energies

Review

Energy in Smart Cities: Technological Trends and Prospects

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Abstract: Energy management in smart cities has gained particular significance in the context of climate change and the evolving geopolitical landscape. It has become a key element of sustainable urban development. In this context, energy management plays a central role in facilitating the growth of smart and sustainable cities. The aim of this article is to analyse existing scientific research related to energy in smart cities, identify technological trends, and highlight prospective directions for future studies in this field. The research involves a literature review based on the analysis of articles from the Scopus and Web of Science databases to identify and evaluate studies concerning energy in smart cities. The findings suggest that future research should focus on the development of smart energy grids, energy storage, the integration of renewable energy sources, as well as innovative technologies (e.g., Internet of Things, 5G/6G, artificial intelligence, blockchain, digital twins). This article emphasises the significance of technologies that can enhance energy efficiency in cities, contributing to their sustainable development. The recommended practical and policy directions highlight the development of smart grids as a cornerstone for adaptive energy management and the integration of renewable energy sources, underpinned by regulations encouraging collaboration between operators and consumers. Municipal policies should prioritise the adoption of advanced technologies, such as the IoT, AI, blockchain, digital twins, and energy storage systems, to improve forecasting and resource efficiency. Investments in zero-emission buildings, renewable-powered public transport, and green infrastructure are essential for enhancing energy efficiency and reducing emissions. Furthermore, community engagement and awareness campaigns should form an integral part of promoting sustainable energy practices aligned with broader development objectives.

Keywords: smart city; energy; sustainability; technology; Internet of Things; 5G/6G; artificial intelligence; blockchain; digital twins

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1. Introduction

Contemporary urban population is increasing every year; according to United Nations (UN) research, more than 50% of the world's population lives in cities and by 2050 the percentage of people in cities is expected to increase to 70% [1]. Cities cover only 3 percent of the Earth's surface; however, they are responsible for 60–80 percent of energy consumption and 75 percent of carbon dioxide emissions [2]. Ongoing urbanisation will lead to increased energy consumption and a rise in greenhouse gas emissions. This has the effect of exacerbating global climate change [3]. In response to this challenge, energy management is becoming a key topic in discussions about sustainable development in smart cities [4].

A smart city is a system that exploits human and social capital [5,6] and, in combination with natural and economic resources based on technological [7–9] and innovative solutions [10,11], and energy production [12–15], achieves sustainable development and a high quality of life [10,16]. Smart cities integrate several dimensions such as environment, life, economy, people, mobility, and government [17]. One important aspect of this integration is energy management, which is essential to the functioning of each of these dimensions.

The energy demand of cities is complex and large. Calvillo et al. outlined five main energy-related activities as generation, storage, infrastructure, facilities, and transport (mobility) [18]. Current global electricity generation is still mainly based on fossil fuels like coal and natural gas (more than 50%) [15]. Nevertheless, renewable energy sources (RESs) such as solar energy, aerothermal energy, geothermal energy, hydrothermal energy, wind energy, biomass energy, and biogas [19] also have an increasing share of production—globally 23% [20]. For example, in Poland renewable energy sources account for 43% of all energy produced [21]. A positive effect during the production process of RESs is that they do not generate any polluting emissions [22]. According to the International Renewable Energy Agency, the share of renewable energy sources should increase to 57% worldwide by 2030 [23].

The way to keep energy production and demand in balance is to store energy using advanced mechanical, electrochemical, chemical, and thermal energy storage systems [22]. By 2030, energy storage demands will triple from current values [24], so it is necessary to implement innovative solutions to efficiently store energy like photovoltaic or solar energy [25] and to manage energy by wireless sensor networks (WSNs) [26,27], street lighting [28], or sensors [29].

Urban energy infrastructure pertains to the networks that deliver energy to homes and businesses in cities through district heating systems and gas [30] and electricity [31] grids. In cities, urban energy infrastructure encompasses the provision of electricity transmission [32] and distribution systems [33] for power supply to consumers. Contemporary solutions such as smart grids, which enable two-way energy flow, integration of renewable energy sources, and better management of power consumption [34], are also increasingly being included.

In an urban context, buildings are major energy consumers—about 40% of total energy consumption [35]. Contemporary efficient energy systems which are used in buildings can save 11% to 16% of the energy used during the year [36]. New technologies like distributed generation and energy storage devices allow demand response to be dynamic, so it is important to adjust production and consumption levels in real time [18]. Therefore, it is crucial to invest in technologies to help monitor and optimise energy consumption by using technologies like artificial intelligence [37], the Internet of Things [38,39], cloud computing [40], or deep learning [41].

Transport is the source of 24% of global carbon dioxide emissions [42]; therefore, energy management has a fundamental impact on the transport sector. Currently, it mainly relies on fossil fuels such as oil and natural gas, which are associated with high levels of greenhouse gas emissions [43] and, as a result, intensify climate change. One of the key trends is the transformation to the electrification of transport. Electric vehicles (EVs) are becoming increasingly popular, and the development of charging infrastructure is making EV use easier and more accessible [44–46].

Urban energy management is key to ensuring sustainability, energy efficiency, and environmental protection. It includes a variety of measures to optimise energy consumption, minimise greenhouse gas emissions, and reduce energy costs in many dimensions of a smart city. Effective management of energy in urban areas can be achieved by leveraging modern technologies like the Internet of Things (IoT), machine learning systems, and smart grids to gather and analyse data on energy usage efficiently. This data analysis enables the optimisation of energy distribution processes and consumption practices in cities. An essential element is the integration of diverse systems across urban sectors and fostering collaboration to facilitate information exchange for informed decision-making. Effective energy management is not just about saving money. It also plays a role in promoting sustainable urban growth and enhancing the well-being of city dwellers while safeguarding the environment.

The structure of this article is divided into five sections. The introduction outlines key information regarding energy systems within the framework of smart cities. The second section details the research methods and tools utilised, as well as the materials analysed. The third section presents the research outcomes, focusing on the topics explored in scientific publications concerning energy in smart cities. The fourth section presents a discussion of the results, divided into two subsections addressing issues related to technological trends and future research directions. This article concludes with a summary of findings and study limitations.

2. Materials and Methods

The analysis of scientific activity is a key measure of the influence that research exerts within a particular field. In order to evaluate the scientific output in the area of energy within smart cities, this study employed a bibliometric analysis.

Bibliometric analysis leverages quantitative data from scientific publications to evaluate the research productivity of individuals, institutions, and even entire countries. It serves as a valuable tool for monitoring the evolution of science and identifying emerging trends in specific research domains. This method is particularly useful for researchers who are delving into a new topic for the first time. Given the abundance of available publications, bibliometric analysis aids in the identification, synthesis, analysis, and critical evaluation of relevant literature [47,48]. By using quantitative techniques, this method helps to map out the current state of research and detect developmental trends within a particular area of study. The insights gained from this approach include understanding key research directions, observing shifts in trends, and tracking changes in publication volume over time. Additionally, bibliometric analysis enables the creation of rankings, highlighting the most productive authors, influential journals, leading research institutions, and active countries within a specific field [16,49–52].

In this study, a substantial volume of scientific data was analysed, consisting of 4922 documents, covering a wide range of topics. Given the scope and complexity of the dataset, the authors believed that both quantitative and qualitative analyses were essential to obtain comprehensive insights. Consequently, three research questions were formulated:

- RQ1: Which authors, countries, organisations, and journals are most relevant in terms of smart city energy publications?
- RQ2: What research areas are addressed in scientific publications on energy in smart cities?
- RQ3: What should be the future research directions concerning energy in smart cities?

Figure 1 illustrates how the bibliometric analysis was conducted.

The process began with qualitative research. The methodology of bibliometric analysis consists of seven steps. It starts with the selection of bibliographic databases (1). The next step is the selection of keywords (2) and criteria for limiting publication searches (3). After this, data are extracted, and duplicate publications are removed (4). This is followed by an analysis of the unique publications (5). In the final phases, research areas are identified (6), and thematic clusters are created (7). These steps are illustrated in Figure 1. After completing the bibliometric analysis, the results were subjected to qualitative analysis, which formed the basis for the discussion and the conclusions drawn.

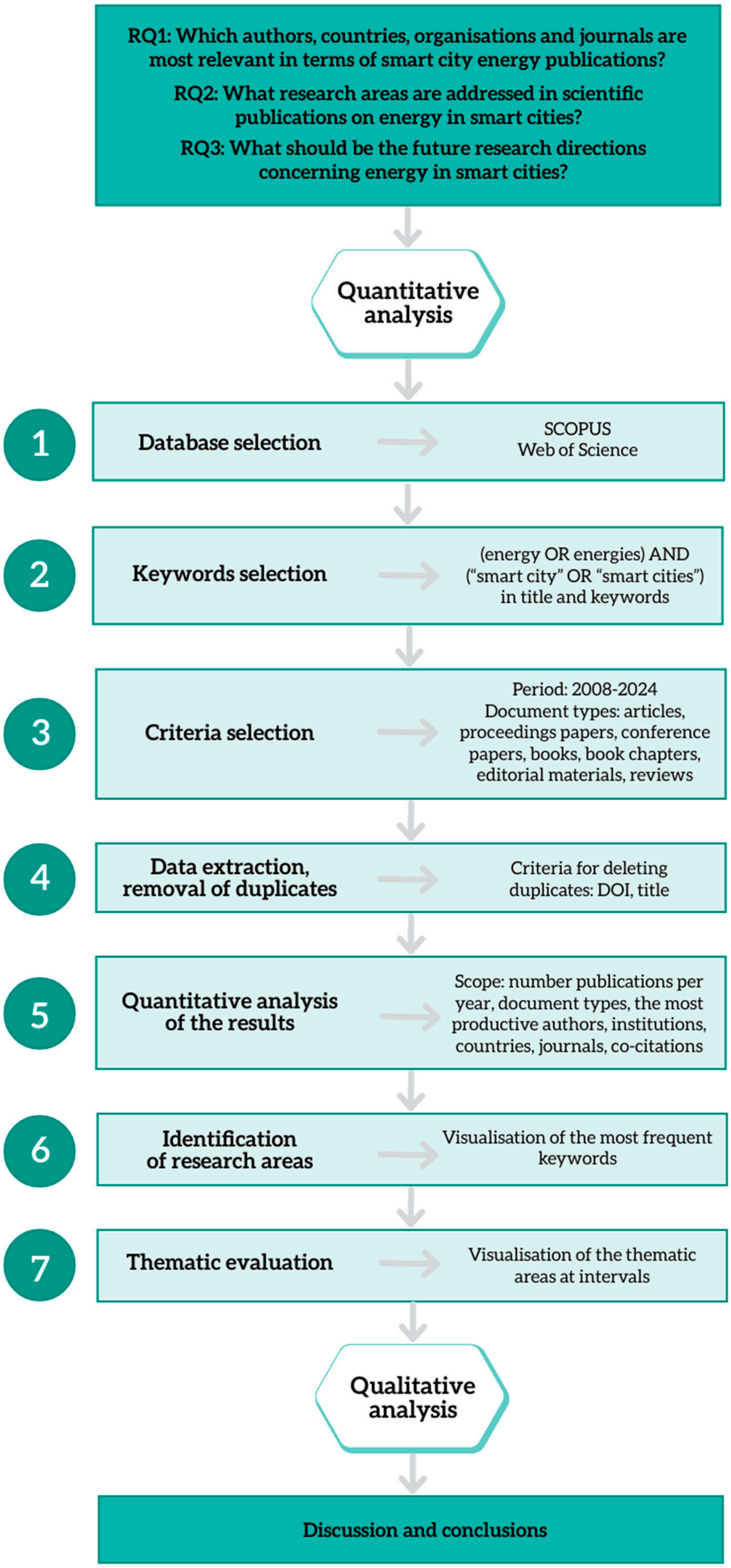

Figure 1. Process of bibliometric analysis.

In the initial stage of this study, the Scopus and Web of Science bibliographic databases were chosen. These platforms were selected to ensure a wide coverage of scientific publications. Scopus and WoS are renowned global databases that index research across a diverse range of fields. They are frequently utilised by researchers for conducting comprehensive review studies. The decision to use these particular databases was influenced by their accessibility and the extensive range of topics they cover across all scientific disciplines.

In the second stage of the analysis, keywords related to the research domain, specifically 'energy' and 'smart cities', were selected. During the initial search, the terms 'energ*' and 'smart cit*' were queried across the entire set of articles. The initial search returned 323,013 records in the Scopus database and 22,058 records in the Web of Science database (Table 1). Upon reviewing the results, it became apparent that many of the publications were not directly relevant to the specific research topic. Consequently, in the second stage, the search criteria were refined to include only publications that contained the specified phrases in their titles, abstracts, and keywords. This more targeted approach significantly reduced the number of records, as shown in the preliminary analysis. The search returned 110,873 records in Scopus and 11,312 records in Web of Science.

Table 1. Preliminary search results.

Stage	Scopus	WoS
	First search	
Research query	ALL (energ* AND smart cit*)	ALL = energ* AND smart cit*
Number of articles before inclusion criteria	323,013	22,058
	Second search	
Research query	ALL ((energy OR energies) AND ("smart city" OR "smart cities"))	ALL = (energy OR energies) AND ("smart city" OR "smart cities")
Number of articles before inclusion criteria	110,873	11,312
	Third search	
Research query	TITLE-ABS-KEY ((energy OR energies) AND ("smart city" OR "smart cities"))	TS = ((energy OR energies) AND ("smart city" OR "smart cities"))
Number of articles before inclusion criteria	9734	5615
	Fourth search	
Research query	TITLE ((energy OR energies) AND ("smart city" OR "smart cities"))	TI = ((energy OR energies) AND ("smart city" OR "smart cities"))
Number of articles before inclusion criteria	951	654
	Fifth search	
Research query	TITLE ((energy OR energies) AND ("smart city" OR "smart cities")) OR KEY ((energy OR energies) AND ("smart city" OR "smart cities"))	TI = ((energy OR energies) AND ("smart city" OR "smart cities")) OR AK = ((energy OR energies) AND ("smart city" OR "smart cities"))
Number of articles before inclusion criteria	4848	1378

* replace any number of any characters. Source: authors' work based on the Scopus and Web of Science databases—July 2024.

In the third stage of the search, further refinement was made by focusing on the titles, abstracts, and keywords, using a more precise query encompassing 'energy' and 'smart cities'. This approach resulted in 9734 records in the Scopus database and 5615 records in

Web of Science. While this step provided satisfactory results, it was determined that further narrowing of the search criteria was necessary.

The fourth stage of the search limited the query exclusively to the titles of the articles, which led to a further reduction in the number of records to 951 in Scopus and 654 in Web of Science. This stage allowed for a more precise selection of relevant studies, although it was acknowledged that including keywords might provide additional valuable insights.

In the fifth and final stage, the search was conducted across both titles and keywords to achieve a more comprehensive dataset. As a result of the search, 4848 records were retrieved from Scopus, while 1378 records were obtained from Web of Science. Each of these findings was carefully reviewed. Upon evaluation, they were found to be highly relevant to the objectives of the research. The quality and pertinence of the data from this final search provided a solid foundation, allowing the research to confidently advance to the subsequent stages of analysis.

In the third step, specific restriction criteria were implemented to improve the accuracy of the search results. The scope of the search was narrowed to include only materials published between 2008 and 2024. To ensure a comprehensive analysis, only certain types of publications were considered eligible, including articles, conference proceedings, books, book chapters, reviews, and editorials. On the other hand, certain publication types, such as retracted articles, conference reviews, notes, errata, and letters, were deliberately excluded from the analysis. The detailed results of this search process are presented in Table 2.

Table 2. Principal search result.

Stage	Scopus	WoS
Research query	TITLE ((energy OR energies) AND (“smart city” OR “smart cities”)) OR KEY ((energy OR energies) AND (“smart city” OR “smart cities”))	TI = ((energy OR energies) AND (“smart city” OR “smart cities”)) OR AK = ((energy OR energies) AND (“smart city” OR “smart cities”))
Number of articles before inclusion criteria	4848	1378
Number of articles after inclusion criteria	4813	1370

Source: authors’ work based on the Scopus and Web of Science databases—July 2024.

The search for the terms (energy OR energies) AND (“smart city” OR “smart cities”) across the entire collection of papers resulted in 4848 records being retrieved from Scopus and 1378 from Web of Science. After applying the specified criteria to narrow down the results, 4813 records from Scopus and 1370 from Web of Science were retained.

In the fourth step, the files downloaded from Scopus and WoS were combined using MS Office Excel 19. The records, saved in *csv format, were merged into a single file, resulting in a combined total of 6183 records. This process was complex due to differences in how data were structured across columns in each database. After merging, duplicates were identified and removed based on a combination of title, author names, and DOI information. This approach was necessary because relying solely on titles and authors did not provide accurate results. Inconsistent formatting and occasional errors in the databases, such as varying use of quotation marks and hyphens, made this step particularly challenging. After removing duplicates, a final set of 4922 unique records was selected for further analysis.

In the fifth step, the consolidated dataset was used to perform various analyses. These analyses focused on the frequency of publications over specific time periods, as well as identifying the most productive authors, institutions, countries, and journals. Additionally, the research aimed to highlight the most influential articles, particularly those with the highest citation counts. The analyses were conducted using both the individual and combined records from Scopus and WoS, with MS Office Excel 19 facilitating this process. Using VOSviewer software version 1.6.20 and RStudio version 2024.04.2+764 (Biblioshiny), a co-citation authors and journals analysis was also conducted. Additionally, an analysis of bibliographic coupling and international collaboration between countries was carried out (Table 3). Detailed results of these analyses are presented in Section 3 of this article.

Table 3. Objectives, methods, and tools of this study.

Objectives	Methods	Tools
Identification of publication dynamics by year and type of publication	analysis of data from individual and merged Scopus and WoS databases	MS Office Excel 19
Determining the highly contributing authors, institutions, countries, journals, articles	analysis of data from the merged Scopus and WoS databases	MS Office Excel 19
Determining the underlying clusters of co-cited authors and journals	co-citation analysis	VOSviewer version 1.6.20
Determining the cooperating countries	analysis of bibliographic coupling; analysis of countries' cooperation	VOSviewer version 1.6.20 RStudio—version 2024.04.2+764 (Biblioshiny)
Determining the thematic structure of keywords	co-occurrence analysis of author keywords	VOSviewer version 1.6.20 RStudio—version 2024.04.2+764 (Biblioshiny)
Identification of research sub-areas	network analysis of influential keywords	VOSviewer version 1.6.20
Exploring the thematic evolution	thematic evolution analysis	RStudio—version 2024.04.2+764 (Biblioshiny)

Source: authors' own elaboration based on [53].

In the sixth step of the bibliometric analysis, a detailed investigation of recurrent keywords was conducted, leading to the creation of a co-occurrence map for keywords related to energy in smart cities. The construction of this co-occurrence map was carried out using VOSviewer software (version 1.6.20) [54]. This co-occurrence analysis helped identify elements frequently appearing together in scientific publications and enabled the discovery of thematic clusters [53]. To improve accuracy and ensure the relevance of the terms, an additional thesaurus file [55,56] was used to eliminate duplicate or redundant terms (e.g., Internet of Things and IoT, artificial intelligence and AI) and non-relevant terms (e.g., article, state, model, scheme, research). This thesaurus was developed by analysing the keywords and reviewing the set of publications. As a result, thematic clusters representing both primary and emerging research areas were identified. Then, the seventh step involved the thematic evolution of this study over five time periods using RStudio—Biblioshiny. The outcomes of this analysis are detailed in Section 3.

After completing the bibliometric analysis, the next phase focused on a qualitative thematic analysis of the literature. In this phase, 1414 articles from 2022–2024 were analysed (abstracts as well as full texts for selected articles). The aim of the qualitative analysis was to identify emerging themes and formulate new research questions for future research; hence, articles from the last 3 years were analysed. The detailed results of this analysis are presented in Section 4.

3. Results

In the early stage of this study, a review was carried out on the annual volume of publications and the types of research outputs related to energy management in smart cities, utilising data from the Scopus and Web of Science databases.

Between 2008 and 2024, a substantial number of publications on the topic of energy in smart cities were published. In Scopus, 4813 publications were indexed, and 1370 in the Web of Science database (Figure 2). In the early years (2008–2011), there were very few publications. The number of publications naturally increased as the concept of smart cities gained popularity. Beginning in 2012, research activity in the field saw a notable rise, reflecting a growing academic interest in energy within smart cities. This increase became even more pronounced between 2017 and 2023. During this time, the number of unique records indexed in Scopus and Web of Science exceeded 500 annually. This period of significant growth underscores the expanding focus on this topic within the scholarly community.

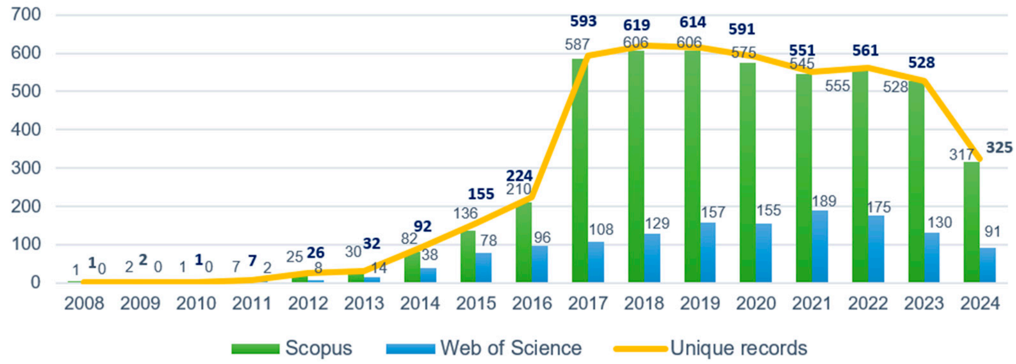

Figure 2. Publications in the Scopus and Web of Science databases (indexed from 2008 to July 2024).

The impact of this research is evident in the citation counts, which reached substantial numbers. Publications indexed in Scopus garnered a total of 73,414 citations, highlighting their influence and importance within the academic discourse. Similarly, publications in the Web of Science database accumulated 24,213 citations, further illustrating the widespread recognition and relevance of the research conducted during this time. Additionally, there were 1021 uncited publications in the Scopus database, and 275 in Web of Science.

In both the Web of Science and Scopus databases, the largest proportion of publications consisted of journal articles (59.7% and 34.7%, respectively) and proceedings papers (32.9% and 55.4%). For unique records, articles accounted for 35.1%, while proceedings papers made up 55.2%. Reviews, editorials, and book chapters made up a smaller share. The breakdown of publication types is shown in Figure 3.

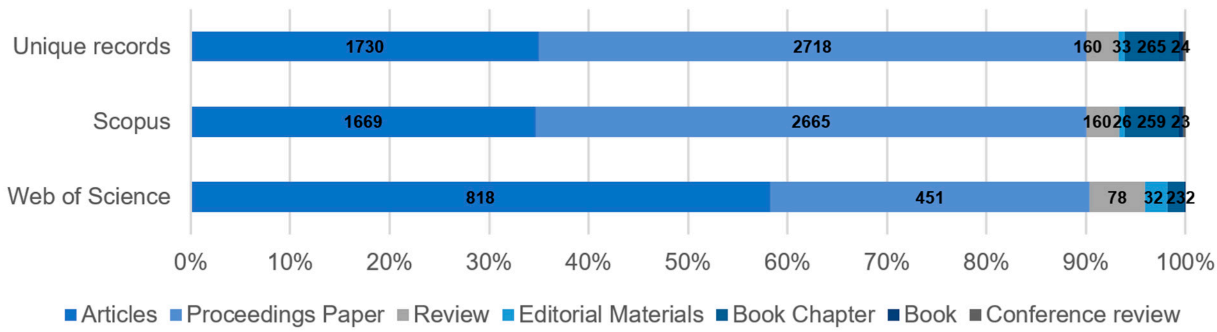

Figure 3. Types of publications in the field of energy in smart cities, as indexed in the Scopus and Web of Science databases (2008 to July 2024).

Al-Turjman and Javaid are recognised as the leading authors in this field, with 20 and 18 publications, respectively. Al-Turjman has an H-index of 8 in Scopus and 1 in Web of Science, which highlights his significant contribution to the research community. Javaid, with H-indices of 12 in Scopus and 6 in Web of Science, also demonstrates substantial influence in this area.

Following closely is Kumar, who has 17 publications. Kumar stands out with an H-index of 14 in Scopus and 9 in Web of Science, coupled with a high average citation count of 77.3 in Scopus and 66.5 in Web of Science. Afonso, with 18 publications, has an H-index of 3 in Scopus and 0 in Web of Science. Patti, who has 15 publications, holds H-indices of 7 in Scopus and 3 in Web of Science.

Roscia is notable for having the highest average citation count per publication among these authors, with 56.7 citations in Scopus and an outstanding 187.5 in Web of Science. Despite having 13 publications, his H-indices are 9 in Scopus and 2 in Web of Science. These data, summarised in Table 4, highlight the impact and productivity of these authors within the field.

Table 4. Authors with the highest number of publications on energy in smart cities.

No.	Item	Publications [N]	[%]	Citations [Average]		H-Index	
				Scopus	WoS	Scopus	WoS
1.	Al-Turjman, F.	20	0.4	48.1	19.7	8	1
2.	Javaid, N.	18	0.4	32.2	19.1	12	6
3.	Afonso, J.L.	18	0.4	1.6	0	3	0
4.	Kumar, N.	17	0.3	77.3	66.5	14	9
5.	Patti, E.	15	0.3	20.9	47.3	7	3
6.	Monteiro, V.	15	0.3	1.1	0	2	0
7.	Roscia, M.	13	0.3	56.7	187.5	9	2
8.	Rodrigues, J.J.P.C.	14	0.3	37.2	2.5	7	2
9.	Doukas, H.	12	0.2	30.1	21.7	7	6
10.	Acquaviva, A.	12	0.2	23.6	0	7	0
11.	Lazaroiu, G.C.	12	0.2	55.7	187.5	6	2
12.	Aujla, G.S.	12	0.2	86.7	69.1	10	7

Note: [N]—number of publications, [%]—percentage of the total number of publications (4922). Source: authors' work.

An analysis of co-citations among authors reveals that the following researchers, in particular, hold the greatest mutual interest, as indicated by the highest number of connections: Zhang Y., Wang J., Wang Y., Liu Y., Li Y., Wang X., Li J., Zhang X., Li X., Liu J., Wang H., Wang Z., Chen J., and Wang Z.L. This suggests that these authors have the most significant impact on advancing research in the area of energy in smart cities. Figure 4 presents a map showing the top 100 authors with the highest number of co-citations.

Among the journals, Energies is the most productive, with 124 publications. This is followed by Sustainable Cities and Society, which has 100 publications, and the International Conference on Technologies for Smart City Energy Security and Power with 87 publications. However, when considering the average citations per article, Sustainable Cities and Society stands out with 45.1 citations in Scopus and 31.3 in Web of Science. IEEE Access also has a high citation average, with 55.3 in Scopus and 31.1 in Web of Science. Sustainability Switzerland follows, with 20.8 citations in Scopus and 13.9 in Web of Science (Table 5).

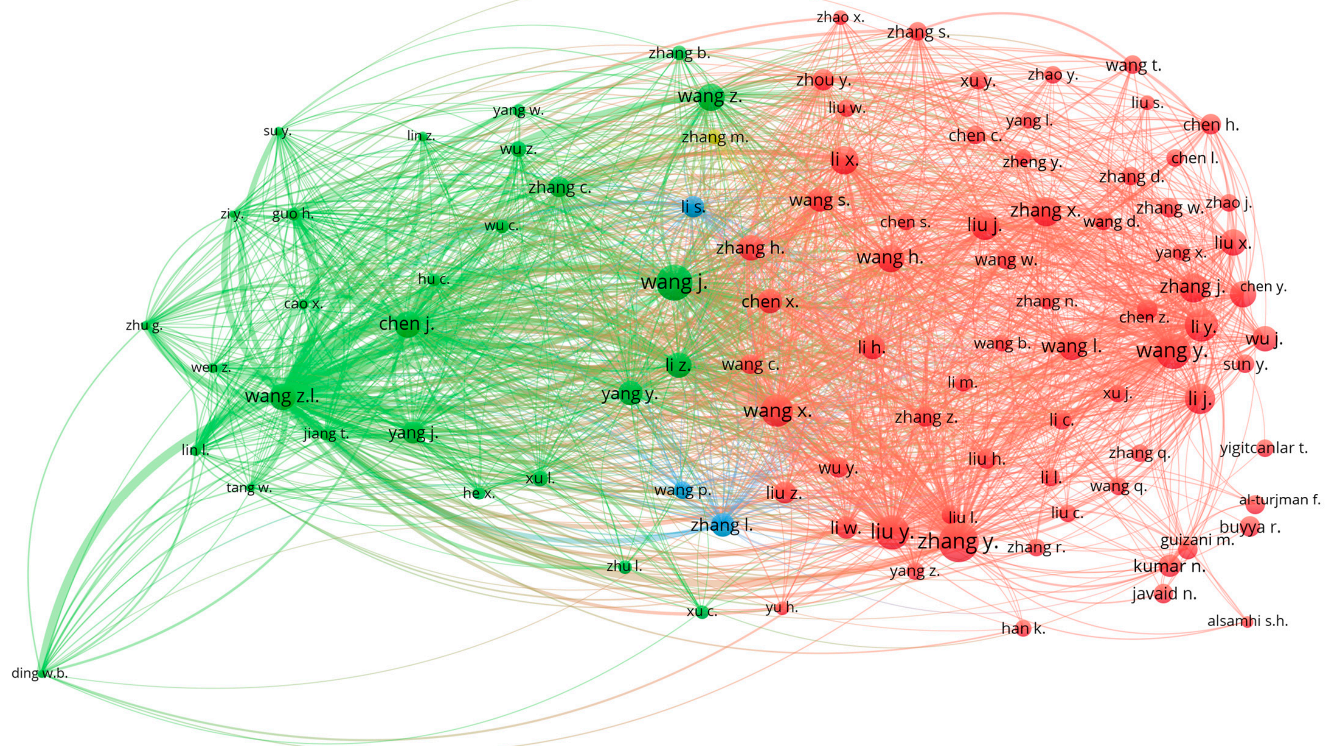

Figure 4. Map of co-citation of authors on energy in smart cities. Source: authors' work using VOSviewer software.

Table 5. Authors and journals with the highest number of publications on energy in smart cities.

No.	Item	Publications [N]	[%]	Citations [Average]		H-Index	
				Scopus	WoS	Scopus	WoS
1.	Energies	124	2.5	18.3	12.7	29	19
2.	Sustainable Cities and Society	100	2.0	45.1	31.3	37	20
3.	International Conference on Technologies for Smart City Energy Security and Power: Smart Solutions for Smart Cities—ICSESP 2018 Proceedings	87	1.8	9.1	N/A	15	N/A
4.	Sustainability Switzerland	81	1.6	20.8	13.9	24	16
5.	IEEE Access	81	1.6	55.3	31.1	34	20
6.	Advances in Intelligent Systems and Computing	79	1.6	2.9	4.6	8	3
7.	ACM International Conference Proceedings Series	77	1.6	3.8	N/A	9	N/A
8.	Lecture Notes of the Institute for Computer Sciences Social Informatics and Telecommunications Engineering LNICST	68	1.4	2.6	2.3	7	3
9.	Communications in Computer and Information Science	68	1.4	3.3	3.1	8	3
10.	E3s Web of Conferences	62	1.3	1.7	2.33	5	2

Note: [N]—number of publications, [%]—percentage of the total number of publications (4922), N/A—not applicable. Source: authors' work.

An analysis of co-citations among journals reveals that the following journals, in particular, hold the greatest mutual interest, as indicated by the highest number of connections: Applied Energy, Renewable and Sustainable Energy Reviews, Energy, IEEE Access, Energies, Sustainable Cities and Society, Journal of Cleaner Production, and Energy and Buildings. This suggests that these journals have the most significant impact on advancing research in the area of energy in smart cities. Figure 5 presents a map showing the top 31 journals with the highest number of co-citations.

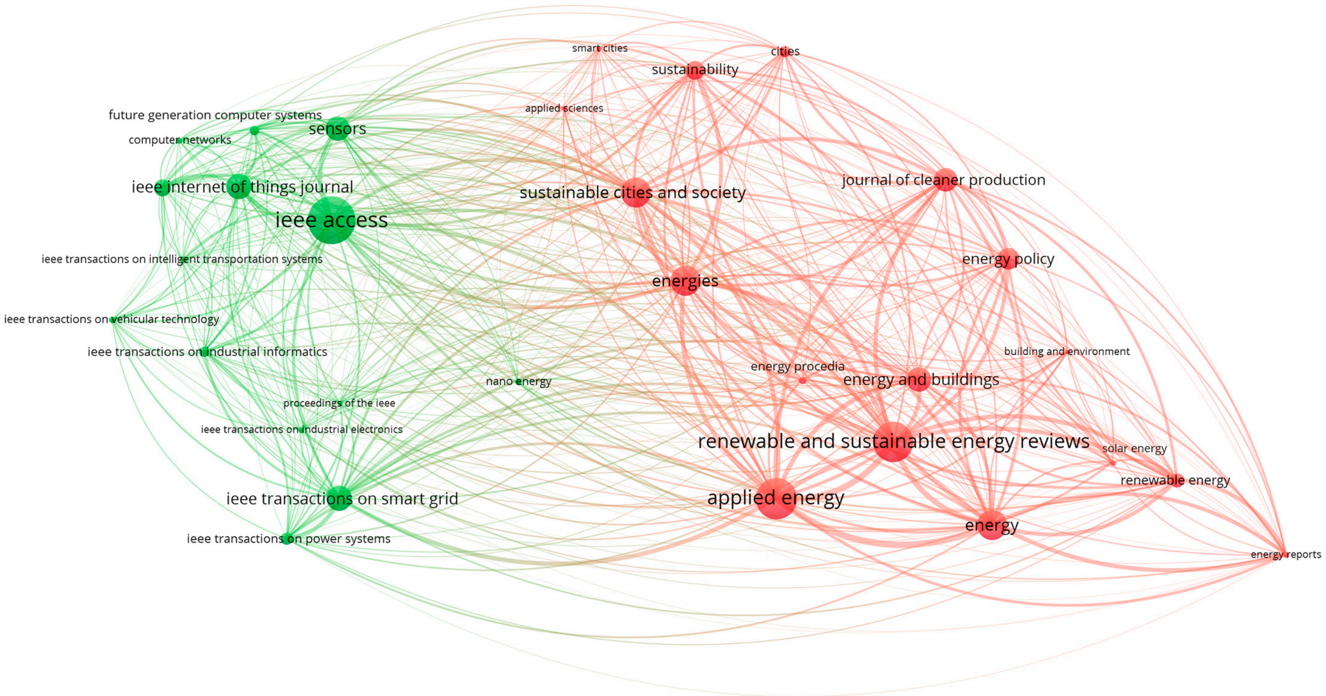

Figure 5. Co-occurrence map of keywords related to energy in smart cities. Source: authors' work using VOSviewer software.

Regarding author affiliations, COMSATS University Islamabad (CUI) leads with 54 publications. Politecnico di Milano follows closely with 43 publications, and the University Politehnica of Bucharest contributes 42 publications. These institutions are notable for their active research output. The citation performance of these institutions is also impressive. Publications from COMSATS University Islamabad average 44.8 citations in Scopus and 31.6 in Web of Science. The University Politehnica of Bucharest averages 23.4 citations in Scopus and 30.8 in Web of Science (per publication). Politecnico di Milano's publications receive an average of 15.1 citations in Scopus and 11.8 in Web of Science (Table 6). These figures underscore the considerable impact these institutions have in the academic community.

When looking at H-indices by country, China and the United States are the leaders, each with an H-index of 59 in Scopus. This indicates their strong research influence on a global scale. India follows with an H-index of 44, showcasing its significant academic impact as well. In Web of Science, China maintains its leadership with an H-index of 37. The United States follows with an H-index of 27, while India holds an H-index of 26. Among institutions, COMSATS University Islamabad is particularly notable. It has an H-index of 21 in Scopus and 11 in Web of Science, which reflects its strong influence in research.

Table 6. Countries and organisations with the highest number of publications on energy in smart cities.

No.	Item	Publications [N]	[%]	Citations [Average]		H-Index	
				Scopus	WoS	Scopus	WoS
		Countries					
1.	India	864	17.6	11.5	15.3	44	26
2.	China	774	15.7	17.7	22.4	59	37
3.	United States	571	11.6	30.0	24.1	59	27
4.	Italy	411	8.4	22.1	18.6	46	29
5.	United Kingdom	317	6.4	25.5	31.1	45	26
6.	Spain	274	5.6	22.4	22.9	39	26
7.	Germany	190	3.9	11.1	13.5	23	14
8.	Saudi Arabia	188	3.8	20.8	20.4	34	23
9.	France	172	3.5	11.6	8.2	20	10
10.	Pakistan	147	3.0	27.0	20.1	33	17
11.	Portugal	145	2.9	14.5	12.3	24	16
		Organisations					
1.	COMSATS University Islamabad (CUI)	54	1.1	44.8	31.6	21	11
2.	Politecnico di Milano/Polytechnic University of Milan	43	0.9	15.1	11.8	14	9
3.	University Politehnica of Bucharest/National University of Science Technology Politehnica Bucharest	42	0.9	23.4	30.8	13	7
4.	Politecnico di Torino/Polytechnic University of Turin	39	0.8	26.1	24.6	13	8
5.	King Saud University	37	0.8	26.3	13.1	16	6
6.	National Institute of Technology (NIT Rourkela)	33	0.7	8.4	7	8	3
7.	Universidade do Minho	33	0.7	5.5	12.0	5	3
8.	Sapienza Università di Roma	30	0.6	26.7	23.7	10	5
9.	Czech Technical University in Prague	29	0.6	4.1	1.2	6	2
10.	Norges Teknisk-Naturvitenskapelige Universitet/Norwegian University of Science Technology NTNU	27	0.5	41.4	14.4	14	8
11.	Thapar Institute of Engineering & Technology	27	0.5	48.7	51.8	14	9
12.	CNRS Centre National de la Recherche Scientifique/CNRS Institute for Engineering Systems Sciences INSIS	29	0.6	14.5	3.0	8	1
13.	Tsinghua University	26	0.5	22.8	35.0	10	5

Note: [N]—number of publications, [%]—percentage of the total number of publications (4922). Source: authors' work.

The countries with the strongest bibliographic coupling are India, China, the United States, the United Kingdom, Italy, Saudi Arabia, Spain, Pakistan, Australia, and Canada. Between these countries, there is the largest number of references on the topic energy in smart cities. A map of the 69 countries with the highest bibliographic coupling is shown in Figure 6.

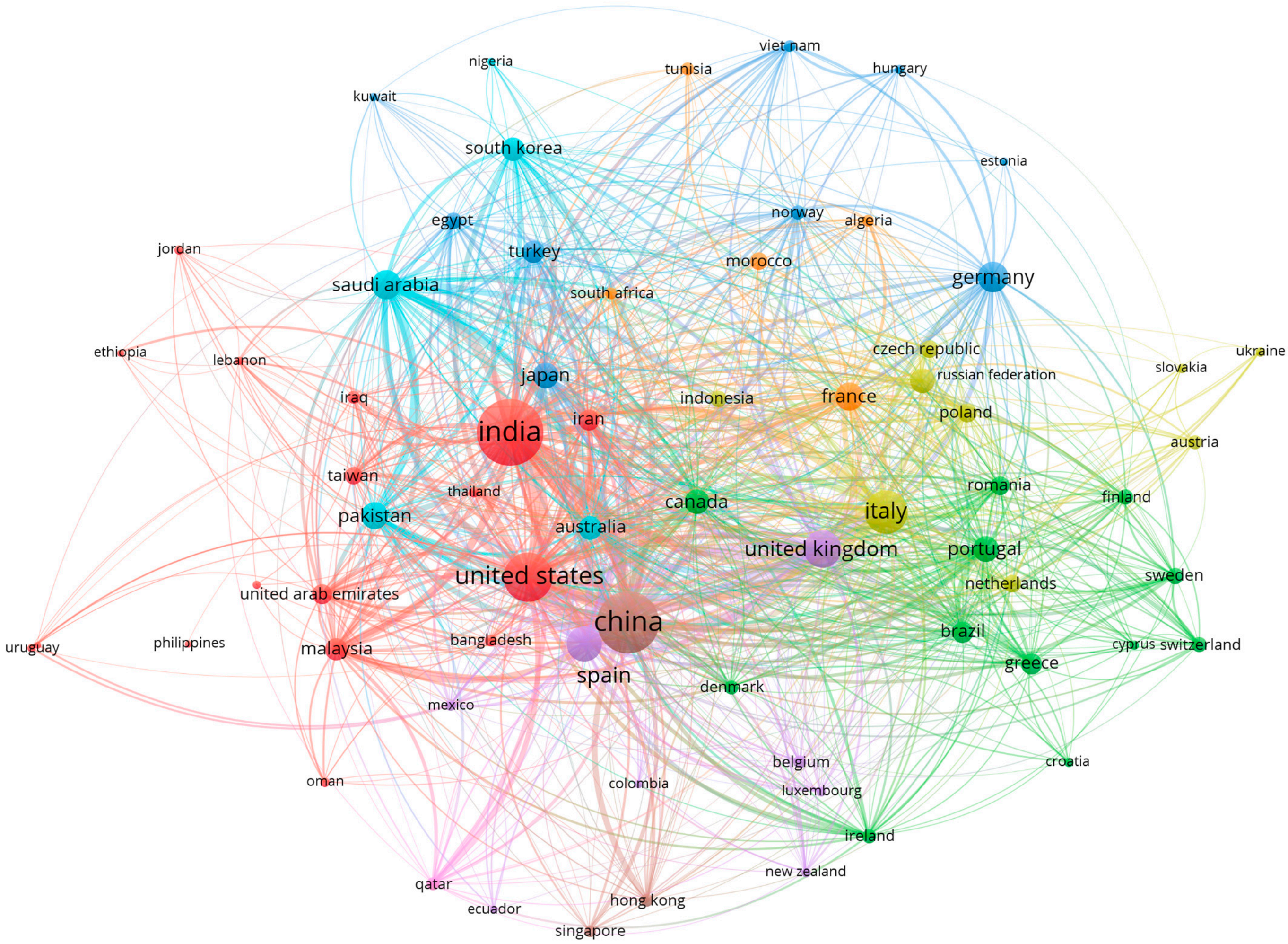

Figure 6. Map of bibliographic coupling of countries on energy in smart cities. Source: authors' work using VOSviewer software.

The network of cooperation between countries on smart city energy research is also shown on the world map in Figure 7. Calculations performed using RStudio software corroborate the findings obtained from analyses conducted with VOSviewer. The key countries leading in research within this field include India, China, the United States, the United Kingdom, Italy, Saudi Arabia, Spain, Pakistan, and Australia.

Only in the Web of Science database is the link between publications and Sustainable Development Goals demonstrated. In this context, the highest number of publications is related with SDG 11: Sustainable Cities and Communities. This category includes 471 publications with an H-index of 50. Following this, SDG 7: Affordable and Clean Energy has 332 publications and an H-index of 37. SDG 13: Climate Action is represented by 168 publications with an H-index of 33. Additionally, SDG 9: Industry, Innovation, and Infrastructure contributes 53 publications and an H-index of 16. These figures highlight the increasing academic focus on sustainability challenges and emphasise the critical role of SDG-focused research in advancing global knowledge and driving academic impact (Table 7).

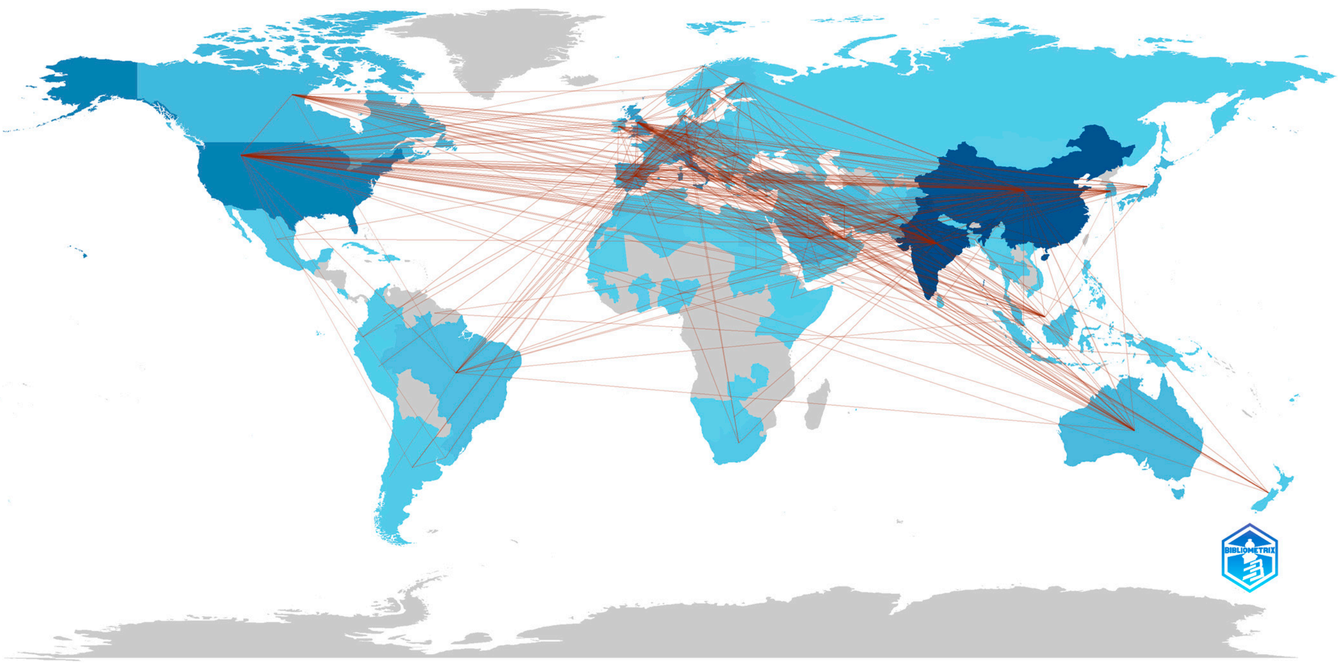

Figure 7. Countries' collaboration map for energy in smart cities. Source: authors' work using RStudio software.

Table 7. Publications relating to the Sustainable Development Goals.

No.	Name of the Sustainable Development Goal	Publications [N]	[%]	Citations [Average]	H-Index
1.	11 Sustainable Cities and Communities	471	9.6	21.5	50
2.	07 Affordable and Clean Energy	332	6.7	19.4	37
3.	13 Climate Action	168	3.4	19.9	33
4.	09 Industry Innovation and Infrastructure	53	1.1	16.2	16
5.	12 Responsible Consumption and Production	32	0.7	19.8	12
6.	03 Good Health and Well Being	19	0.4	10.8	6
7.	06 Clean Water and Sanitation	13	0.3	10.4	5
8.	04 Quality Education	8	0.2	8.5	3
9.	08 Decent Work and Economic Growth	6	0.1	13.0	4
10.	15 Life on Land	3	0.1	9	2

Note: [N]—number of publications in Web of Science, [%]—percentage of the total number of publications (4922). Source: authors' work.

Among the most frequently cited works is Mancarella's 2014 article, "MES (multi-energy systems): An overview of concepts and evaluation models". This paper has received 1138 citations in Scopus and 937 in Web of Science. Another highly cited work is Yu et al.'s 2017 paper, "A Survey on the Edge Computing for the Internet of Things". It has accumulated 1074 citations in Scopus and 800 in Web of Science. Additionally, Alonso-Mora et al.'s 2017 study, titled "On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment", has 825 citations in Scopus and 676 in Web of Science.

Other significant contributions include Minoli et al.'s 2017 paper, "IoT Considerations, Requirements, and Architectures for Smart Buildings-Energy Optimization and Next-Generation Building Management Systems". This paper has received 613 citations in Scopus and 454 in Web of Science. Bibri's 2018 article, "The IoT for Smart Sustainable Cities of the Future", has also been widely referenced (Scopus—506, WoS—350), as have Nižetić et al.'s 2020 work, "Internet of Things (IoT): Opportunities, Issues and Challenges Towards a Smart and Sustainable Future" (Scopus—503, WoS—279), and Lazaroiu and Roscia's "Definition methodology for the smart cities model" (Scopus—466, WoS—365).

Several of the most cited articles were published in journals such as Energy, IEEE Access, Proceedings of the National Academy of Sciences of the United States of America, and the Journal of Cleaner Production. Most of these top-cited papers were published between 2017 and 2020. This trend reflects recent developments and the growing interest in the IoT and smart cities research.

The most cited articles were published in journals such as Energy (2 articles), IEEE Access, Proceedings of the National Academy of Sciences of the United States of America, and Journal of Cleaner Production. A majority of them were published between 2017 and 2020 (Table 8).

Table 8. The most cited articles for energy in smart cities.

No.	Authors		Article Title	Journal	Citations [N]	
					Scopus	WoS
1.	Mancarella, P. (2014)	[57]	MES (multi-energy systems): An overview of concepts and evaluation models	Energy	1138	937
2.	Yu, W. et al. (2017)	[58]	A Survey on the Edge Computing for the Internet of Things	IEEE Access	1074	800
3.	Alonso-Mora, J. et al. (2017)	[59]	On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment	Proceedings of the National Academy of Sciences of the United States of America	825	676
4.	Minoli, D. et al. (2017)	[38]	IoT Considerations, Requirements, and Architectures for Smart Buildings-Energy Optimization and Next-Generation Building Management Systems	IEEE Internet of Things Journal	613	454
5.	Bibri, S.E. (2018)	[60]	The IoT for smart sustainable cities of the future: An analytical framework for sensor-based big data applications for environmental sustainability	Sustainable Cities and Society	506	350
6.	Nižetić, S. et al. (2020)	[61]	Internet of Things (IoT): Opportunities, issues and challenges towards a smart and sustainable future	Journal of Cleaner Production	503	279
7.	Lazaroiu, G.C., Roscia, M. (2012)	[62]	Definition methodology for the smart cities model	Energy	466	365
8.	Plageras, A.P. et al. (2018)	[63]	Efficient IoT-based sensor BIG Data collection–processing and analysis in smart buildings	Future Generation Computer Systems	464	345
9.	Liu, Y. et al. (2019)	[9]	Intelligent Edge Computing for IoT-Based Energy Management in Smart Cities	IEEE Network	423	302
10.	Ullah, Z. et al. (2020)	[37]	Applications of Artificial Intelligence and Machine learning in smart cities	Computer Communications	416	257
11.	Ejaz, W. et al. (2017)	[8]	Efficient Energy Management for the Internet of Things in Smart Cities	IEEE Communications Magazine	387	293

Note: [N]—number of citations. Source: authors' work.

In the context of the bibliometric analysis focused on energy in smart cities, keywords that were frequently associated with this subject were carefully extracted. VOSviewer software was utilised to conduct this analysis, leading to the identification of key terms.

Initially, the dataset included 118 words or phrases that appeared at least fifteen times in the keywords of the 4922 articles reviewed.

The dataset contained synonymous terms, abbreviations, and repeated phrases, such as 'Internet of Things', 'internet-of-things', 'IoT', 'artificial intelligence', and 'AI'. It also included terms that were not directly related to energy in smart cities, such as 'article', 'state', 'analysis', 'scheme', 'model', 'knowledge', and 'literature review'. To refine this collection, a thesaurus file was meticulously curated and applied, ensuring the terms were organised and consistent.

Keywords directly associated with energy and smart cities, such as 'energy', 'energies', 'smart city', and 'smart cities', were deliberately excluded from the final collection to focus on more specific and nuanced terms. The standardisation of terms and abbreviations with similar meanings was performed, and irrelevant words were discarded. After this process, a refined collection of 97 keywords remained, each appearing at least 15 times. The most significant terms related to energy in smart cities, along with their interconnections, are depicted in Figure 8.

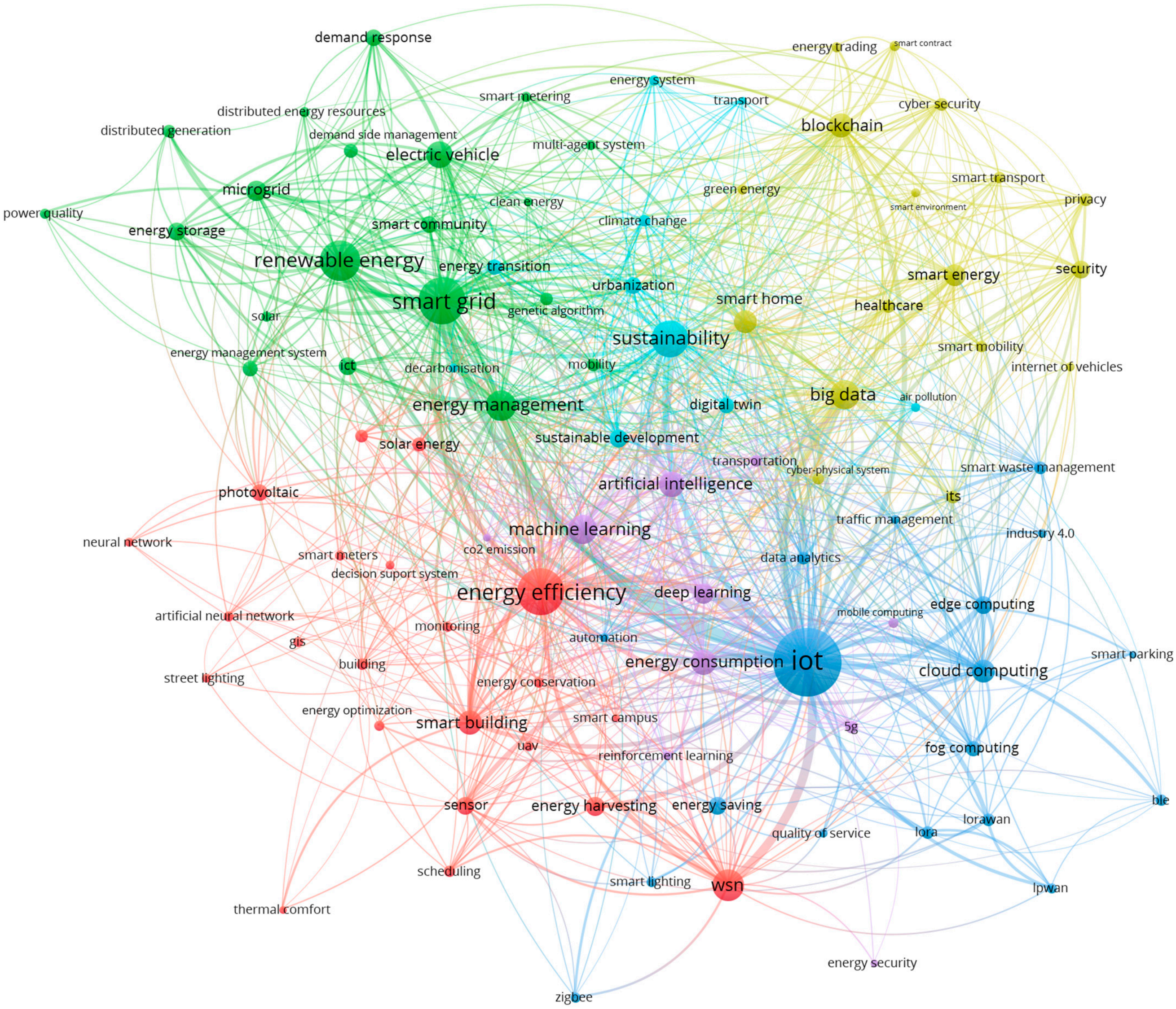

Figure 8. Map of co-occurrence of keywords related to the energy sector in smart cities. Source: authors' work using VOSviewer software.

In order to synthesise the main themes in the study of energy within smart cities, a keyword analysis was performed based on data from five subareas identified as crucial in the realm of smart city development. The analysis included keywords that appeared at least 15 times across various studies and reviews, revealing a comprehensive view of interconnected themes.

The core keywords identified encompass a wide range of technologies and strategies pivotal to smart cities:

- Intelligent energy systems and building management (red): key terms include energy efficiency (377), wireless sensor networks (179), and smart buildings (107). This cluster emphasises the integration of technology in building management, focusing on optimising energy use and enhancing sustainability through advanced monitoring and automation technologies.
- Smart grids and renewable energy management [64]: dominated by keywords such as smart grid (382) and renewable energy (287). This category highlights the shift towards sustainable energy sources, supported by smart technology for better energy management and distribution.
- Internet of Things systems and advanced digital technologies (blue): Internet of Things (IoT) leads with 784 occurrences, followed by cloud computing (103) and edge computing (61). The focus here is on the role of the IoT in enhancing various aspects of energy management, from savings to smart waste management.
- Intelligent machine learning systems for energy and mobility (violet): Features machine learning (162) and energy consumption (124). This cluster explores how AI and machine learning are applied to optimise energy usage and mobility in urban environments.
- Sustainable energy transition (turquoise): sustainability (245) and sustainable development (65) are prominent, stressing the importance of transitioning to sustainable energy practices as a core component of smart city development.

These thematic clusters are not only rich in specific technological terms but also interlink with broader concepts like sustainability and urbanisation, indicating a multi-faceted approach to energy management in smart cities. The most connected terms across clusters highlight an integrated strategy to enhance energy efficiency, management, and sustainability through advanced technologies and intelligent systems. The results are visually mapped, showing the frequency and connections of keywords, illustrating the complex interdependencies and focus areas within the domain of smart city energy management. This holistic view is further detailed in a comprehensive table, presenting a structured breakdown of key areas and their associated technologies and strategies. All keywords from the five sub-areas are presented in Table 9.

The first area, 'Intelligent energy systems and building management', emerges from scholarly investigations that elucidate the integration and optimisation of energy systems within smart urban configurations, with a particular focus on enhancing building management through cutting-edge technologies. This thematic area aligns with scholarly discourse on energy efficiency, deploying technologies such as wireless sensor networks, intelligent building solutions, and energy harvesting mechanisms. Significant technological interventions include the utilisation of photovoltaic systems, solar energy, and sustainable energy methodologies, complemented by smart meters and GIS for refined energy optimisation and conservation strategies. The research underscores the critical function of artificial intelligence, incorporating neural networks and decision support systems, to advance energy management and promote environmental sustainability in urban structures.

Table 9. Research sub-areas for energy in smart cities.

No.	Sub-Area Name	Keywords
1.	Intelligent energy systems and building management (red)	energy efficiency (377), wireless sensor networks—WSN (179), smart building (107), energy harvesting (72), sensor (62), photovoltaic (54), solar energy (38), sustainable energy (32), scheduling (27), building (26), energy optimization (23), monitoring (23), smart meters (23), GIS (22), artificial neural network (21), energy conservation (21), unmanned aerial vehicle—UAV (21), street lighting (19), decision support system (18), neural network (18), smart campus (15), thermal comfort (15)
2.	Smart grids and renewable energy management [64]	smart grid (382), renewable energy (287), energy management (165), electric vehicle (135), microgrid (84), energy storage (64), ICT (61), demand response (56), smart community (52), energy management system (44), demand side management (37), genetic algorithm (34), mobility (34), distributed generation (31), power quality (24), smart metering (24), multi-agent system (21), solar (21), distributed energy resources (20), clean energy (19)
3.	Internet of Things systems and advanced digital technologies (blue)	Internet of Things—IoT (784), cloud computing (103), edge computing (61), energy saving (60), fog computing (49), data analytics (35), smart waste management (35), LoRa (33), LoRaWAN (33), bluetooth low energy—BLE (27), low-power wide-area network—LPWAN (21), smart lighting (21), ZigBee (20), industry 4.0 (19), quality of service (19), traffic management (19), automation (17), smart parking (15), big data (154), blockchain (113), smart home (95), smart energy (90), security (63), healthcare (36), its (36), cyber security (35), privacy (34), smart mobility (28), smart transport (28), cyber-physical system (26), green energy (24), energy trading (20), smart contract (20), smart environment (18), internet of vehicles (17)
4.	Intelligent machine learning systems for energy and mobility (violet)	machine learning (162), energy consumption (124), artificial intelligence—AI (119), deep learning (77), 5G (33), transportation (27), mobile computing (22), reinforcement learning (17), CO_2 emissions (15), energy security (15)
5.	Sustainable energy transition (turquoise)	sustainability (245), sustainable development (65), urbanization (51), digital twin (47), energy transition (47), climate change (30), energy system (24), air pollution (16), decarbonisation (16), transport (15)

Source: authors' work.

The second area, 'Smart grids and renewable energy management', is informed by academic studies focusing on the implementation and administration of smart grid technologies alongside renewable energy sources. This research explores the transformative capabilities of smart grids in revolutionising energy management via the integration of electric vehicles, microgrids, and energy storage solutions. The scholarly narrative emphasises the importance of ICT, demand response systems, and intelligent metering in enhancing efficient energy management practices. Additionally, it addresses the complexities associated with integrating distributed generation and pristine energy technologies into existing urban frameworks, aiming to foster a circular economy and enhance power quality within intelligent urban locales.

The third domain, 'Internet of Things systems and advanced digital technologies', is derived from academic research highlighting the pivotal role of the Internet of Things in augmenting energy efficiency and smart city operations. It emphasises the convergence of cloud, edge, and fog computing with the IoT to optimise energy usage and manage smart infrastructures effectively. This research domain also ventures into the potential of data analytics and blockchain technology in revolutionising smart waste management, traffic management, and energy-saving initiatives. The integration of smart home and energy systems within this framework is aimed at bolstering security, privacy, and overall urban quality of life.

The fourth thematic area, 'Intelligent machine learning systems for energy and mobility', explores the application of machine learning and artificial intelligence to optimise energy use and improve mobility solutions in smart cities, as examined in the academic literature. It emphasises the role of deep learning and reinforcement learning in addressing transportation issues and reducing CO_2 emissions. This area also explores the impact of 5G technology and mobile computing on urban energy and transportation systems, emphasising the importance of energy security and sustainable mobility practices highlighted in recent studies.

The final area, 'Sustainable energy transition', is critically assessed through the lens of scholarly research focused on the long-term sustainability objectives of smart cities, concerning energy transition and sustainable development. Academic discourse examines the impacts of urbanisation, digital twins, and climate change on energy systems, underlining the imperative for decarbonisation and effective air pollution management. This thematic exploration promotes a holistic understanding of the transition towards more sustainable, resilient urban frameworks, capable of adapting to evolving environmental challenges.

Using RStudio software, a thematic map was developed based on axes representing the level of significance and the level of development (Figure 9). This map highlights that the thematic drivers in the field of energy within smart cities are urbanisation, climate change, energy policy, and energy transition. Core topics include issues related to energy management, smart grids, microgrids, renewable energy, and electric vehicles. Sustainability and technologies linked to energy efficiency, such as the IoT, WSN, and machine learning, are also essential components. Niche topics identified are clean energy technology, wireless security, and MPPT (maximum power point tracking). Emerging themes are centred around energy security.

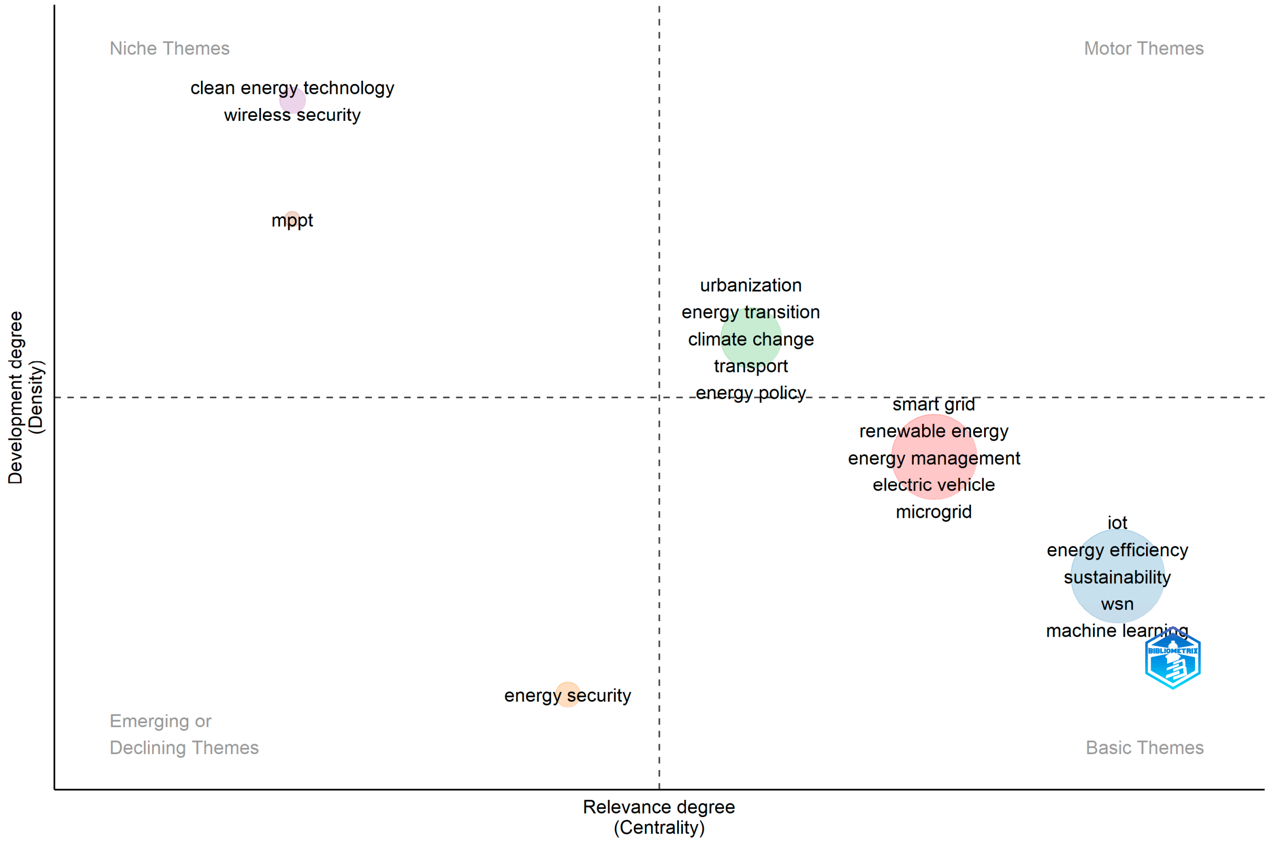

Figure 9. Thematic map based on author keywords related to energy in smart cities. Source: authors' work using RStudio software.

To identify emerging research areas in the field of energy in smart cities, an analysis of keyword co-occurrence in articles published between 2022 and 2024 was conducted. This analysis indicates that the emerging topics primarily include the following keywords: digital twin, smart meters, cyber security, buildings, intelligent transportation system—ITS, mobility, transportation, building, sustainable energy, energy harvesting, energy conservation, energy management, demand response, machine learning, deep learning, convolutional neural networks—CNN, urbanization, and smart community. These keywords are highlighted in yellow and light green in Figure 10.

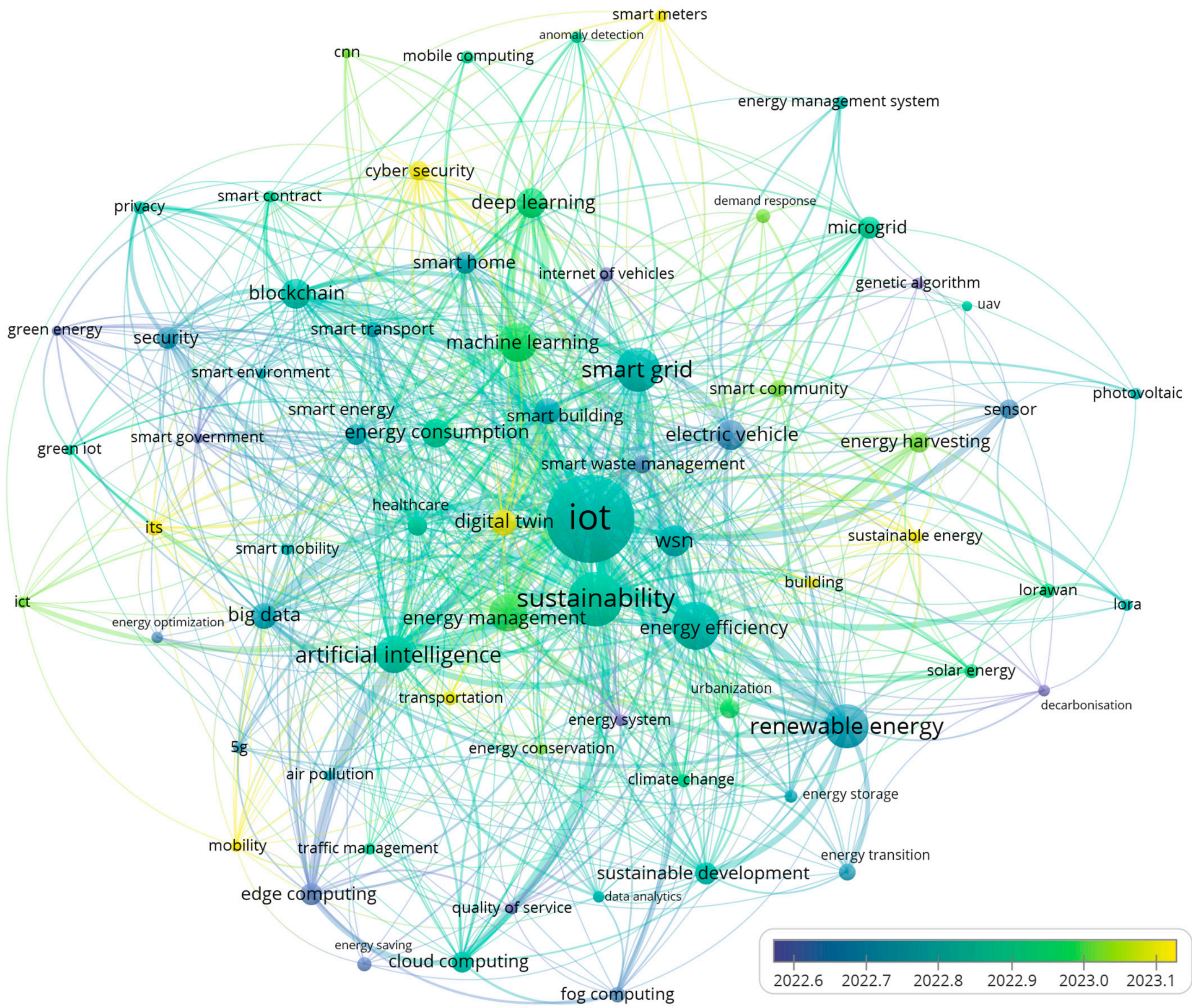

Figure 10. Keyword co-occurrence map for energy in smart cities in 2022–2024. Source: authors' work using VOSviewer software.

Analyses conducted using RStudio software further refined the findings, indicating that the topic of digital twins in the context of energy is an emerging area of interest that is likely to be explored in the coming years. A trend map based on keywords related to energy in smart cities from 2014 to 2024 is presented in Figure 11.

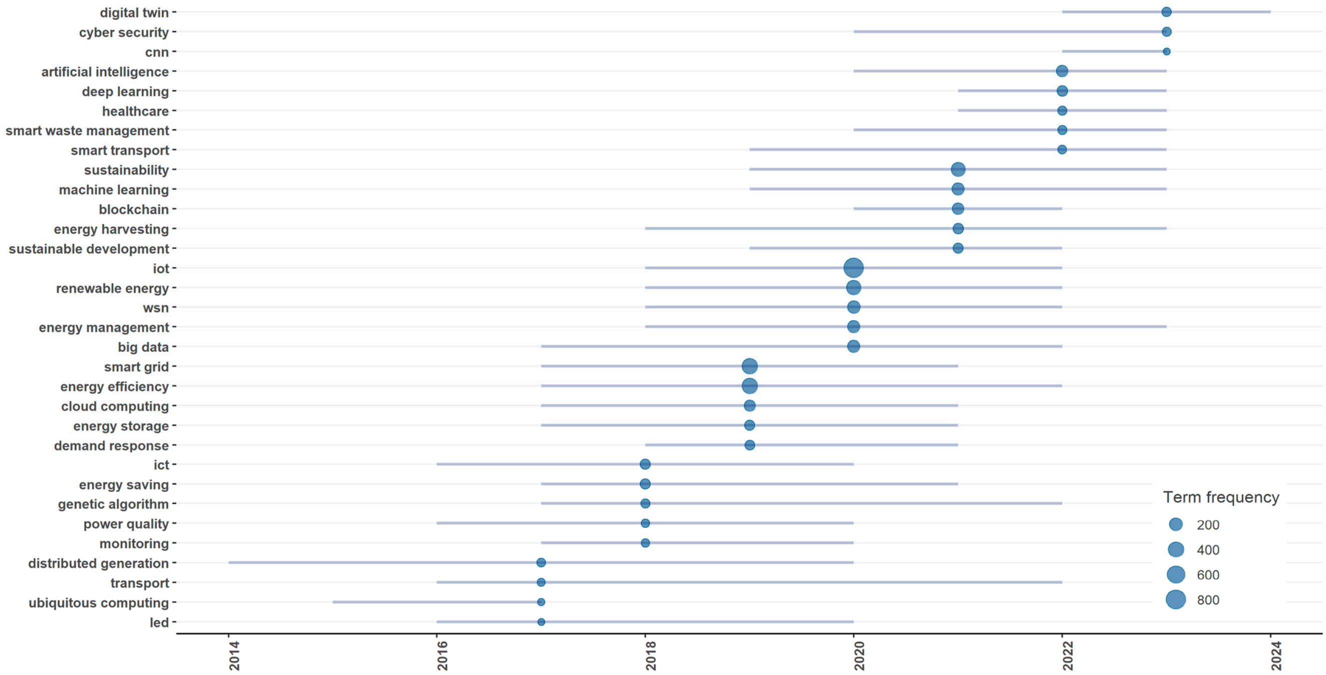

Figure 11. Recent trends based on author keywords for energy in smart cities in 2014–2024. Source: authors' work using RStudio software.

The analysis of the thematic progression of energy research in smart cities shows how research focus has evolved over time (Figure 12). Between 2008 and 2016, research focused on the themes of 'smart energy' and the 'IoT'. This period also saw the introduction of energy management technologies, including 'smart grid' and 'data analytics'. These trends reflected early interest in optimising urban energy systems. The term 'security' appeared during this period. It signalled an increasing recognition of the importance of protecting these emerging systems. Issues of 'sustainable development' and 'urbanisation' were also mentioned in the research.

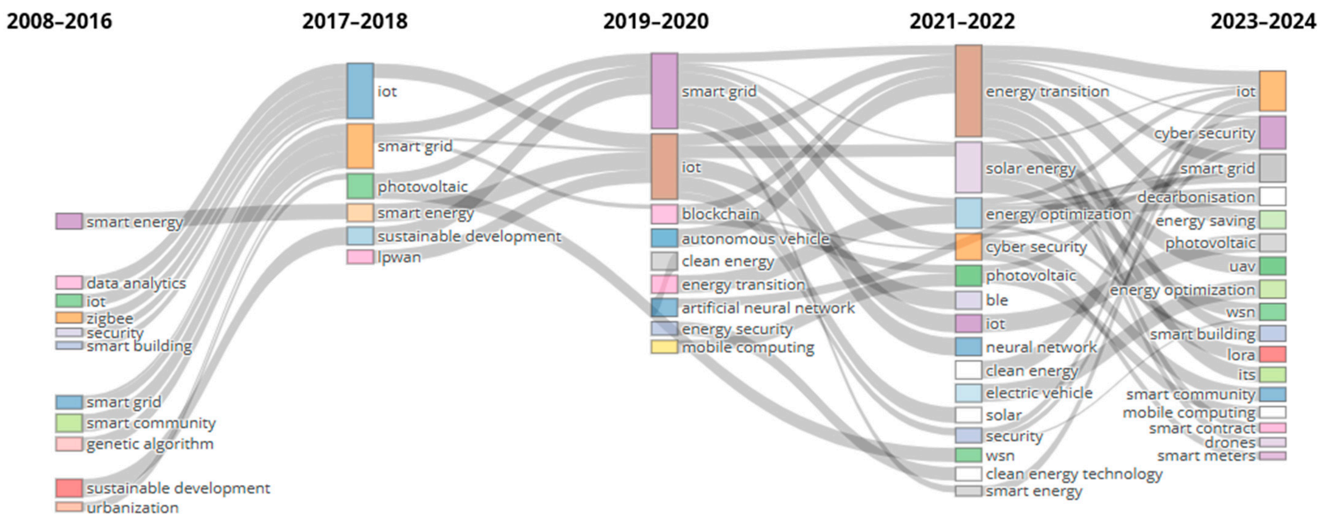

Figure 12. Thematic evolution based on author keywords related to energy in smart cities. Source: authors' work using RStudio software.

In 2017 and 2018, research topics like the 'IoT' and 'smart grids' remained a key focus for researchers. At the same time, new themes began to emerge. Topics related to renewable energy, such as 'photovoltaic', became more prominent. This shift indicated a growing emphasis on environmentally conscious energy solutions. Researchers were also focusing on integrating these technologies with sustainability concepts. This is evidenced by a number of studies in the field of 'sustainable development'.

In 2019–2020, topics such as 'smart grid' and the 'IoT' continued to be important research areas. However, the research began to shift more towards innovative technologies. These new solutions aimed to support advanced energy transition. New keywords such as 'blockchain' and 'autonomous vehicle' illustrate that smart cities were beginning to adopt modern technologies for the automation and decentralisation of energy management. At the same time, terms like 'clean energy' and 'energy security' became key, suggesting a growing need for both security and sustainability in energy resource management. This was a period when research shifted from theory to practice, introducing new technologies that support energy transformation.

The period of 2021–2022 saw intensified research into energy system optimisation, as indicated by the emergence of terms like 'energy transition', 'solar energy', 'energy optimisation', 'photovoltaic', and 'Bluetooth Low Energy'. These technologies aim to improve energy efficiency in cities, which is crucial for creating smart, energy-saving cities of the future. Topics related to security, such as 'cyber security' and 'WSN' (Wireless Sensor Networks), represent the continuation of trends from previous years, reflecting growing concerns about securing expansive, digitalised energy systems.

In the latest period, 2023–2024, topics related to the 'IoT' and 'cyber security' continued to be of interest, demonstrating ongoing engagement with these areas. New topics, such as 'decarbonisation' and 'energy saving', reflect increasing pressures to develop low-emission energy systems in cities, responding to global climate challenges. Emerging technologies, such as 'unmanned aerial vehicle' and 'smart contract', have entered the smart cities research landscape, showing increasingly advanced methods of energy and security management within complex urban systems.

The transitions between research periods demonstrate that areas like the 'IoT', 'smart grid', and 'cyber security' have remained central to the evolution of research, being continually developed and adapted to address changing technological challenges. In contrast, emerging topics such as 'blockchain', 'decarbonisation', and 'unmanned aerial vehicle' reflect the constant need for innovation in the field of energy in smart cities.

4. Discussion

4.1. Technological Trends in Energy in Smart Cities

Smart energy management is one very important element of smart city development. With increasing urbanisation, rising energy demand, and the need to reduce greenhouse gas emissions, technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), and blockchain are increasingly important when it comes to optimising urban energy systems. These tools enable efficient resource management, minimising energy waste and supporting the transformation towards more sustainable cities.

One of the pillars of this transformation is intelligent energy management systems in buildings [65–67]. Through IoT technology, it is possible to monitor energy consumption in real time, allowing for dynamic control of heating, cooling, and lighting processes. Sensor networks deployed throughout the building collect data on temperature, humidity, and occupancy, enabling the optimal adjustment of internal conditions to meet user needs [68–71]. This enhances the energy efficiency of buildings and leads to a reduction in greenhouse gas emissions [72,73]. As a result, zero-emission buildings that utilise renewable energy and advanced energy management algorithms are becoming increasingly common [74–76]. These buildings serve as a model for sustainable construction [77–80].

The Internet of Things plays a role also on a city-wide scale. IoT sensors gather data on energy usage, air quality, traffic patterns, and water management systems [81–84]. These data are analysed to optimise energy distribution, detect anomalies, and predict future needs [85,86]. For instance, a sudden spike in energy consumption in a particular district could indicate a malfunction or illegal connection, enabling rapid intervention by technical services. The IoT and big data analytics are also employed to monitor air quality and water resources, which are vital for sustainable development [87,88]. These systems also support smart urban lighting that automatically adjusts light intensity based on external conditions, time of day, or the number of people on the streets, resulting in energy savings and improved public safety [89–94].

To effectively utilise the vast amounts of data generated by the IoT, advanced digital technologies such as AI and ML are essential. Artificial intelligence analyses energy consumption data, forecasting future needs and optimising supplies [81,95–99]. For example, AI can predict demand peaks based on historical data and weather conditions, enabling better energy production planning. Machine learning, on the other hand, automates energy management processes and dynamically adjusts supplies to current needs [100–107]. This allows cities to better integrate renewable energy sources and minimise energy losses [25,108–113].

Smart grids are another key element of the energy transition. These networks integrate renewable energy sources into urban systems, allowing for dynamic energy distribution management and minimising losses. Smart grids adjust the energy supply to demand in real time, helping to avoid overloads and outages. They enable bidirectional energy flows, where consumers can become prosumers, generating energy for their own needs and feeding excess back into the grid [66,106,114]. This dynamic adjustment of supply to demand minimises losses and enhances the stability of energy systems. The implementation of energy storage systems, such as lithium-ion batteries or compressed-air energy storage systems, further contributes to system stability by storing excess energy for use during periods of increased demand [66,115–119]. Through smart grids, cities can reduce energy losses, increase the share of renewables, and better manage resources, ultimately reducing CO_2 emissions and moving closer to achieving carbon neutrality [120,121].

The integration of renewable energy into urban energy systems is becoming increasingly crucial in response to the challenges posed by climate change. Smart grids monitor the production of renewable energy sources, such as photovoltaic panels installed on building roofs or wind turbines. They ensure the efficient distribution of this energy, which is essential for supply stability [122–127]. Energy storage plays a significant role in avoiding supply disruptions caused by the variability of renewable sources and better managing energy continuity [128–130]. Wind energy, particularly in coastal cities, is an important component of urban energy systems. Intelligent energy management systems optimise the distribution of energy from wind turbines [131–133].

The 5G technology also plays a crucial role. It supports dynamic energy management by enabling fast and reliable data transmission between devices. With low latency and high bandwidth, 5G allows systems to respond instantly to changing conditions, which is key to effective grid management [134–138]. This technology also supports the large-scale development of the Internet of Things, enabling the connection of many diverse devices and sensors across the city [135,139,140]. Meanwhile, work is underway on 6G technology, which promises to further increase data speeds and connectivity [141–143]. This development will set a new standard for future smart cities and energy management solutions [144–147].

Another tool supporting efficient energy management is digital twins—virtual models of real-world energy systems. They allow the simulation of various scenarios, such as failures, demand changes, or the integration of new energy sources, without risking the actual system [148–154]. This enables cities to better plan investments and manage resources [155–158].

As electric mobility develops, the demand for appropriate infrastructure to charge electric vehicles is also growing. Through smart grids, charging processes can be managed, optimising energy supplies and preventing overloads [45,159,160]. As a result, drivers can use charging stations without concerns about energy availability, while the energy networks are protected from overloads [161–165]. Moreover, intelligent transport solutions, such as autonomous electric vehicles, can reduce energy consumption in public transport, mainly through route optimisation and minimisation of empty runs [166,167].

However, it is important to note that the implementation of intelligent energy systems involves numerous challenges. One obstacle is the need to modernise existing infrastructure and ensure interoperability between different systems and devices. Additionally, the costs of implementing new technologies can be high. As energy systems become more digitalised, the risk of cyber-attacks also increases. These systems can become targets for hackers, who may disrupt energy supplies or gain access to sensitive data. Therefore, cities should invest in security technologies such as blockchain and advanced intrusion detection and encryption systems [168]. These measures will ensure the transparency, reliability, and security of energy transactions [169–174]. Blockchain technology not only enhances security but also promotes transparency and decentralisation in energy management. Users can trade excess renewable energy directly with each other, supporting the development of peer-to-peer systems and increasing the flexibility of grid management [175–179].

The future of energy in smart cities relies on the full integration of renewable energy sources, the automation of management processes, and the development of technologies such as 5G/6G, blockchain, and AI. Smart grids will enable more sustainable resource management, contributing to carbon neutrality and maximising energy efficiency [143,172,180–185]. Distributed energy management (DER) systems will also be important. They support the integration of local renewable energy sources with urban grids. In this way, they reduce dependence on traditional, often non-renewable energy sources [186–188].

Thus, intelligent energy management in future cities is a complex process that requires the synergy of many technologies and systems. From smart buildings, IoT, and AI to smart grids and blockchain—all these elements work together to create more sustainable, energy-efficient, and environmentally friendly urban environments. Challenges related to the implementation of these technologies, such as cybersecurity, infrastructure modernisation, and public education, must be addressed to fully harness the potential of smart cities and improve the quality of life for their inhabitants.

4.2. Future Research on Energy in Smart Cities

Future research on energy in smart cities should focus on the integration of advanced digital technologies and renewable energy systems. According to the authors, future studies should address:

- The potential of IoT integration within urban energy networks. Special attention should be paid to IoT and 5G/6G applications for optimising energy efficiency in street lighting, water management, and heating and cooling systems. The advancement of these technologies will facilitate sustainable resource management and enhance urban energy systems, thereby reducing energy consumption and emissions. The integration of IoT with next-generation networks will enable real-time data collection and analysis, promoting improved integration of renewable energy and the development of resilient urban systems. Research in this field is crucial for addressing climate challenges and improving the quality of life for urban residents in future cities.
- The integration of decentralised solar, wind, and biomass energy systems. Future studies should concentrate on effective methods of energy storage and distribution, particularly from renewable sources. Furthermore, research should explore prosumer models and energy-sharing platforms, analysing consumer behaviours and willingness to collaborate within peer-to-peer energy exchange systems. Examining consumer behaviour and participation in initiatives will deepen understanding of energy sharing and local energy micro-communities. These solutions may improve the flexibility of urban energy networks, optimise resource utilisation, and reduce emissions, aligning with sustainable development goals and efforts to mitigate climate change.
- Artificial intelligence and machine learning for energy demand forecasting and management. Future research should focus on the capacity of AI to predict consumption trends based on historical data and environmental conditions, enabling optimised

energy delivery schedules. Machine learning algorithms that automate energy management processes may significantly reduce energy losses. The implementation of these technologies enables improved integration of renewable energy and adaptive supply management, thereby enhancing energy network stability and reducing operational costs. This is essential for the development of sustainable, flexible, and resilient energy systems in the future.

- Cybersecurity of energy networks and data transmission, with blockchain applications. Research should encompass the security of energy transactions and data privacy protection. Additionally, studies should examine how blockchain can support the decentralisation of energy distribution and the development of local energy markets (e.g., peer-to-peer trading models). This technology can not only enhance transparency and trust in energy exchanges but also enable efficient resource management and increase prosumer participation in municipal energy systems. These solutions have the potential to improve the safety, flexibility, and stability of such systems.
- Electric mobility in the context of urban energy management. Future studies should focus on technologies that can optimise electric vehicle charging processes, prevent grid overload, and ensure supply stability. Research on autonomous electric vehicles should address their potential to enhance energy efficiency in public transportation. Optimising electric vehicle charging and preventing power grid overloads are essential for ensuring future urban energy stability. The advancement of autonomous electric vehicles will enhance the energy efficiency of public transport, supporting the goals of reducing energy consumption and CO_2 emissions.
- Digital twins as virtual models of urban energy systems. Future research should explore the use of digital twins for optimal energy resource allocation, risk minimisation, and long-term planning for sustainable urban development. Digital twins act as virtual representations of urban energy systems, enabling optimal energy resource allocation and supporting sustainable urban planning. Their deployment can mitigate risks associated with energy system failures by facilitating scenario simulations, including changes in energy demand and the integration of renewable sources. In future urban contexts, digital twins may play a pivotal role in decision-making by providing accurate assessments of the impacts of new investments on energy system performance. Their application can significantly enhance energy efficiency, reduce greenhouse gas emissions, and improve the stability of energy supply.
- Integrating energy management with circular economy principles, such as recycling and reusing energy and materials. Research should focus on technologies supporting closed-loop energy systems in urban areas, including waste heat recovery and the integration of recycling systems with urban energy sources. The integration of energy management with circular economy principles can transform urban energy systems by enhancing resource efficiency and minimising waste. These solutions not only reduce energy losses but also convert waste into valuable resources, thereby supporting greenhouse gas emission reductions and environmental protection. The adoption of technologies that close material loops within urban energy systems could significantly improve their efficiency.
- Development of energy management systems capable of flexible responses to crisis situations, such as extreme weather events, infrastructure failures, or sudden changes in energy demand. Studies should examine the potential of highly responsive, integrated systems that could alter energy distribution patterns using predictive algorithms, minimising crisis impacts on residents and urban infrastructure. Research on predictive algorithms for integrated systems may enable real-time adjustments in energy distribution. These technologies could mitigate the impacts of urban crises and strengthen resilience against future threats. Implementing such solutions would improve resource management, minimise energy disruptions, and reduce economic and environmental losses during crises.

- Climate change driving the demand for smart energy solutions. Future research should evaluate the impact of rising temperatures, shifting precipitation patterns, and extreme weather events on energy demand. Smart city technologies must be adaptable to changing climate conditions, ensuring flexibility and resilience in energy systems. These technologies should facilitate the forecasting of energy demand variations and the agile adjustment of energy production and distribution, thereby mitigating the adverse effects of climate change on urban operations and resident comfort. The adoption of such solutions will improve energy supply stability and reduce greenhouse gas emissions.
- The impact of urban energy systems on local biodiversity. Research should identify technologies, such as silent wind turbines, green roofs, and renewable energy sources integrated with green spaces, that minimise biodiversity impact and best support urban ecology. The adoption of these technologies should support biodiversity protection and the development of sustainable smart cities by integrating energy systems with natural ecosystems.

Future research on energy management in smart cities should, therefore, focus on enhancing efficiency, sustainability, and security through advanced technologies. This will be crucial in creating resilient, low-emission, and sustainable smart cities.

5. Conclusions

This research has primarily focused on identifying technological trends and directions for investigations into energy within intelligent urban areas, particularly those incorporating sophisticated digital solutions and sustainable energy sources into city infrastructure. Smart energy management plays a significant role in the development of cities, especially as energy demands rise and there is a pressing need to reduce greenhouse gas emissions. Internet of Things (IoT) technology, along with intelligence technologies such as machine learning and blockchain, help streamline energy systems by managing resources and reducing energy waste. In structures like buildings and homes, today's technology enables real-time tracking of energy usage to customise lighting and temperature control based on occupants' preferences, thereby helping to lower emissions.

In cities, IoT gathers information on air quality, energy consumption, and traffic flow, facilitating resource allocation and future planning. Advanced digital tools, including artificial intelligence and machine learning, analyse these data to improve energy distribution and minimise waste. Smart grids enable the integration of diverse energy sources. Additionally, blockchain technology and 5G networks promote decentralisation, strengthen security measures, facilitate data processing, and support energy sharing among users.

Considering the impact of climate change on cities today and in the future, smart city technologies need to be adaptable and resilient to manage evolving challenges. To ensure energy efficiency for future needs, implementing cutting-edge tools such as the IoT, artificial intelligence (AI), and machine learning is essential. Progress in grid technology and energy storage systems also supports the integration of renewable energy sources, reducing waste and ensuring a stable energy supply. Thanks to these advancements, cities can not only reduce carbon emissions but also develop sustainable communities that are more environmentally friendly and effectively manage resources.

The analyses carried out made it possible to formulate conclusions on practical and policy directions in the context of energy management in smart cities. First of all, it should be emphasised that the construction of smart grids is the basis for adaptive energy management, integration of renewable energy resources, and minimisation of system inefficiencies. Their development should be supported by appropriate regulations that facilitate cooperation between energy system operators and consumers (including prosumers).

Moreover, the use of modern technologies is key to increasing the efficiency of energy management systems. Municipal policies should support the development of infrastructure based on technologies such as the Internet of Things, artificial intelligence, blockchain, and machine learning. This will allow better forecasting of energy demand and more efficient use of resources. City policymakers should also prioritise promoting and supporting investment in energy storage systems. Technologies such as lithium-ion battery systems and compressed-air energy storage technologies can significantly improve the stability of energy systems. This is particularly important in the context of the variability inherent in renewable energy production. The development of digital twins as tools for simulation and urban planning can also contribute to more effective management of energy systems. The use of this technology will enable more efficient planning and management of urban energy resources.

The allocation of municipal resources for the development of zero-emission buildings integrated with advanced energy management systems is also an extremely important measure. The deployment of technologies such as photovoltaics, heat pumps, and energy recovery systems can make a significant contribution to reducing greenhouse gas emissions in the building sector. Urban transportation is also a key area for action. It is worth noting that the transformation of the transportation sector towards electrification requires the construction of charging infrastructure for electric vehicles. In addition, it is necessary to support public transportation systems powered by renewable energy. Public policies should support investment in infrastructure while encouraging citizens to use low-carbon transportation solutions.

In addition, city policies should comprehensively support and promote the integration of sustainable energy practices with broader sustainable development goals. Investments in green infrastructure play a key role in achieving these goals. Care should also be taken to work with local communities and raise their awareness of environmentally friendly energy sources. This action will further increase the opportunity for smart cities to achieve greater energy efficiency.

The conducted research also has certain limitations. The bibliometric analysis included only articles indexed in the Scopus and Web of Science databases. While these are reputable sources, the exclusion of other significant databases and grey literature may have overlooked valuable scholarly contributions, potentially impacting the comprehensiveness of this review. The research queries were based on specific keywords, such as “smart city” and “energy”. The choice of keywords may have excluded studies employing different terminology or examining related aspects of urban energy, possibly omitting important insights. Furthermore, this study focusing on smart cities primarily emphasised technological advancements and the integration of modern methods, such as the IoT, machine learning, and blockchain, within urban energy management. It is possible that it may not have considered challenges and solutions particular to specific contexts.

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