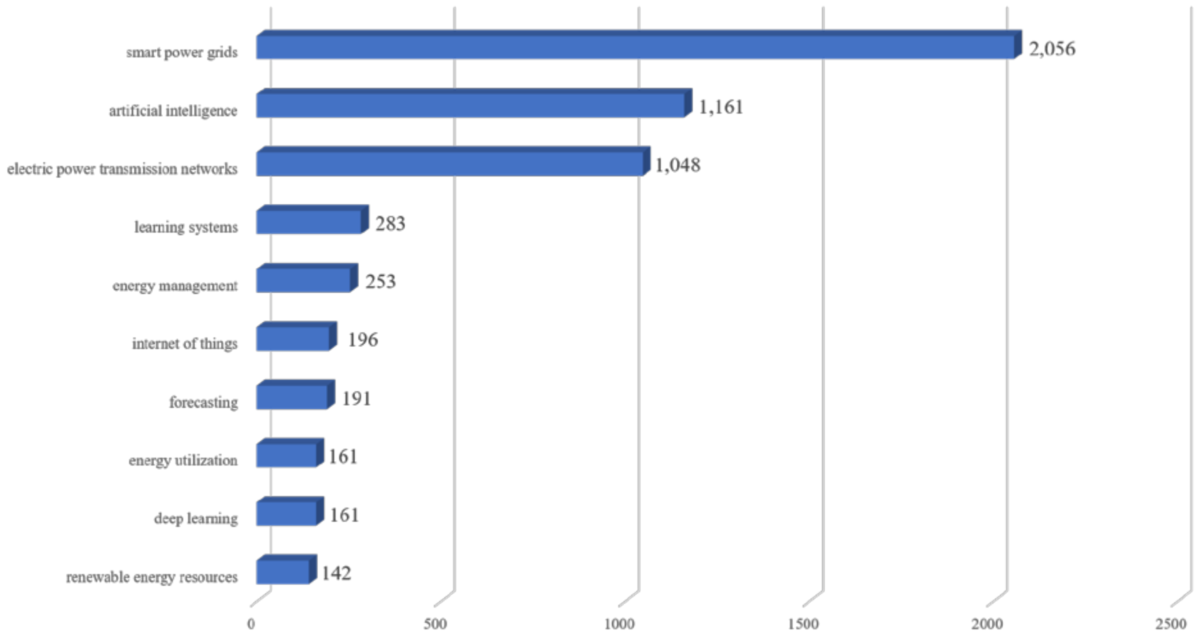

Figure 22. Most frequent keywords plus

The topic conceptual structure map and the dendrogram of each emerged topic keyword are depicted in Figure 30 and Figure 31, respectively. The conceptual structure map consists of two clusters, one related to the use of artificial intelligence in smart grids and one to advances in the power sector and smart cities. Additionally, the various themes that emerged from clustering the keywords for the use of artificial intelligence in smart grids are presented in Figure 32 and Figure 33. These figures showcase the four clusters created, which are related to i) energy use and management and renewable resources, ii) smart power grids and artificial intelligence, iii) machine learning and forecasting, as well as iv) embedded systems and network performance and security.

Figure 34 and Figure 35 display the thematic evolution of this topic which presents the data divided into two time periods (2005-2017 and 2018-2022) and three time periods (2005-2010, 2011-2016, and 2017-2022). Although the use of artificial intelligence and intelligent systems and autonomous decision-making systems has been studied since 2005, only recently has there been a drastic increase in the development of smart power grids and ways to digitalize and optimize the power sector. Network security, fault detection, and forecasting still remain important aspects within artificial intelligence-enabled power grids (RQ10).

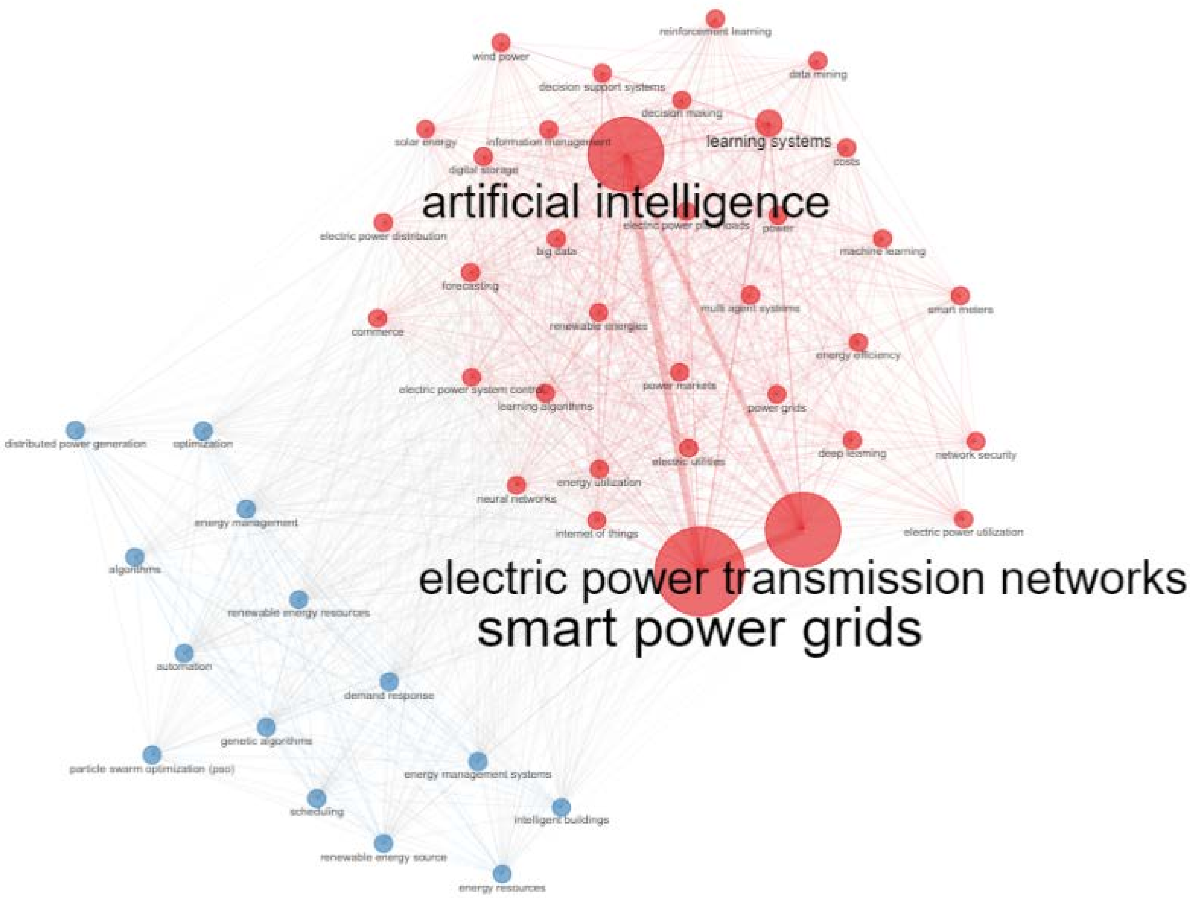

Figure 23. Keywords co-occurrence network

G. Discussion and result analysis

As the realization of sustainable development and the achievement of sustainable development goals are becoming essential, the digital transformation of the power sector is imminent. The use of artificial intelligence in smart grids is becoming more popular as it can support and enrich the whole value chain of the power sector. Artificial intelligence-based systems can improve the stability, control, and productivity of the power sector through the development of intelligent and autonomous control, monitoring, production, and management systems [30][31][47]. Moreover, artificial intelligence can improve network connectivity, stability, and performance, enhance fault detection, disaster recovery, predictive maintenance, and load forecasting, as well as improve system and process optimization, security and privacy, and stability evaluation [47][48][49]. To reap the full benefits of artificial intelligence in smart grids and the power sector in general, there are some open challenges that should be addressed. These challenges are related to the effective application of artificial intelligence algorithms, reductions in cost and risks, improvement in system security, ensuring privacy, analysis of the impact on the workforce, and efficient use and management of renewable resources [47][49].

This bibliometric and mapping study aimed at analyzing how the use of artificial intelligence in smart grids has evolved over the years. Hence, it involved the analysis of 1,926 related to the topic articles from Scopus and WoS without any search limitations. The analysis process included the descriptive statistics of the related studies and the annual scientific production, the identification of the most relevant and impactful authors, articles, outlets, affiliations, and countries, and the examination of the most commonly used keywords and their relation to other factors. The most popular topics and the advancement of the research focus were also explored. The use of only two databases to identify the related data can be regarded as a limitation of this study.

To sum up the results of the analysis, the scientific interest in the use of artificial intelligence in smart grids has been increasing on a yearly basis since 2005, with the only exception being the year 2007. The annual growth rate is 27.5 %, the average age of the documents is 4.89 years, and each article received an average of 14.3 citations which highlights the novelty and significance of this field of study. Most studies were published as conference papers, and although the vast majority of articles were co-authored (1,749), the international co-authorship rate was extremely low (1.56 %), and

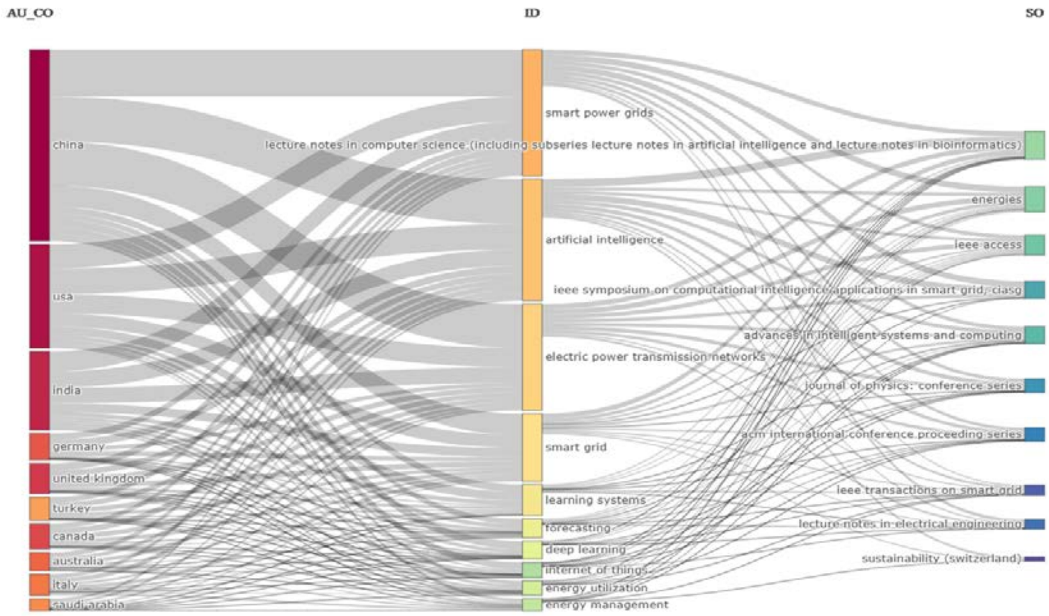

Figure 24. Top-10 countries, author's keywords, and sources relationship

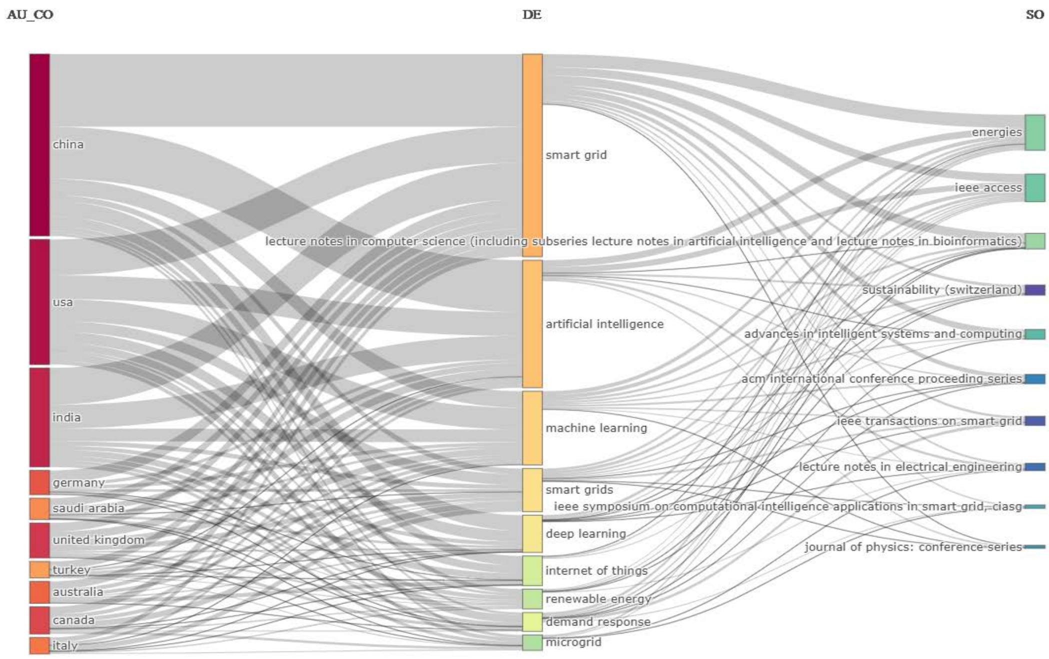

Figure 25. Top-10 countries, keywords plus, and sources relationship

there was a clear lack of cross-country studies. In total, 947 international outlets were used, which were clustered into three groups following Bradford's law. "IEEE Transactions on Smart Grid," "Energies," "IEEE Access," and "Applied Energy" were the most impactful sources based on their h-index and number of total citations. A total of 4,746 different authors contributed to these studies.

The vast majority of authors were involved either in a single article (79 %) or five articles at the most. Vale Zita, Liu Yun, Chen Yung-Yao, Faria Pedro, and Venayagamoorthy Ganesh Kumar were the top-5 most impactful authors based on the h-index of their related articles, while Han Zhu, Zhang Huaying, Rogers Alex, and Ren Yan were the top-4 most impactful authors according to their total number of citations of their related to the topic articles. Vale Zita, Liu Yun, Wang Yujie, Chen Yung-Yao, and Lin Yu-Hsiu were the five most productive authors in terms of publication number. China Electric Power Research Institute, North China Electric Power University, Nanyang Technological University,

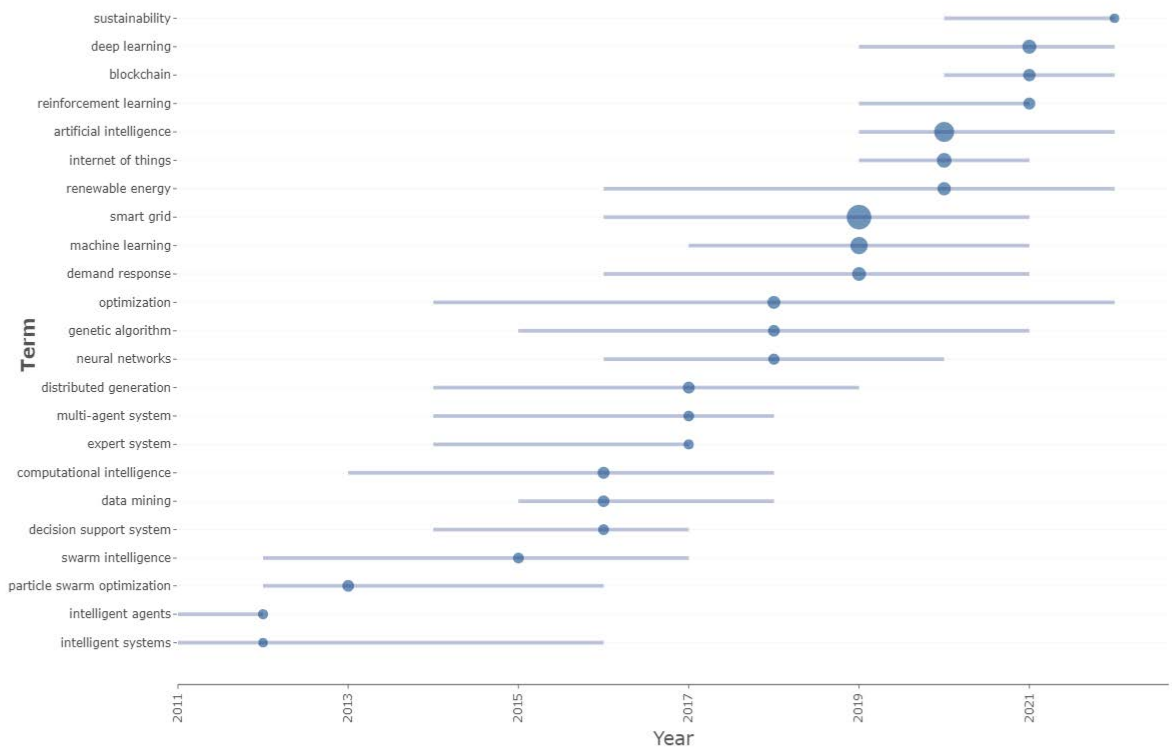

Figure 26. Topic trends based on the author's keywords

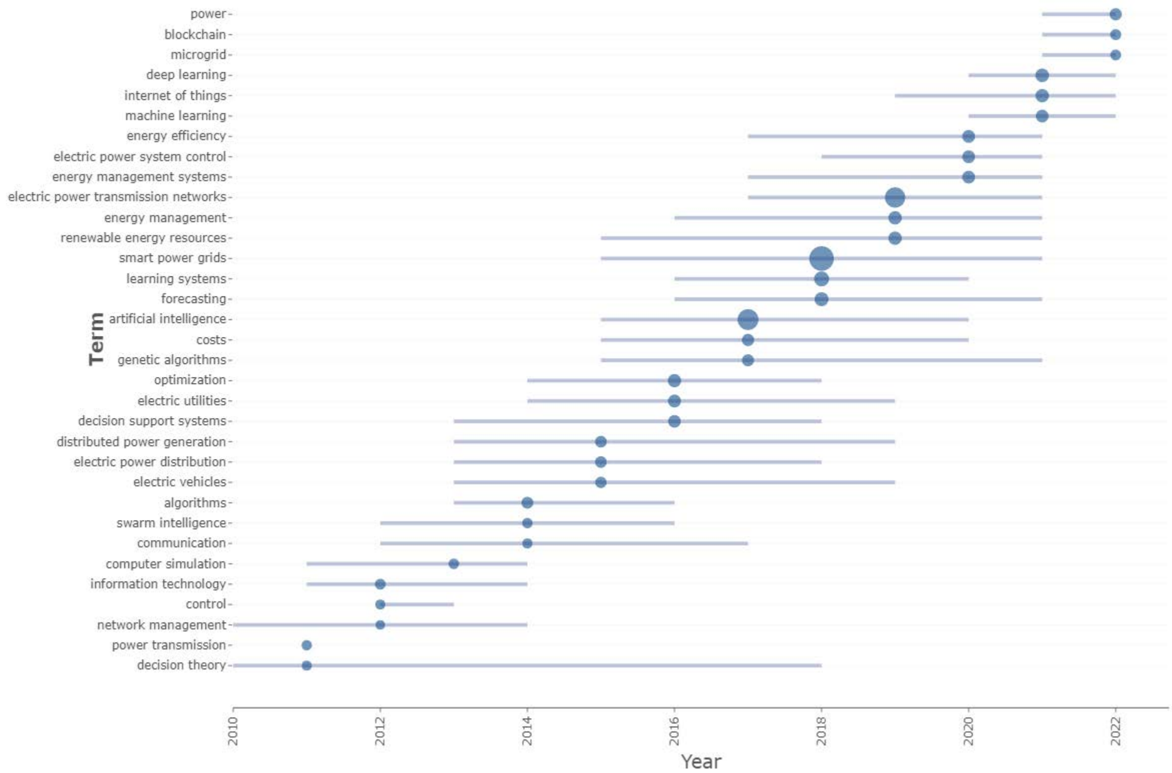

Figure 27. Topic trends based on keywords plus

Zhejiang University, and Carnegie Mellon University were the top-5 affiliations that produced the largest number of publications out of the 2,132 different affiliations within this dataset. In total, authors from 66 different countries were involved in the studies examined.

The countries that received the most citations were China, the United States, Canada, the United Kingdom, and Korea, while the countries that published the most articles were China, the United States, India, Germany, and Italy. The top-5 most impactful articles according to the total number of citations were [20][37][38][39][40].

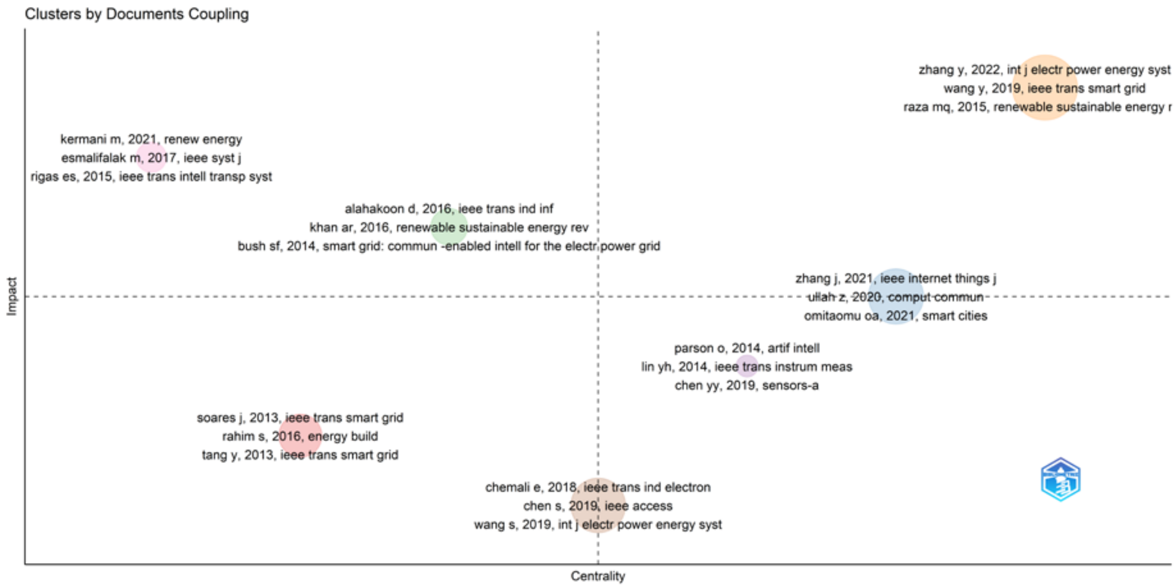

Figure 28. Map of documents clustered by coupling

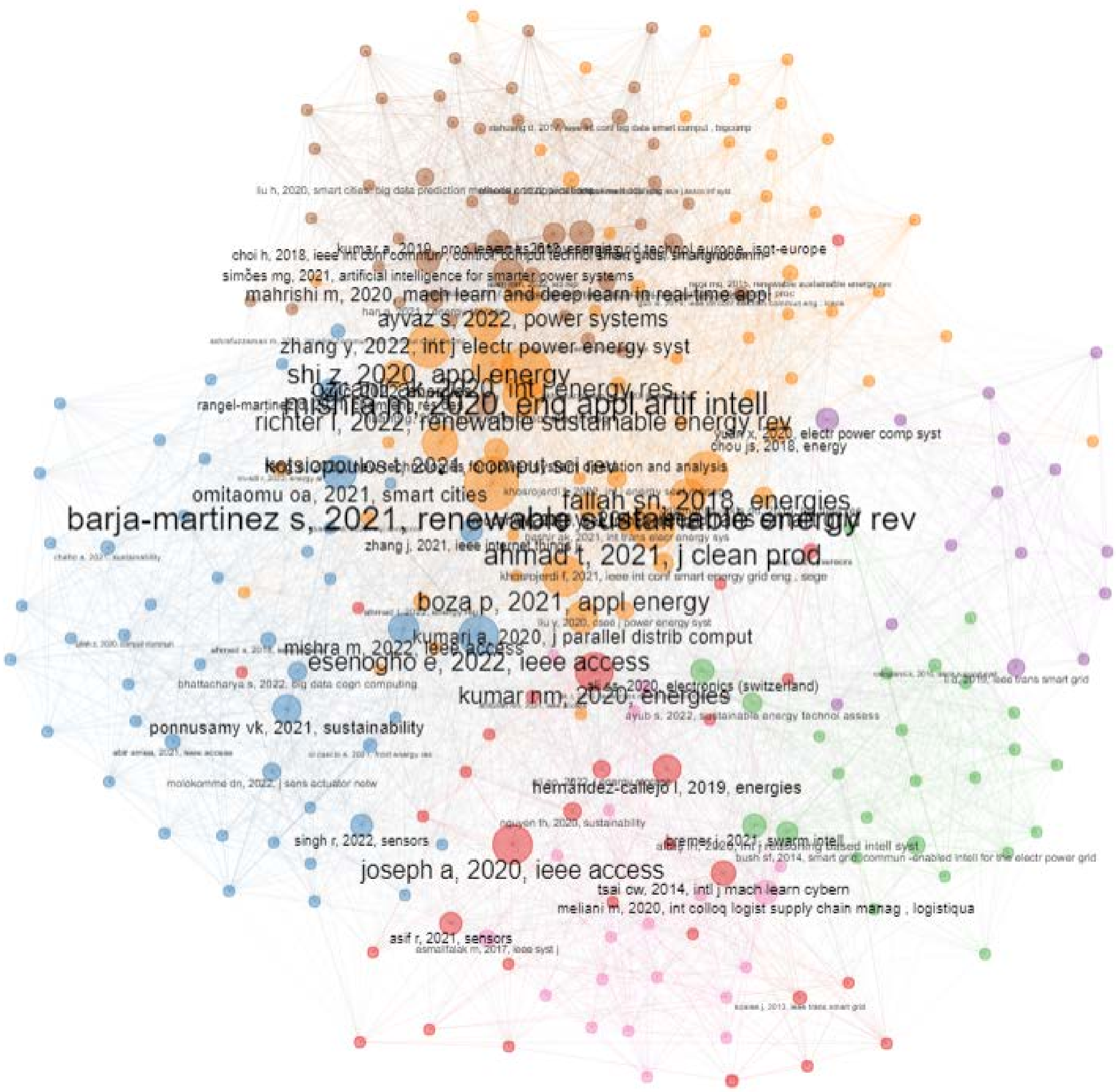

Figure 29. Network of documents clustered by coupling

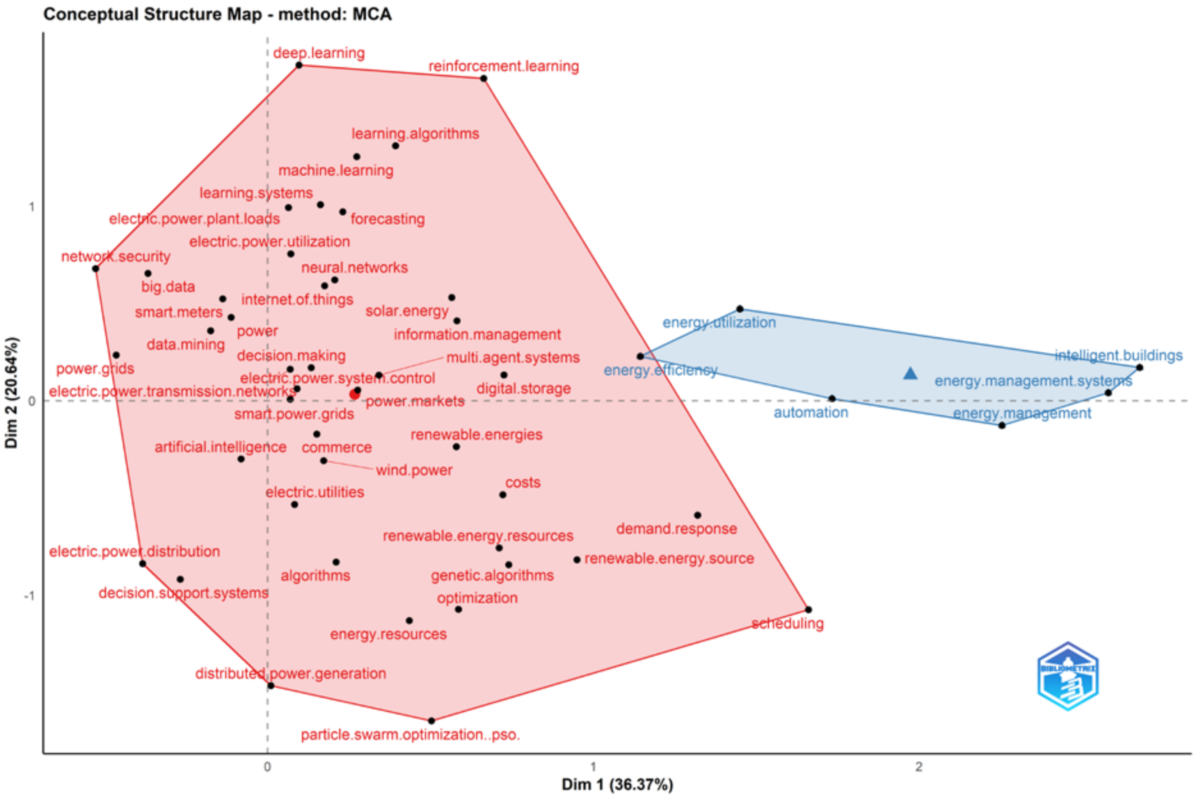

Figure 30. Conceptual structure map of the topic

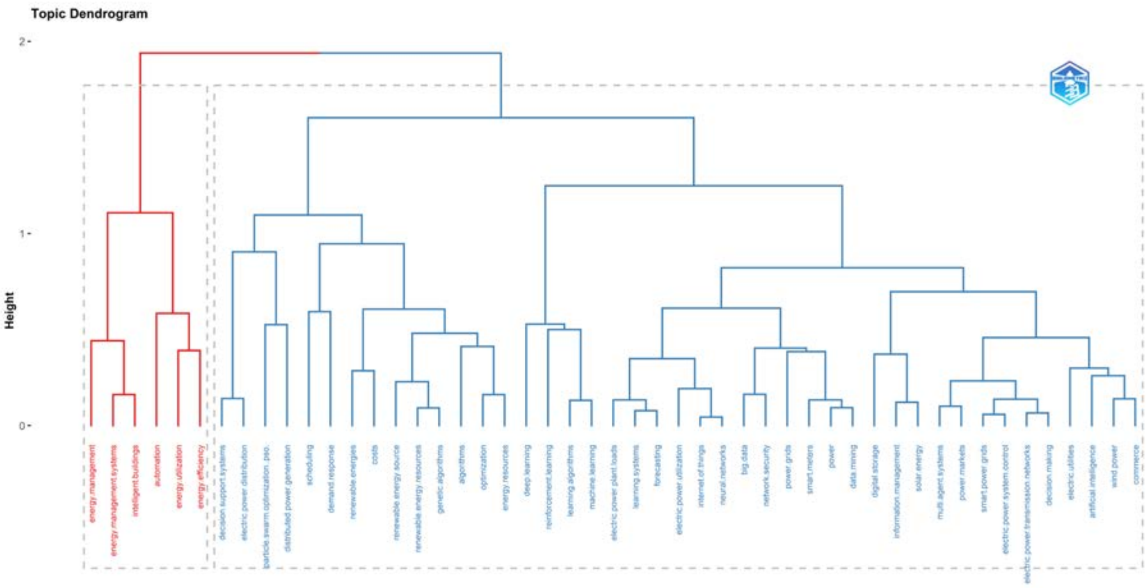

Figure 31. Topic dendrogram

The keywords mostly used by authors were smart grid, artificial intelligence, machine learning, internet of things, and renewable energy, which are a clear representation of the advancement and future directions of the topic and the focus on sustainability, machine learning, deep learning, blockchain, artificial intelligence, and internet of things. When analyzing the keywords, four clusters emerged. Energy use and management and renewable resources emerged as the motor theme, smart power grids, and artificial intelligence as the basic theme, machine learning and forecasting as the niche theme, and embedded systems and network performance and security as emerging or declining themes. This fact was in line with the thematic evolution of the topic, which highlighted the recent focus on developing smart power grids and finding ways to digitalize and optimize the power sector.

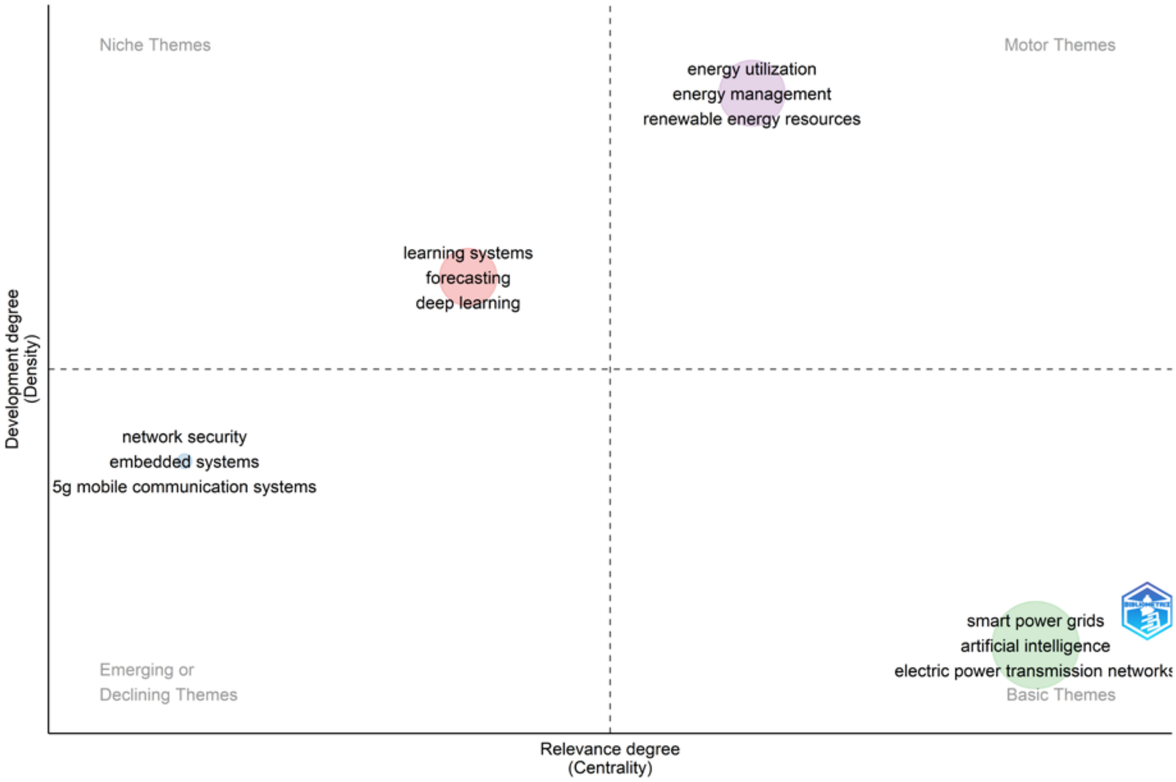

Figure 32. Thematic map of the topic

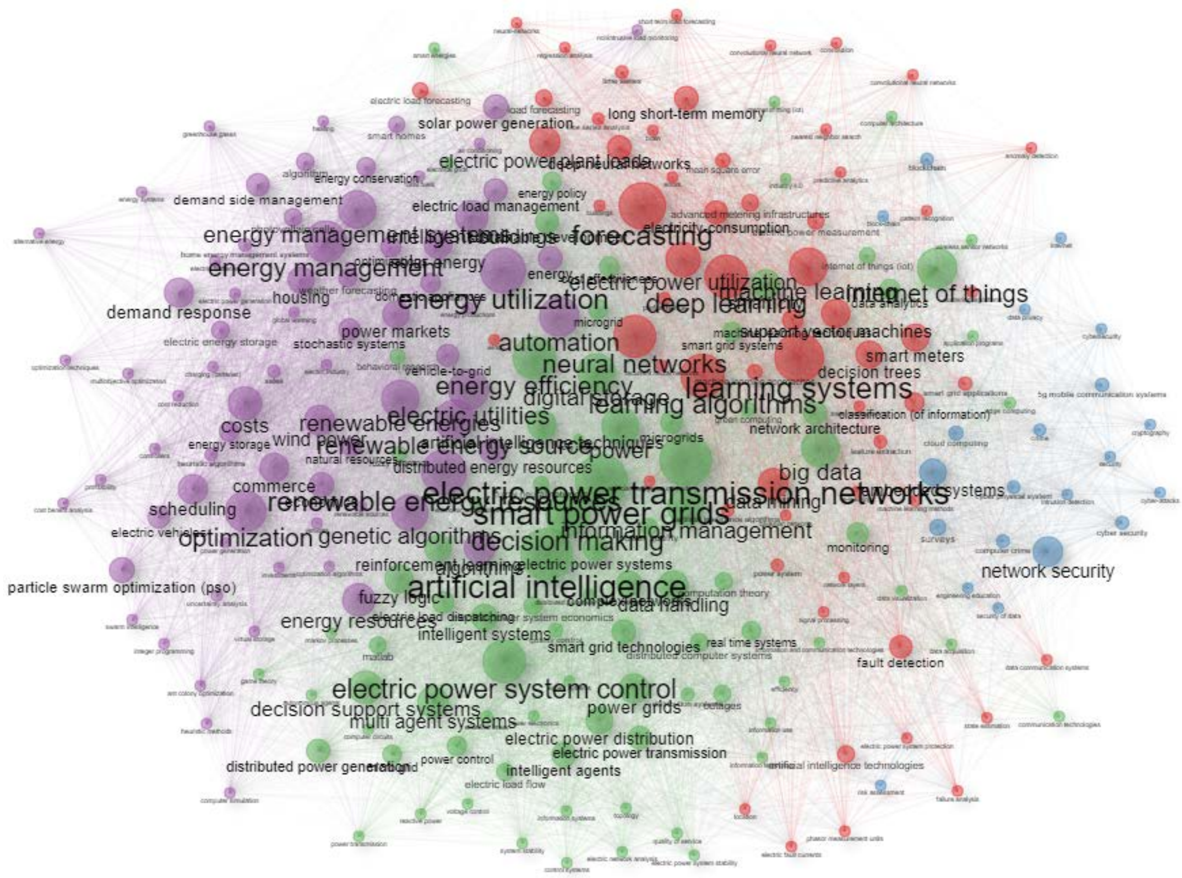

Figure 33. Thematic network of the topic

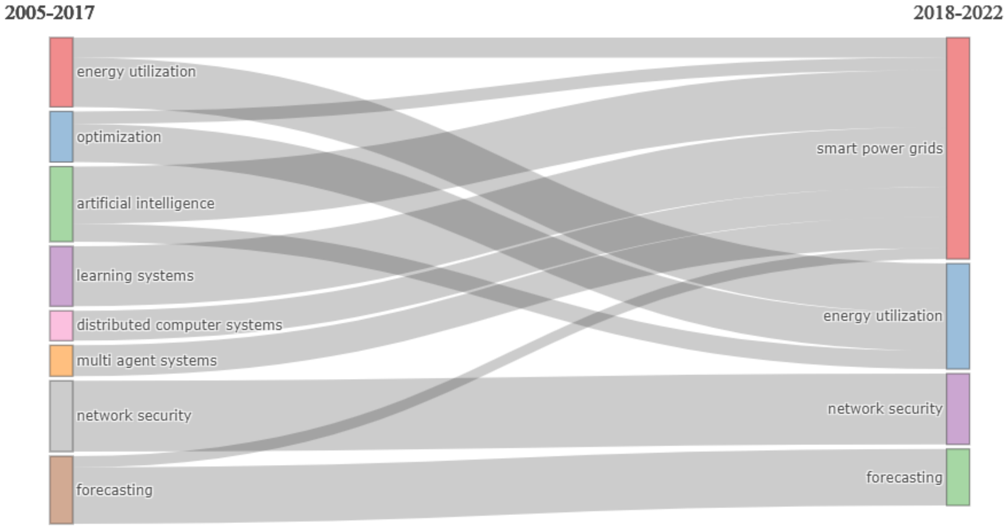

Figure 34. Thematic evolution of the topic using two time periods

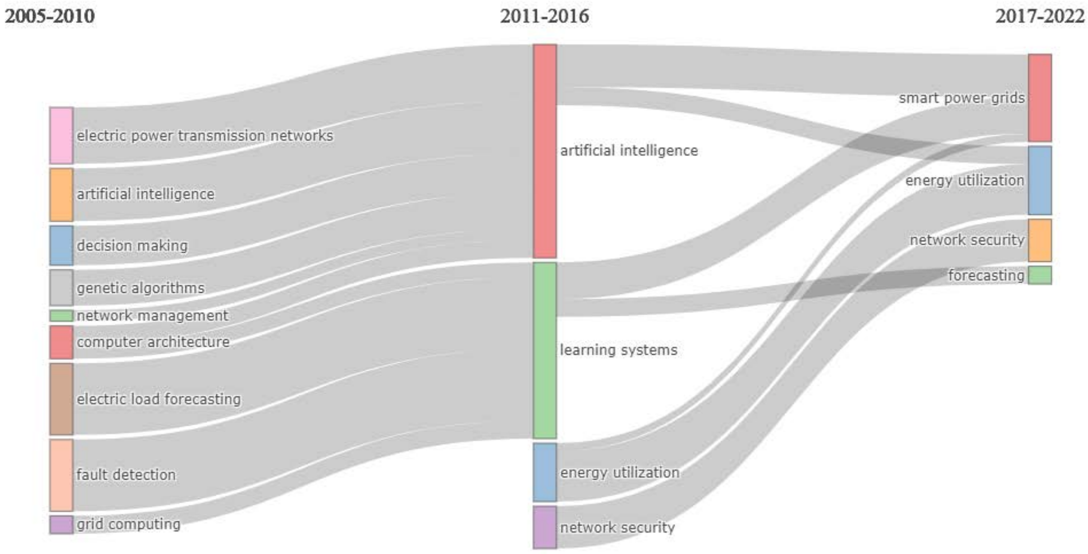

Figure 35. Thematic evolution of the topic using three time periods

IV. Conclusion

The aim of this study was to explore artificial intelligence in smart grids and how the topic has evolved over the years. Hence, ten research questions were set to be examined following an extensive bibliometric analysis which involved 1,926 articles from Scopus and WoS over the period 2005-2022. The analysis included descriptive statistics of the related studies and the annual scientific production, the identification of the most relevant and impactful authors, articles, outlets, affiliations, and countries, and the examination of the most commonly used keywords. Additionally, the most popular topics and the advancement of the research focus were also explored. Therefore, the findings of this study contribute to bridging the gap in the literature regarding the integration of artificial intelligence in smart grids. This study highlighted the significant role of artificial intelligence in the realization of smart grids and the digitalization of the power sector. In addition, it presented the research directions and main areas of focus. Given the importance of creating ideal conditions that will enable sustainable development and the achievement of sustainable development goals, this study hopes to pave the way for new lines of work to be developed.

Declarations

Author contribution

This is a single-authored paper. The author is the main contributor of this paper and he has read and approved the final version of the paper.

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Competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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