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Review

A Bibliometric Analysis and Visualization of Building Decarbonization Research

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Abstract: The building sector is responsible for approximately 40% of global energy consumption and carbon emissions, making it a key area of focus in addressing the urgent global challenge of climate change and in achieving the 1.5-degree target. This study concentrated on building decarbonization, using bibliometric and network visualization analyses based on a dataset of 2494 publications retrieved from the Web of Science up to 25 June 2023. Findings revealed a rapid growth in publications, with China being the largest contributor (approximately 31%). Notably, the journals of *Cleaner Production* and *Applied Energy* emerged as the most influential journal in this field. Although leadership teams and authors have gained prominence, cross-national collaboration and communication among them remain limited. Furthermore, an analysis of keywords and co-citations revealed that the main research themes and hotspots encompass "energy", "life cycle assessment", "storage", and related "models" and decarbonization "strategies". As the field progresses, a clear trend toward multidisciplinary integration and diversified research directions and content was observed. Researchers can further concentrate their efforts on countries with historically limited research but substantial emissions, and enhance international collaboration and interdisciplinary integration. Overall, this study offers valuable insights for researchers and facilitates future investigations in the field of building decarbonization.

Keywords: building decarbonization; bibliometric analysis; CiteSpace; VOSviewer

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1. Introduction

The World Meteorological Organization State of the Global Climate Report 2022 underscored a concerning fact: the global average temperature was 1.15 ± 0.13 °C warmer than the pre-industrial average (1850–1900) [1]. Keeping warming below 1.5 °C is impossible without immediate and substantial emission reductions across all sectors and regions. According to the Paris Agreement's target, global emissions should peak by 2025, followed by a further 43% reduction by 2030, until net zero emissions by 2050 [2]. The urgency of decarbonization is further highlighted by a 50% likelihood that the global carbon budget will deplete within 9 years [3]. As one of the three key contributors to global carbon emissions, the building sector holds significant cost-effective mitigation potential [4].

Nearly 40% of all energy-related carbon emissions worldwide and 50% of all extracted materials come from the building sector [5]. Since 2020, the building sector's decarbonization has negatively rebounded, and operational emissions increased by 5% in 2021 compared with 2020 levels, reaching an all-time high of about 10 $GtCO_2$, which is 2% more than the peak in 2019 [6]. The decarbonization of the global building sector is being challenged, whereas an increasing number of governments are acknowledging the crucial role of buildings in their decarbonization initiatives and making commitments. As part of their nationally determined contribution action plans, 80% of countries now include buildings, and 40% of countries have implemented mandatory or voluntary regulations or codes for building energy performance. Investment in global building energy efficiency rose by 16% in 2021 compared with 2020 levels, amounting to USD 237 billion, primarily driven by developed countries [7]. However, if the developed countries do not achieve deeply decarbonized buildings, then the developing countries do not stand a chance. Floor area is expected to increase by about 20% to in 2030, with more than 80% of this growth occurring in emerging and developing economies, offering a significant opportunity for achieving zero carbon [8]. Global issues on the topic of building decarbonization are worthy to be discussed. Faced with the urgency of the current decarbonization situation, building decarbonization has garnered significant interest from numerous scholars. In order to address the existing gaps in the literature concerning building decarbonization, this study aims to visualize the knowledge area of building decarbonization by addressing the following three questions:

- Which journals and literature studies are of interest to scholars?
- What are the contributions of research forces (authors, institutions, and countries) and their collaboration?
- How can the process of decarbonizing buildings be effectively achieved, and what are the current research gaps in this field?
- What are the focal topics and evolving trajectories in the field of building decarbonization?

To address the above questions and gain a comprehensive understanding of the current research landscape in building decarbonization, this study proposes to use bibliometrics to complement existing empirically qualitative reviews. Although many scholars have conducted review studies on building carbon emissions from various perspectives and have gathered rich literature, limited efforts have been made to objectively and quantitatively analyze the literature using scientometric tools. For instance, Onat et al. [9] made a global review and macro-supply chain analysis of the carbon footprint of the global construction industry over the period of 2009–2020 based on the Scopus database. Chastas et al. [10] analyzed 95 case studies of residential buildings and reviewed the importance of embodied energy and embodied carbon. Wang et al. [11] extensively reviewed greenhouse gas abatement policy options for the building sector, focusing on indirect (regulations and incentives) and direct (carbon tax and emissions trading scheme) pricing mechanisms. The majority of the literature reviews are qualitative and subjective, with a subjective interpretation of content, and this approach often leads, intentionally or unintentionally, to an overestimation or underestimation of the contributions of particular authors. By contrast, quantitative research through knowledge mapping provides an objective reflection of the current status, research hotspots and development trends in the field. This study fills this gap.

This study contributes to three main aspects. First, it directly depicts the current status and content of building decarbonization research, including influential journals and cited references, to enhance traceability and facilitate accurate searches for journals, authors, and papers. Second, it visualizes the collaborative network relationships among relevant research forces, offering insights into the contributions and collaborations among authors, institutions, and countries in the field. Third, it reveals the research hotspots and development trajectories in building decarbonization research, helping scholars gain insight into the evolution of the field and identify new directions.

The remainder of the study is presented as follows. Section 2 presents the data sources and related software used for the bibliometric analysis. Section 3 provides a detailed analysis and discussion of the study's results from four aspects. Section 3.1 analyzes the overall status of building decarbonization, including annual publication trends, influential journals, and the literature. Section 3.2 examines the collaboration of research efforts, encompassing authors, institutions, and countries' collaboration networks. Section 3.3 analyzes the hotspots of building decarbonization research through keyword co-occurrence and clustering. Section 3.4 explores the trends and key literature works in the field through literature co-citation analysis and clustering. Finally, Section 4 presents the conclusions.

2. Materials and Methods

2.1. Data Sources and Search Strategies

The data utilized were collected from the Web of Science (WOS) Core Collection, widely acknowledged as a significant and frequently used source of documentary data for bibliometric analysis across various research fields [12]. The search was conducted using the "topic" method with the topic being "building decarbonization". To maintain coherence in the study period, the search spanned from 1995 to 2023, and the search deadline was set as June 25, 2023. According to a methodological study, the sub-datasets [13] and coverage years [14] were provided to ensure reproducibility, and we selected the subset of WOS Core Collection subscribed by Chongqing University (see Table 1). In addition, the topic words were supplemented with the term "sector" for qualification. The language and document type were filtered, resulting in a total of 2494 research objects, comprising 1935 article papers (with 57 of them being proceedings papers), 189 review papers, and 427 proceeding papers.

Table 1. Summary of data search strategies.

Set	Search Queries
Search terms	TS = (((building OR architecture OR construction) AND (sector OR department OR industry OR division)) AND (decarburization OR decarboni* OR carbon Near/2 abatement OR carbon Near/2 reduction OR carbon Near/2 mitigation OR CO_2 Near/1 abatement OR CO_2 Near/1 reduction OR CO_2 Near/1 mitigation))
Citation indexes	(1) Science Citation Index Expanded (SCIE) 1900–present (2) Conference Proceedings Citation Index—Science (CPCI-S) 2000–present (3) Conference Proceedings Citation Index—Social Sciences and Humanities (CPCI-SSH) 2000–present
Language	English
Document type	Exclude (Correction or Book Chapters or Data Paper or Editorial Material)
Sample size	2494
Time span	1995–2023

Details on data processing are as follows. First, topic words with the same meaning could be expressed in different forms, such as "decarburization", "decarbonization", "decarbonisation", "carbon reduction", "carbon dioxide reduction", "carbon emission reduction", and "carbon dioxide emission reduction." For such cases, the search formula was constructed, as shown in Table 1. Second, when a paper has more than one author and these authors do not belong to the same country, then the national property of the paper depended on the types of countries, and Section 3.1.1 handled the statistics in this way. Third, for ranking purposes, the "Norm. Citations" indicator (NCs) was utilized. The "NCs" of a document represents the number of citations divided by the average number of citations for all sample documents for the same year [15]. The normalization corrects for the fact that older documents have had more time to receive citations than more recent documents and offers a more accurate reflection of the relative influence of the analyzed subject in the field of study.

2.2. Analysis Methods and Tools

Bibliometric analysis is a quantitative method used to review and describe published papers, providing researchers with a systematic approach to assess the state of scholarship in a specific area [16]. It involves statistically examining various publication-related factors, such as citations, co-occurrence of keywords, and co-authorship relationships. Although bibliometric analysis complements traditional narrative literature reviews based on personal judgment, it is not intended to replace manual reviews. To conduct bibliometric analysis, some software tools have been developed, each with its advantages and specific functionalities [17]. For example, CiteSpace, a widely used Java-based software package, specializes in analyzing citation networks and patterns in a scientific literature [18]. It helps researchers identify emerging trends, influential papers, and research clusters based on keyword co-occurrence and co-citation of cited references [19]. VOSviewer, a free software developed by Eck and Waltman, is a powerful tool for visualizing bibliometric networks. It enables co-occurrence and co-citation analysis, offering a user-friendly graphical interface for generating network visualizations [20]. By using VOSviewer, researchers can identify research clusters, collaborations, and key areas of interest. Moreover, Gephi is a versatile software that utilizes data center analysis to construct network relationships and visualize complex networks. Although it is not designed exclusively for bibliometric analysis, researchers can use Gephi to visualize collaborative relationships and networks in bibliometric studies. In this study, VOSviewer was utilized to create co-authorship networks and perform co-occurrence and co-citation analyses. This tool allowed for the visualization of research collaborations and identified prominent research themes. Furthermore, Gephi was employed for complex network visualization to gain insights into the network of collaborative relationships between the subjects analyzed. Lastly, CiteSpace was used to conduct an in-depth analysis of keyword co-occurrence and co-citation patterns, which enabled the creation of knowledge graphs and the identification of influential papers and research trends.

3. Results and Discussion

3.1. Overall Situation Analysis

3.1.1. Time-Series Analysis of Publications

Figure 1 presents the annual publication changes over time for the top 10 countries in the number of publications, based on the collected sample literature. The cumulative bar chart indirectly reflects the research progress and trend of the total number of publications in the field. Since the adoption of the United Nations Framework Convention on Climate Change at the Earth Summit in 1992, the international community has been actively addressing global climate change issues. Commencing from 1995, countries worldwide have been organizing annual conferences of the parties. As efforts to reduce global greenhouse gas emissions intensified, researchers increasingly turned their attention to decarbonizing the built environment. In the early years (1995–2005), the number of publications was notably modest, averaging only 4.7 publications per year. However, interest in building decarbonization resurged in 2006, and since the 2010 Copenhagen conference, publications from each country have exhibited rapid growth, with a positive annual growth rate, signifying heightened research efforts in this area. In 2021, the growth rate of publications surged to 73%, resulting in 458 publications. This anomalous growth should be given a possible explanation [21]. The significant increase in the number of researchers, from 684 in 2020 to 1689 in 2021, may help elucidate the reasons behind the rapid expansion of publications. Figure 1 shows that China, the United States (US), and the United Kingdom (UK) were the main research forces, with the US and the UK being early contributors. Conversely, China has emerged as the dominant force in recent years, comprising approximately 40% of the total number of publications in 2022, nearly three times that of the US. Additionally, some studies have also highlighted that China has ranked first in SCI-indexed research articles since 2018 [22].

Overall, the general trend of the growth of exponential publications signifies that research in this field is currently experiencing a phase of rapid development. The observed trends suggest that research interest will continue to rise in the coming years, maintaining its significance and eventually reaching a stable peak state. The increasing global focus on decarbonization highlights the urgency and importance of advancing research in this field to achieve a sustainable and low-carbon built environment.

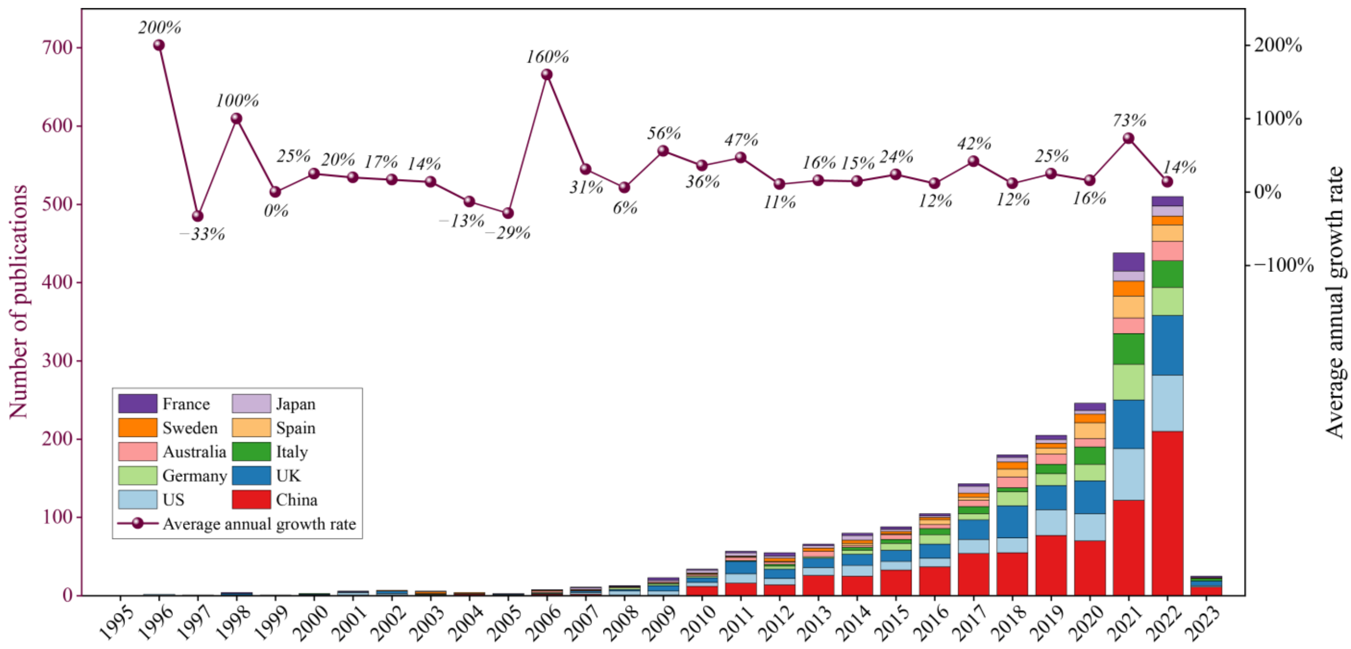


Figure 1. Annual growth rate and the number of publications on building decarbonization from the top 10 contributing countries.

3.1.2. Analysis of Journals and Highly Cited Papers

The investigation covered a total of 2494 sample documents from 779 journals. Table 2 presents the characteristics of the top 10 most active journals, with the *Journal of Cleaner Production* (164 publications), *Sustainability* (120 publications), and *Applied Energy* (120 publications) emerging as the top three journals in terms of publications. To assess the journals, the study employed Norm. Citations (NCs) rankings, along with other metrics such as the total citations, which is the sum of the number of citations received by documents according to the WOS database; average annual citations; and impact factor (IF). Across the board, the *Journal of Cleaner Production* (NCs: 216.5; IF: 11.1) and *Applied Energy* (NCs: 206.3; IF: 11.2) were the most influential in this research field. Their publications hold crucial reference value for researchers and practitioners alike. In recent years, authors have shown a preference for publishing in *Buildings* (AY: 2021.6), *Sustainability* (AY: 2020.3), *Journal of Environmental Management* (AY: 2019.2), and the *Journal of Cleaner Production* (AY: 2019.2). Overall, building decarbonization is closely related to energy and the environment. Furthermore, the findings underline the close interconnection among building decarbonization, energy, and the environment.

Over the past three decades, numerous important and influential publications have emerged in the field of building decarbonization, and the top 20 are listed in Table 3. The article published by Nejat et al. [23] ranked first with 905 total citations, combined with some additional information on the paper, indicating its strong influence (NCs:23, Average annual citations:100.6). The paper extensively reviewed the current status and trends in energy consumption, CO_2 emissions, and energy policies in the residential sector for the top 10 global emitting countries. Additionally, in 2022, many strong articles were published, such as one by Li et al. [24] (NCs:21.7), which assessed carbon reduction changes in commercial building operations across 30 provinces in China during the period 2001–2016. Sachs et al. [25] proposed six transformational approaches to achieving sustainable development goals, highlighting the crucial role of decarbonizing energy systems and emphasizing the necessity of cross-sectoral collaboration involving the building and construction sectors. Further analysis showed that most of these articles are review articles, published in many different journals, largely led by the journals in Table 2.

Table 2. Top 15 journals for the main sources of the literature on building decarbonization.

Rank	Journals	Publications	NCs	Total Citations	Average Annual Citations	IF (2022)	AY
1	Journal of Cleaner Production	164	216.5	4636	28.3	11.1	2019.2
2	Applied Energy	120	206.3	3940	32.8	11.2	2018.6
3	Renewable and Sustainable Energy Reviews	79	157.1	3371	42.7	15.9	2018.4
4	Energy Policy	104	147.0	3567	34.3	9.0	2014.5
5	Energy and Buildings	92	108.9	2285	24.8	6.7	2017.9
6	Energy	73	95.9	1769	24.2	9.0	2017.8
7	Building and Environment	29	66.6	1711	59.0	7.4	2014.7
8	Journal of Environmental Management	19	60.1	1199	63.1	8.7	2019.2
9	Resources Conservation and Recycling	27	59.8	713	26.4	13.2	2018.5
10	Sustainability	120	52.7	744	6.2	3.9	2020.3
11	Energies	109	52.2	727	6.7	3.2	2020.5
12	Science of the Total Environment	17	51.1	566	33.3	9.8	2020.8
13	Buildings	25	38.3	154	6.2	3.8	2021.6
14	Renewable Energy	28	37.0	638	22.8	8.7	2018.2
15	Energy Conversion and Management	27	33.8	695	25.7	10.4	2018.1

Notes: NCs = Norm. citations; IF = Impact factor; AY = Average publication year.

Table 3. Top 15 papers with the most citations on building decarbonization according to WOS.

Literature	Title	First Author	Source	Year	NCs	Total Citations	Average Annual Citations
[23]	A global review of energy consumption, CO_2 emissions, and policy in the residential sector (with an overview of the top ten CO_2 emitting countries)	Nejat, Payam	Renewable and Sustainable Energy Reviews	2015	23.0	905	100.6
[24]	Carbon reduction in commercial building operations: A provincial retrospection in China	Li, Kai	Applied Energy	2022	21.7	67	22.3
[25]	Six transformations to achieve the Sustainable Development Goals	Sachs, Jeffrey D	Nature Sustainability	2019	20.9	451	90.2
[26]	A review on thermal and catalytic pyrolysis of plastic solid waste (PSW)	Al-Salem, S. M	Journal of Environmental Management	2017	16.6	484	69.1
[27]	Historical carbon abatement in the commercial building operation: China versus the US	Zhang, Shufan	Energy Economics	2022	15.2	47	23.5
[28]	Strategies to achieve a carbon neutral society: a review	Chen, Lin	Environmental Chemistry Letters	2022	14.6	45	2.7
[29]	The role of new energy in carbon neutral	Zou, Caineng	Petroleum Exploration and Development	2021	14.1	127	42.3
[30]	Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts	Basbagill, J	Building and Environment	2013	13.5	341	31.0
[31]	A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018	Lamb, William F	Environmental Research Letters	2021	12.6	114	38.0
[32]	Fifth generation district heating and cooling systems: A review of existing cases in Europe	Buffa, Simone	Renewable and Sustainable Energy Reviews	2019	10.5	228	45.6
[33]	Environmental impacts and decarbonization strategies in the cement and concrete industries	Habert, G	Nature Reviews Earth and Environment	2020	10.1	179	44.8
[34]	Cement and carbon emissions	Barcelo, Laurent	Materials and Structures	2014	8.7	260	26.0

Table 3. *Cont.*

Literature	Title	First Author	Source	Year	NCs	Total Citations	Average Annual Citations
[35]	Methodology and applications of city level CO_2 emission accounts in China	Shan, Yuli	Journal of Cleaner Production	2017	8.1	236	33.7
[36]	Power-to-heat for renewable energy integration: A review of technologies, modeling approaches, and flexibility potentials	Bloess, Andreas	Applied Energy	2018	7.8	216	36.0
[37]	Review of technological design options for building integrated photovoltaics (BIPV)	Kuhn, Tilmann E	Energy and Buildings	2021	7.5	68	22.7

Notes: AY = Average publication year.

Overall, Section 3.1 analyzes the journals and the literature, answering the first question raised in Section 1.

3.2. Collaborative Network of Research Forces

Collaboration analysis in bibliometrics offers crucial insights into the research landscape of building decarbonization. In this section, the contribution and collaboration networks were mapped using VOSviewer and Gephi software for highly productive authors, institutions, and countries. The graph's node size is proportional to the number of publications, and the label size corresponds to Norm. Citations (NCs). Moreover, the thickness of the connecting lines between nodes denotes the strength of collaboration, whereas diverse colors represent separate clusters of collaborative networks.

3.2.1. Author Collaboration Network Analysis

The analysis of the author collaboration network provides insights into the main authors in the field of building decarbonization and their collaborations. Among a total of 11,260 authors contributing to research in this field, authors without collaborative ties to others (9580) account for approximately 85% of the total. Table 4 presents the top 10 influential authors and their relevant information. The most published author was Weiguang Cai from Chongqing University (23 publications; total citations: 1171), followed by Minda Ma (16 publications; total citations: 901), and Wenying Chen from Tsinghua University (14 publications; total citations: 492). The high NCs suggested that these authors have made a significant influence on the research field and have assumed leading roles to a large extent. Authors' contributions to this field were relatively limited before 2007. After 2009, authors began to focus their attention on this field, leading to a gradual rise in publication output and the emergence of highly productive authors. Notably, Wenying Chen, Francesco Pomponi, and Boqiang Lin were early authors with their first published works in 2011, 2015, and 2015, respectively. The period from 2015 to 2018 marked the emergence of more authors contributing to the field. As shown by the average publication year (AY), recent noteworthy contributors include Kairui You (AY:2023, NCs:23.9) [38,39], Shufan Zhang (AY:2022, NCs:16.5) [40] and Xiwang Xiang (AY:2022, NCs:45.1) [41–43] who have exhibited increased activities.

Figure 2 plots the highly productive authors' collaboration network map, revealing distinct clusters of research groups. The network displays a mature collaboration pattern within the clusters, indicating close ties and research partnerships. However, there remains room for improvement in strengthening collaboration and fostering communication among different research groups. The research interests of different research groups are different. Notably, Weiguang Cai's team has emerged as a prominent force in the field of building carbon emission research in China. They have collaborated with the China Building Energy Conservation Association and established a database [44]. They also regularly publish annual research reports about China's building energy consumption and carbon emissions. The latest 2022 report showed that the total carbon emission from the building lifecycle in China is 5.08 billion tCO_2, accounting for 50.9% of the national carbon emission. Minda Ma's team has been more focused on building carbon emissions from a global perspective in recent years, e.g., a recent study evaluating the historical decarbonization progress of commercial building operations in multiple countries [45]. In addition, Wenying Chen's team has developed a series of energy–environmental–economic models. In a seminal paper published in 2019, they introduced a downscaling framework for modeling mitigation pathways specifically designed for the building sector [46]. Overall, mutual collaboration among highly productive authors was highly common in China. Collaborative exchanges among authors from different countries demonstrate some limitations that can benefit from further enhancement.

Table 4. Top 10 authors with the most publications on building decarbonization.

Rank	Authors	Publications	Country	FY	AY	Total Citations	NCs
1	Cai, Weiguang	23	China	2017	2020.9	1171	107.6
2	Ma, Minda	16	China	2017	2020.8	901	68.6
3	Chen, Wenying	14	China	2011	2017.7	492	19.4
4	Feng, Wei	13	China	2018	2021.2	560	52.1
5	Huo, Tengfei	10	China	2017	2021.5	310	32.3
6	Xiang, Xiwang	9	China	2021	2022.0	280	45.1
7	Pomponi, Francesco	9	UK	2015	2017.7	522	19.1
8	Geng, Yong	9	China	2011	2016.3	500	16.7
9	Johnsson, Filip	9	Sweden	2013	2017.1	373	14.9
10	Ma, Zhili	8	China	2017	2021.3	300	41.3

Notes: FY = First publication year; AY = Average publication year; NCs = Norm. citations.

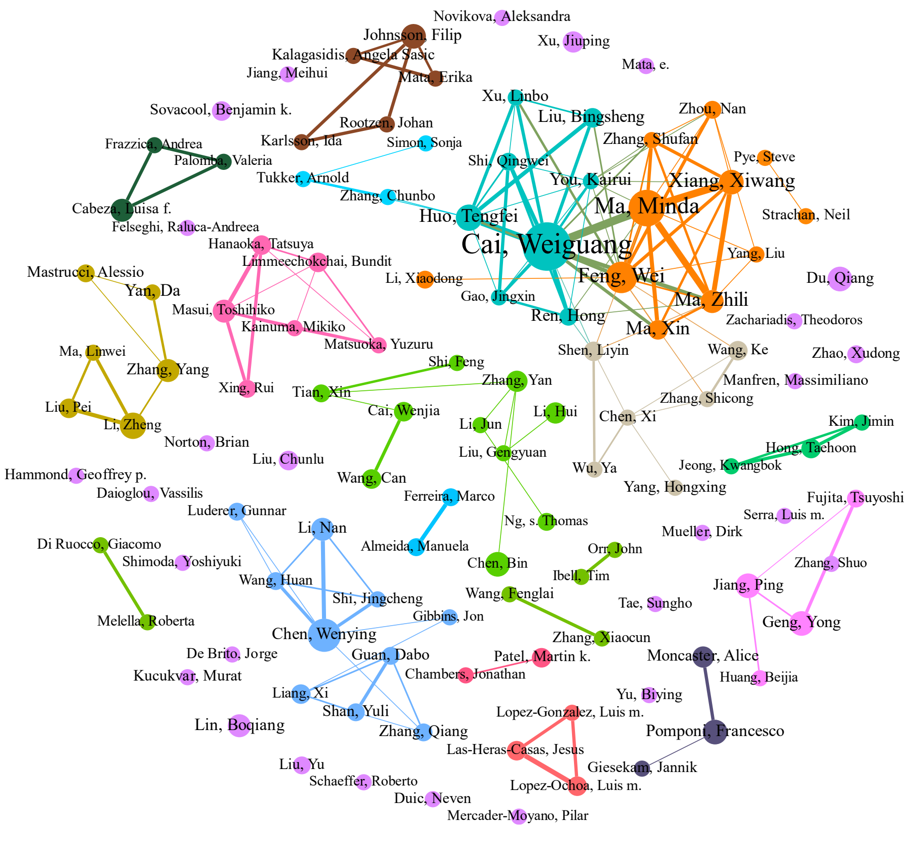


Figure 2. Overlay visualization map of co-authors. Note: According to Price's law and its formula $N_{min} = 0.749\sqrt{N_{max}}$, the nodes in the figure are all high-productivity authors (publications ≥ 4).

3.2.2. Institution Cooperation Network Analysis

Table 5 presents the top 10 most influential research institutions in the field of building decarbonization. Tsinghua University, with 89 publications, accounting for 3.6% of the total, held the top position in all citation counts. Other notable institutions in terms of publication volume include the Chinese Academy of Sciences (CAS; 49), Chongqing University (41), and University College London (UCL; 37). Notably, Tsinghua University (NCs: 178.2), Chongqing University (NCs: 144.1), and Lawrence Berkeley National Lab (LBNL) (NCs: 124.3) demonstrated higher citation counts, indicating that articles from these institutions are more influential than others. In terms of institutional publication timeline, the University of California, Berkeley (1998), Hong Kong Polytechnic University (2001), Chalmers University of Technology (2002), Tsinghua University (2006), Cambridge University (2006), and LBNL (2007) initiated research in this field early on. However, LBNL (AY: 2020.1) and Chongqing University (AY: 2019.9) emerged as major forces in the field, indicating consistent growth and significant influence.

Table 5. Top 10 most influential institutions on building decarbonization.

Institution	NCs	Total Citations	Publications	Country	FY	AY
Tsinghua University	178.2	2254	89	China	2006	2018.0
Chongqing University	144.1	1464	41	China	2011	2019.9
LBNL	124.3	1233	32	US	2007	2020.1
UCL	81.3	1791	37	UK	2007	2017.7
CAS	75.4	1991	49	China	2011	2018.0
University of California, Berkeley	39.0	961	20	US	1998	2013.8
Universiti Teknologi Malaysia	38.3	1113	11	Malaysia	2015	2019.5
University of Cambridge	37.7	787	31	UK	2006	2017.3
Beijing Institute of Technology	34.6	408	29	China	2014	2020.1
Tianjin University	32.7	498	23	China	2014	2018.5

Notes: NCs = Norm. citations; FY = First publication year; AY = Average publication year.

The data transcoded from VOSviewer was imported into Gephi visualization software to create a graph representing the institutional network cooperation, as shown in Figure 3. Tsinghua University, LBNL, and Chongqing University exhibit a strong collaborative relationship, whereas the CAS and the University of Chinese Academy of Sciences also engage in frequent collaborations. Furthermore, the high total link strengths (TLSs) of Tsinghua University (55), Chongqing University (51), and CAS (42) indicate their strong networking capabilities. These collaborative efforts underscore the influential role these institutions play in driving research and innovation in the field of building decarbonization. On the basis of the results obtained from the keywords, Tsinghua University's research extensively explored various aspects related to energy consumption and energy efficiency in buildings within China. Chongqing University's research analyzed energy consumption patterns in China and their relationship with economic growth using decomposition analysis to identify key drivers of changes in energy consumption. LBNL primarily emphasized energy efficiency, whereas UCL placed more emphasis on scenarios, systems, energy, electricity, models, policies, and related aspects.

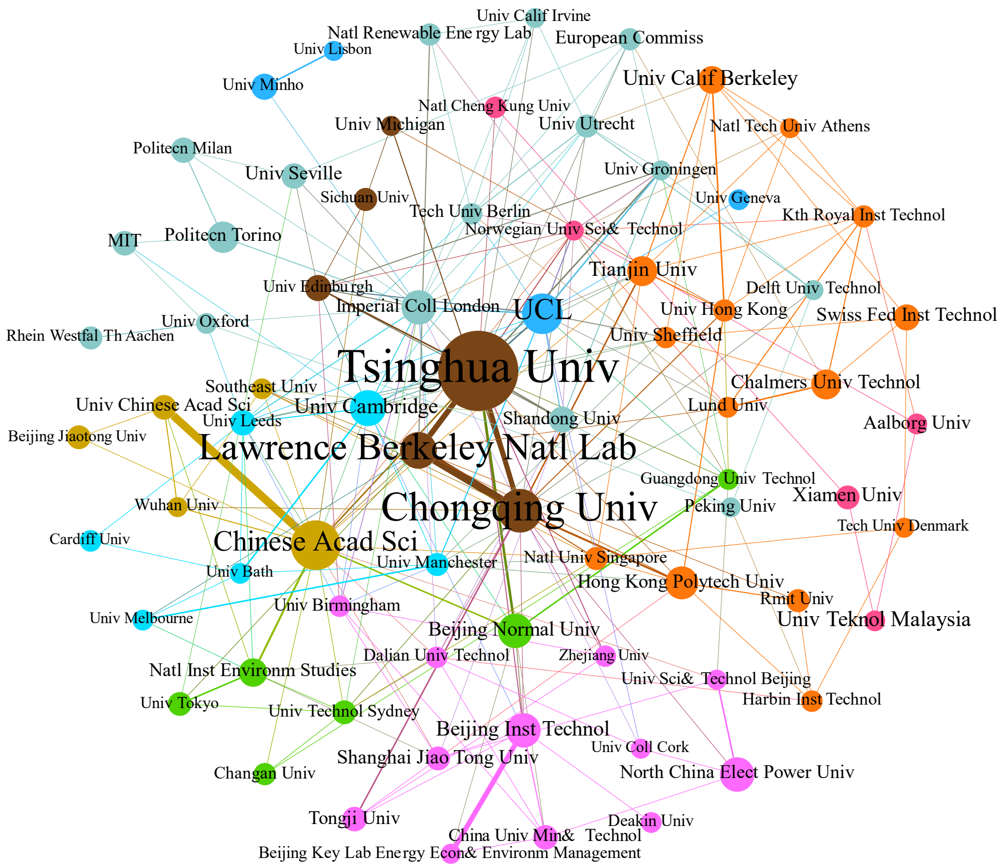


Figure 3. Knowledge domain map of institutional contributions and collaboration. Note: The number of publications of the institution ≥ 10.

3.2.3. Country Cooperation Network Analysis

Table 6 presents the top 10 most influential countries in building decarbonization research. The data indicated that China, the UK, and the US had notably higher numbers of publications and citations compared with other countries. This finding of the significant effects and value of research papers published in these countries is consistent with the previous analysis of authors and institutions. In addition, the data from Table 6 reveal that the UK (FY: 1998) and China (FY: 2002) were early adopters of building decarbonization research. However, the majority of countries began actively focusing on this field between 2017 and 2019, as evident from the AY.

Table 6. Top 10 most influential countries on building decarbonization.

Rank	Country	Publications	NCs	Total Citations	FY	AY	TLS
1	China	768	977.7	14889	2001	2018.7	320
2	US	343	517.1	8574	1996	2017.9	256
3	UK	364	436.2	8602	1998	2017.6	265
4	Germany	184	197.2	3580	2003	2018.8	176
5	Italy	146	170.5	2757	2000	2019.5	117
6	France	81	146.5	2654	1998	2017.7	91
7	Australia	126	146.0	2741	2006	2017.8	131
8	Netherlands	78	132.6	1569	2001	2017.5	96
9	Sweden	89	125.5	2405	1997	2017.3	87
10	Spain	105	101.4	1438	2008	2019.5	90

Notes: NCs = Norm. citations; FY = First publication year; AY = Average publication year; TLSs = Total link strengths.

To further observe and analyze the cooperation relationships among countries, this study utilized VOSviewer and Scimago software to construct a circulation graph (see Figure 4). The data were extracted from the top 30 countries with the most publications, with node size representing the number of publications and TLSs reflecting the cooperation intensity among countries. China actively engaged in cooperation and knowledge exchange in this field, establishing strong collaborative ties with the US, the UK, Japan, Singapore, and Malaysia, among others. Particularly noteworthy is the significantly higher cooperation intensity between China and the US compared with other countries. This finding is intensified by their collaborative nature, which encompasses a wide range of topics, including building energy efficiency, energy-saving technologies, and emission reduction strategies. Australia and Spain initially entered the research field of building decarbonization later, but they have since become important forces in the field. As a significant carbon emitter, India has comparatively limited research in the field of building decarbonization. In light of this, researchers could consider directing more attention toward studies conducted within India.

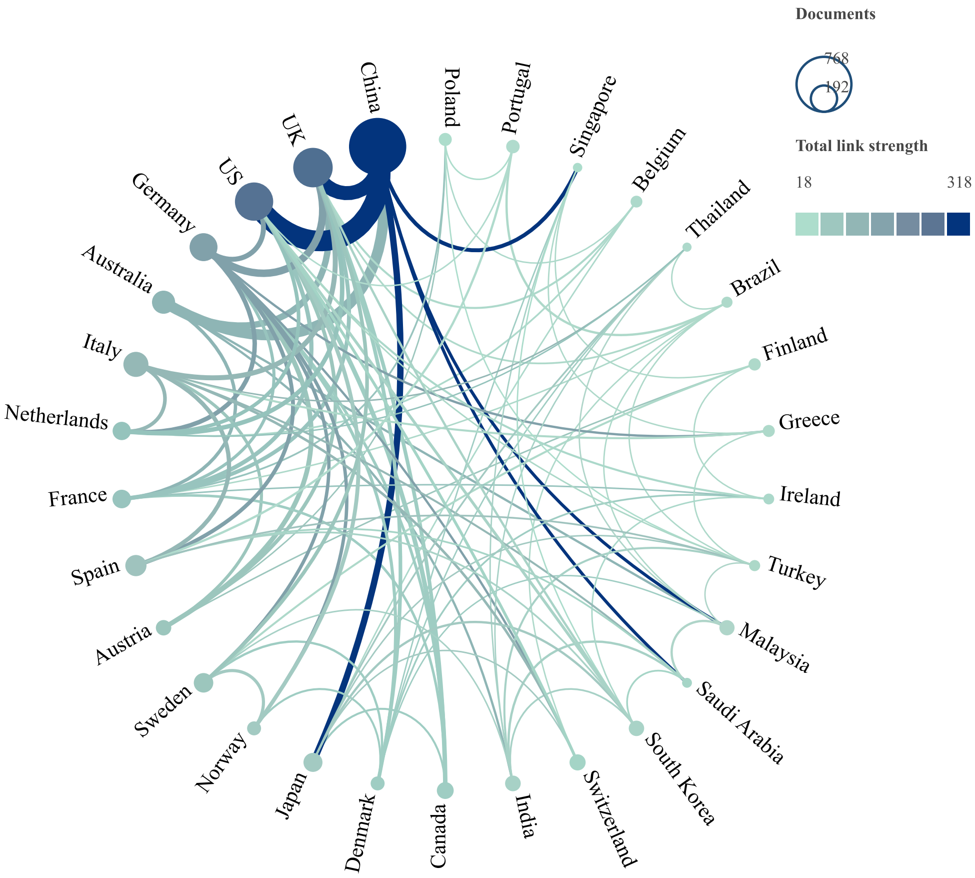


Figure 4. Cooperation network circulation graph of the top 30 countries with the most publications.

Overall, Section 3.2 addresses the second question posed in Section 1 by analyzing the collaborative network of research forces.

3.3. Term Network Analysis

Keywords are precise summaries and highly aggregated representations of research content in the academic literature. They can reveal the research topics and reflect the core content of the literature. In the sample documents, synonyms were merged and replaced; for example, CO_2 was mapped to "carbon dioxide emission", and "decarburization" was mapped to "decarbonization." CiteSpace 6.1. R6 was used for keyword co-occurrence analysis, and the relevant software operations were set as follows. Time Slice was set to 1, Node Types were selected as "Keyword", Selection Criteria was set to "Top 30 Per Slice", Filter Criteria was set to k = 25, and Pathfinder and Pruning were used to enhance the readability of the network graph by pruning sliced networks and the merged network. The resulting keyword co-occurrence and clustering network maps (Figure 5) consist of 149 nodes with 282 connections (N = 149, E = 282).

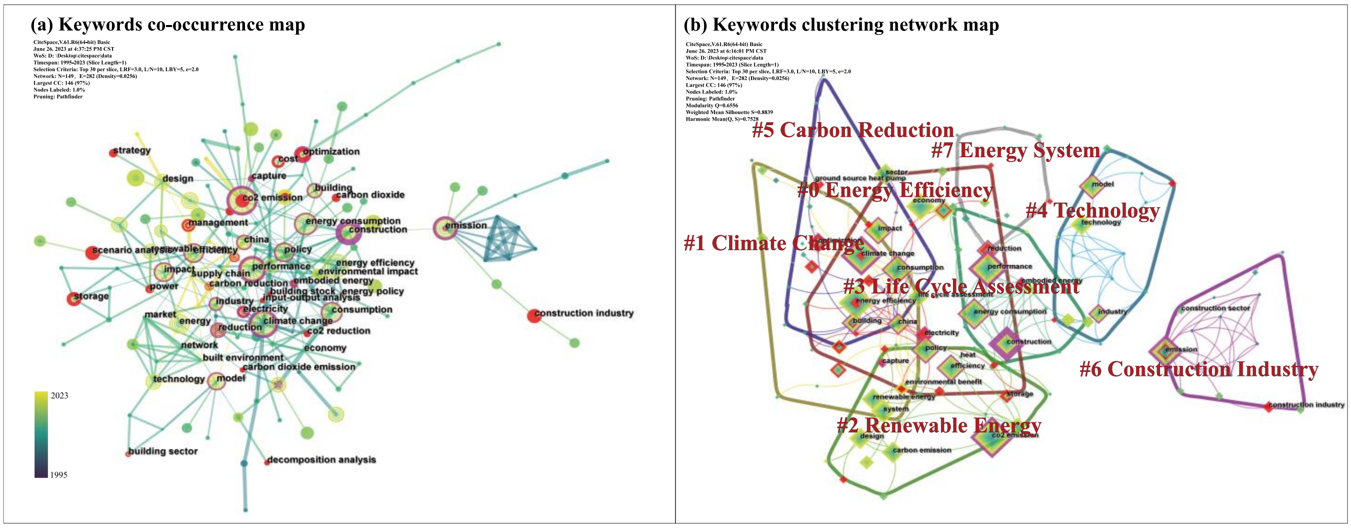


Figure 5. Keyword co-occurrence and clustering network mapping on building decarbonization.

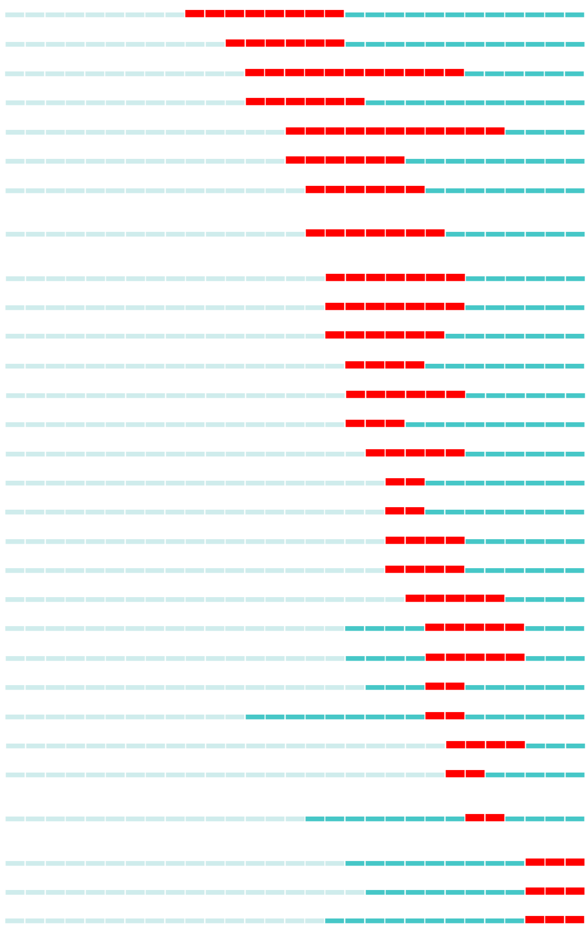
The circle in Figure 5a represents the keyword nodes, the shade of the color represents the change in time, and the overall color is lighter, indicating that the keywords appear later and the centralized study starts later. The size of the nodes characterizes the frequency of keywords, and the connections between nodes represent co-occurrence relationships. Undoubtedly, the keywords "CO_2 emissions" (333), "carbon emissions" (171), and "emissions" (153), which are closely related to the search term, are the most common. Other high-frequency terms include "impact" (241), "energy" (236), "system" (224), and "life cycle assessment (LCA)" (192). Particularly, "climate change" (2004) is the earliest high-frequency keyword, appearing more than 100 times. Nodes with a purple outer circle indicate words with high betweenness centrality (>0.1), serving as crucial "bridge" nodes in the network. Examples of such nodes include "construction" (0.66), "emission" (0.35), "performance" (0.34), "CO_2 emission" (0.28), and "climate change" (0.25).

Keyword clustering is performed based on the degree of association and similarity between keywords, consolidating closely related keywords into conceptually independent clusters and generating corresponding cluster labels. The smaller the cluster number, the more nodes it will contain. The Silhouette value is used to measure the homogeneity of the network; the closer to 1, the higher the homogeneity of the network is reflected. Modularity reflects the clustering result's quality, with higher values indicating better clustering. In Figure 5b, which was generated using CiteSpace, Modularity Q = 0.6556, indicating a significant clustering structure, and Weighted-Mean Silhouette S = 0.8839, suggesting good homogeneity within each cluster and reasonable clustering results. The LSI algorithm is employed in this study for cluster analysis based on the keyword co-occurrence network, resulting in a total of 10 clusters comprising 149 nodes and 282 connections. Eight clusters have a size greater than 10, accounting for 89% of the total nodes. Hence, this study focuses on the analysis of the top eight clusters: #0 Energy Efficiency, #1 Climate Change, #2 Demand Response, #3 Life Cycle Assessment, #4 Technology, #5 Carbon Reduction, #6 Construction Industry, and #7 Energy System. The clusters intersect, and no significant separation exists between keywords. Particularly, #0 Energy Efficiency is the largest cluster, encompassing the majority of the main keywords.

Moreover, in Figure 5, the red-filled nodes, including "storage", "scenario analysis", "strategy", "power", "electricity", and "optimization", exhibit surge changes during the study period, suggesting areas of increased focus and research interest. Keyword emergence analysis can detect keywords with a sudden increase in frequency over a period of time, and high-emergence keywords can, to a significant extent, reflect research hotspots and developmental changes during that period. Table 7 presents the Top 30 keywords with the strongest co-occurrence bursts. According to "The CiteSpace Manual" [47], the year numbers indicate the year when keywords first appeared. The strength value reflects the intensity of the keyword cited and represents the number of studies related to the keyword. In the final column of Table 7, this time interval is depicted as a blue line. The period of time in which a subject category was found to have a burst is shown as a red line segment, indicating the beginning year and the ending year of the duration of the burst. "Climate change" has been present since 2004 and continued to burst through 2011 with a strength of 7.16, signifying a classic and enduring research theme. "CO_2 reduction" has shown sustained interest, persisting the longest among the listed keywords. "CO_2 emission" emerged with the highest intensity, undoubtedly representing a crucial element in building decarbonization. Noteworthy trends include the recent burst in interest in "storage" and "optimization", evident from their high emergence intensities during 2021–2023, with burst intensities of 7.89 and 7.66, respectively. Overall, the analysis of keyword bursts indicates that research directions and focus points in the field of building decarbonization are beginning to diversify.

Table 7. Top 30 keywords with the strongest co-occurrence bursts on building decarbonization.

Keywords	Year	Strength	Begin	End	1995–2023
Climate Change	2004	7.16	2004	2011	
Energy Efficiency	2006	3.6	2006	2011	
CO_2 Reduction	2007	5.31	2007	2017	
Building Stock	2007	4.47	2007	2012	
Electricity	2009	7.33	2009	2019	
Energy Policy	2009	3.47	2009	2014	
Carbon Reduction	2010	7.88	2010	2015	
Carbon Dioxide Emission	2010	3.51	2010	2016	
CO_2 Emission	1997	9.95	2011	2017	
Power	2011	6.5	2011	2017	
Strategy	2011	4.06	2011	2016	
Building Sector	2012	6.18	2012	2015	
Embodied Energy	2012	5.78	2012	2017	
Capture	2012	3.61	2012	2014	
Carbon Dioxide	2013	3.72	2013	2017	
Integration	2014	4.25	2014	2015	
Decomposition Analysis	2014	3.65	2014	2015	
Input–Output Analysis	2014	3.43	2014	2017	
Carbon Footprint	2014	3.43	2014	2017	
Scenario Analysis	2015	4.82	2015	2019	
Reduction	2012	4.34	2015	2019	
Demand	2012	9.6	2016	2020	
Building	2013	4.8	2016	2017	
Emission	2007	3.67	2016	2017	
Construction Industry	2017	4.59	2017	2020	
Economic Growth	2017	3.86	2017	2018	
Greenhouse Gas Emission	2010	4.23	2018	2019	
Storage	2012	7.89	2021	2023	
Optimization	2013	7.66	2021	2023	
Cost	2011	3.66	2021	2023	



To further explore the evolution of research themes, a timeline view was drawn using CiteSpace (Figure 6), illustrating the relationship between clusters and the changes in keywords within each cluster. The starting point of keywords varies among clusters. As the largest cluster, #0 Energy Efficiency exhibits significant keyword changes over time, starting from “policy instrument” (2004), leading to “energy efficiency” (2006), “electricity” (2009), “decomposition analysis” (2014), “economic growth” (2017), and finally, “GHG emission” (2022). These transformations in keywords indicate substantial changes in research directions within this cluster. By contrast, Cluster #3 Life Cycle Assessment has remained active for 16 years, spanning from 2007 to 2022. Notably, nodes do not solely develop horizontally within the same cluster label but also extend vertically across cluster labels, reflecting the high mobility of knowledge across various topic studies. Particularly, the nodes “energy efficiency” (#0 Energy Efficiency), “policy instrument” (#1 Climate Change), “energy consumption”, and “construction”, (#3 Life Cycle Assessment), and “mission” (#6 Building Sector) form a thickened line (degree > 5), signifying their close interrelationships. The analysis of the year of the initial appearance of keywords (AY: 2012.5) indicated a significant emergence of keywords during the period from 2010 to 2015. This period coincides with the time when climate negotiations contributed to the establishment of the Paris Agreement, thereby effectively shaping the international climate regime beyond 2020. Several key terms, including “scenario simulation”, “dynamics”, “carbon neutrality”, “economy”, “multi-objective optimization”, and “heat pump”, appeared relatively infrequently and at later stages, suggesting that these research directions have recently gained the researchers’ attention.

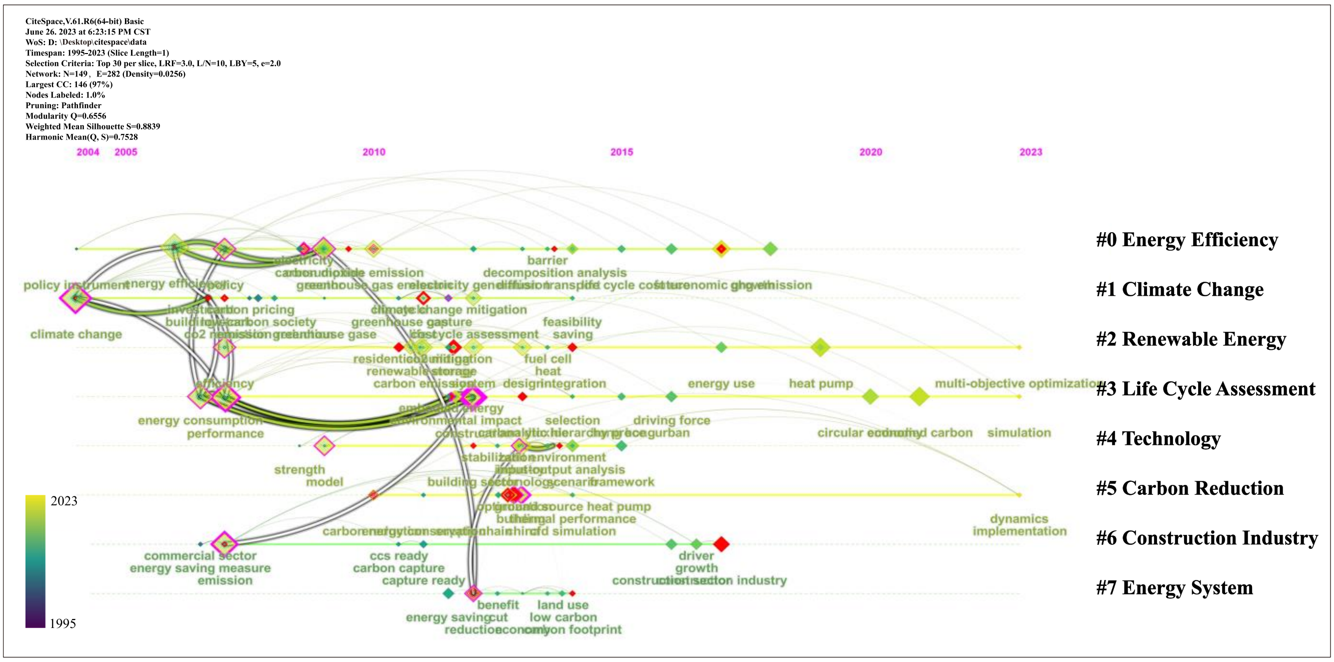


Figure 6. Timeline view of keywords year by year on building decarbonization.

The results of the keyword analysis indicate that the topic of “climate change” has significantly driven attention to the issue of building decarbonization, showing a strong correlation with “energy.” On the basis of the examination of high-frequency and prominent keywords, current research focuses on several aspects:

(1) The research scope includes direct emissions, indirect emissions, and embodied carbon emissions related to buildings. Keywords observed include “carbon dioxide emission”, “embodied energy”, “electricity”, “building sector”, “construction industry”, and “built environment.” Chen et al. [48] analyzed the embodied energy and carbon emissions of building materials in China, revealing that cement, steel, and

brick contribute to over 70% of the total embodied energy and carbon, emphasizing potential opportunities for reducing carbon emissions.

(2) Different researchers have also approached the study from various perspectives, such as "market", "cost", "government", "supply chain", and "environment." For example, Karlsson et al. [49] conducted a decarbonization roadmap study for the Swedish building and construction industry, focusing on the supply chain perspective. The results show that CO_2 emissions associated with the construction of buildings and transport infrastructure will reduce by 50% by 2030 through the implementation of available measures and achieve close to zero emissions by 2045.

(3) In terms of research methods, researchers in the field of building decarbonization have primarily employed decomposition analysis, input–output analysis, scenario analysis, LCA, and model optimization approaches to conduct relevant studies. Guo et al. [50] used the input–output method to identify five key sectors contributing to China's energy consumption and carbon emissions, including the sectors of manufacture of basic chemicals, building construction, wholesale and retail trade, road transportation, and real estate. Zhang et al. [51] applied LMDI and scenario analysis to investigate the decarbonization level of commercial building operations in China and the US. The results showed that the historical annual carbon abatement intensity in China was 9.8 $kgCO_2/m^2$, whereas in the US, it was 17.7 $kgCO_2/m^2$. Under the moderate decarbonization scenario, China is projected to reach a carbon peak of 1365 ($\pm$255) $MtCO_2$ in 2039, whereas the US would stabilize at a carbon lock-in state of 664 ($\pm$155) $MtCO_2$ after 2030.

(4) In addition, in the field of building decarbonization, achieving decarbonization is a primary focus of research. These measures primarily include enhancing energy efficiency, utilizing renewable energy sources, employing Carbon Capture, Utilization, and Storage (CCUS), as well as reducing embodied carbon. For example, to improve energy efficiency, one can adopt efficient equipment and enhance insulation, ventilation, and lighting systems to lower energy consumption. Moreover, the utilization of renewable sources like solar, wind, and geothermal energy is crucial to reduce reliance on fossil fuels. For instance, the adoption of photovoltaic panels and wind turbines is actively promoted. Simultaneously, the implementation of CCUS is of paramount importance in effectively reducing CO_2 emissions. This can be achieved by technologically capturing and storing CO_2 or using biological means, like plants, to absorb atmospheric CO_2, thus reducing building CO_2. Additionally, the use of low-carbon materials and the incorporation of sustainable building design contribute to the reduction in embodied carbon. Through keyword co-occurrence and burst analysis, we can observe that the key areas of focus include "energy efficiency", "energy systems", "carbon storage", "renewable energy", and innovative "heat pump" technologies.

Keyword analysis unveiled research focal points in building decarbonization. The varying economic levels and developmental stages among countries lead to differing research levels in building decarbonization. While the current research hotspots merit attention from all researchers, past research areas should not be overlooked, particularly for economically less developed countries, as they hold valuable reference significance. Overall, Section 3.3 addresses the third question posed in Section 1.

3.4. Co-Citation Network Analysis of Cited References

Co-citation analysis investigates the relationships among co-cited references, revealing the development and evolution of specific disciplines through an investigation of the co-citation network in cited references. When a publication is cited by multiple articles, it indicates a shared research interest among those articles and suggests that the cited publication may address crucial aspects of the field. The higher the citation count, the greater the academic value of the publication will be. In this section, using CiteSpace, the co-citation network map of the literature was generated by setting the network nodes as

"Reference" as depicted in Figure 7a. Subsequently, a clustering analysis was conducted on the literature, and the results are presented in Figure 7b.

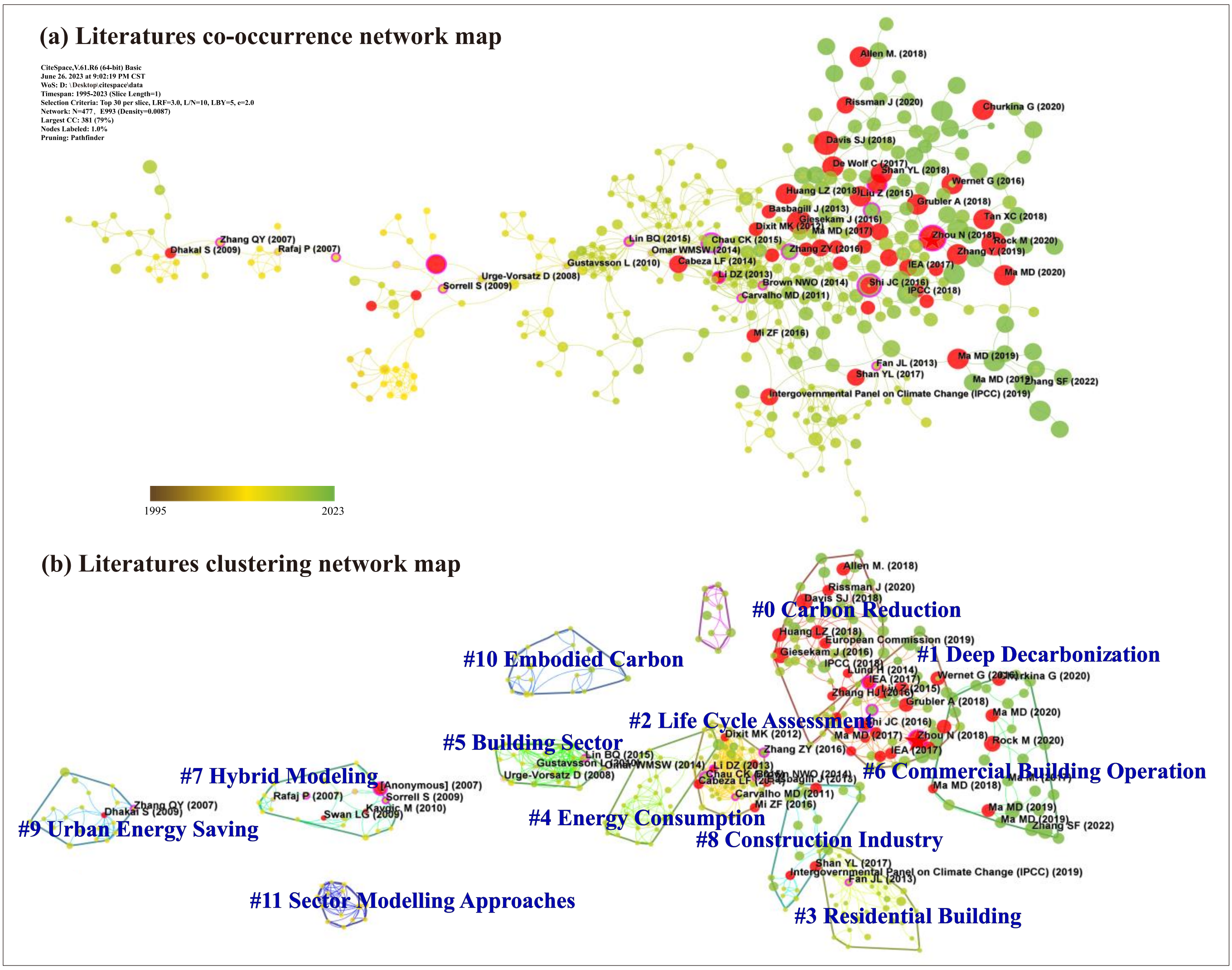


Figure 7. Co-citation network of cited references on building decarbonization.

Two noteworthy types of nodes exist in the network maps. First, there exist key node documents with a high centrality of intermediaries, marked by purple outer circles. These so-called turning points often act as "bridges" that connect nodes in different clustering paths and can help identify "boundary spanners" in the network. Secondly, nodes marked with red fillings reflect the burstiness in the documents. The burst rate of a document reflects the surge in citations within a specific specialty during a particular period. A stronger burst indicates higher attention to the research topic, exemplifying the research frontier during that period. By analyzing these two types of key node document, this study aims to assist researchers in identifying core researchers and classic documents in the field. In light of this, the main focus of this section is the analysis of several key clusters.

Table 8 shows top 20 References with the strongest citation bursts on building decarbonization.

Table 8. Top 20 References with the strongest citation bursts on building decarbonization.

Literature	Title	Journal	First Author	Year	Strength	Begin	End	1992–2022
[52]	Urban energy use and carbon emissions from cities in China and policy implications	Energy Policy	Dhakal, Shobhakar	2009	3.56	2011	2014	
[53]	Modeling of end-use energy consumption in the residential sector: A review of modeling techniques	Renewable and Sustainable Energy Reviews	Swan, Lukas G.	2009	4.22	2012	2014	
[54]	A review of bottom-up building stock models for energy consumption in the residential sector	Building and Environment	Kavgic, M.	2010	3.62	2012	2014	
[55]	Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review	Renewable and Sustainable Energy Reviews	Cabeza, Luisa F.	2014	4.55	2015	2019	
[56]	A methodology for estimating the life-cycle carbon efficiency of a residential building	Building and Environment	Li, D.Z.	2013	4.2	2015	2017	
[57]	Need for an embodied energy measurement protocol for buildings: A review paper	Renewable and Sustainable Energy Reviews	Dixit, Manish K.	2012	3.73	2015	2017	
[58]	Operational vs. embodied emissions in buildings—A review of current trends	Energy and Buildings	Ibn-Mohammed, T.	2013	5.1	2016	2018	
[59]	Reduced carbon emission estimates from fossil fuel combustion and cement production in China	Nature	Liu, Zhu	2015	7.18	2017	2020	
[60]	Global Warming of 1.5°C	/	IPCC	2018	4.39	2019	2020	
[61]	Construction sector views on low carbon building materials	Building Research and Information	Giesekam, Jannik	2016	4	2017	2021	
[62]	Modelling building's decarbonization with application of China TIMES model	Applied Energy	Shi, Jingcheng	2016	3.96	2017	2020	
[63]	Measuring embodied carbon dioxide equivalent of buildings: A review and critique of current industry practice	Energy and Buildings	De Wolf, Catherine	2017	3.83	2018	2021	

Table 8. *Cont.*

Literature	Title	Journal	First Author	Year	Strength	Begin	End	1992–2022
[64]	Scenarios of energy efficiency and CO2 emissions reduction potential in the buildings sector in China to year 2050	Nature Energy	Zhou, Nan	2018	7.14	2019	2023	
[65]	Carbon emission of global construction sector	Renewable and Sustainable Energy Reviews	Huang, Lizhen	2018	6.98	2019	2021	
[66]	China CO_2 emission accounts 1997–2015	Scientific Data	Shan, Yuli	2018	6.61	2019	2021	
[67]	Carbon emission and abatement potential outlook in China's building sector through 2050	Energy Policy	Tan, Xianchun	2018	5.01	2019	2023	
[68]	Net-zero emissions energy systems	Science	Davis, Steven J.	2018	8.16	2020	2023	
[69]	Embodied GHG emissions of buildings—The hidden challenge for effective climate change mitigation	Applied Energy	Röck, Martin	2020	7.58	2020	2023	
[70]	A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies	Nature Energy	Grubler, Arnulf	2018	4.74	2020	2023	
[71]	Carbon-dioxide mitigation in the residential building sector: A household scale-based assessment	Energy Conversion and Management	Ma, Minda	2019	3.9	2020	2023	

The largest cluster, Cluster #0 Carbon Reduction, contains a total of 52 articles, which primarily explore decarbonization strategies in the field of architecture. For instance, one notable contribution by Giesekam et al. [61] in 2016 proposed increasing the use of alternative materials with lower embodied carbon as a key strategy to address the growing challenge of carbon intensity in the UK construction industry. An important paper [68] (frequency: 29), published in *Science* in 2018, presented a comprehensive review of the conditions necessary for achieving decarbonization in energy systems. This study examined the barriers and opportunities associated with services and processes that are challenging to decarbonize. Furthermore, the paper identified potential technological solutions and outlines research and development priorities in this field. Additionally, within Cluster #0, the most frequently cited source is the Intergovernmental Panel on Climate Change report "Global Warming of 1.5 °C" released in 2018. The citing articles mainly focus on the embodied carbon emissions in the construction industry, as well as the carbon footprint [72,73] from a supply chain perspective [74,75].

Cluster #1 Deep Decarbonization comprises multiple highly influential nodes with frequent citations and centrality. Consequently, the cluster as a whole captures an active area of research or an emerging trend. The inclusion of several highly influential articles further highlights the importance of this cluster in advancing knowledge in the field. Notably, marked by a pentagram in Figure 7 is an article published by Zhou et al. [64] in 2018, which has an extremely burst (strength: 7.18) and intra-cluster impact (frequency: 34; degree: 15). This article used the LBNL's China 2050 Demand Resource Energy Analysis Model and scenario analysis method to explore the growth of building energy demand and CO_2 in the Chinese building sector under four energy demand scenarios. Another notable contribution is the work of Liu et al. (2015), who reevaluated China's carbon emissions by employing updated and harmonized energy consumption and clinker production data, as well as measured emission factors for Chinese coal [59]. Furthermore, recently emerged articles have utilized various models and methods to calculate and predict carbon emissions and energy consumption. Regarding citing articles, they mainly encompass reviews of building emissions [76] and studies on decarbonization roadmaps [77–79]. For instance, Sun et al. [80] published a comprehensive review article in 2022 on achieving carbon peak and carbon neutrality in the building sector, which exhibits close relevance to the cited references within Cluster #1 (coverage cited references: 12).

In Cluster #2 Life Cycle Assessment, the AY of articles is 2013.5. During this period, the cited references in these articles primarily focus on LCA research in the building sector. Within the cluster, corresponding citing articles have a higher total number of citations [81–83]. For instance, in a comprehensive review by Nejat et al. (total citations: 985), the article examined residential energy consumption, CO_2 emissions, and energy policies in ten major countries. The study revealed that all developed nations exhibit a promising trend of reducing CO_2 emissions, while developing countries still face challenges due to the absence of robust policies [23]. This article (total citations: 142) by Pomponi et al. [84] approached the body of academic knowledge on strategies to discuss embodied carbon and used a systematic review of the available evidence.

Cluster #3 Residential Building contains 34 articles. This cluster primarily investigates carbon emissions in residential buildings, including driving factors, energy performance assessment, and energy savings potential. Clusters #0–3, comprising the aforementioned articles, account for 39% of the total and include a majority of the key articles. Additionally, although Cluster #6 Commercial Building Operation consists of a relatively small number of articles (27), it holds significant influence in the field, as evidenced by its high citation rate. Furthermore, Cluster #6 is relatively recent (AY: 2019.3) and represents a research hotspot. For example, Martin et al. [69] analyzed over 650 LCA case studies to examine global trends in greenhouse gas emissions from buildings. The study revealed that although operational energy performance has improved, the contribution of embodied emissions come from building materials. Cluster #6 includes seven articles authored by Ma. In 2018, one of these articles calculated carbon emission reduction in Chinese commercial buildings and evaluated the driving factors using the LMDI method [85]. In 2019, another article proposed a decoupling method to analyze the relationship between the economic development in China's tertiary industry and carbon emissions from commercial building operations [86].

By analyzing the temporal development trends of co-citation networks and clustering in cited references, the study is divided into three phases. The first phase spans from 1995 to 2010 (AY: 2008.4). During this period, cited references primarily centered on modeling techniques and approaches [87] to understand and mitigate carbon emissions in the building sector, such as Cluster #11 Sector Modeling Approaches (AY: 2005.7), #7 Hybrid Modeling (AY: 2008.7), and #9 Urban Energy Saving (AY: 2010.1). For instance, Dhakal et al. [52] investigated energy use in Chinese cities and its contribution to national energy consumption and CO_2 emissions, revealing that cities contribute up to 84% of China's commercial energy use. Additionally, Zhang et al. [88] developed an electricity demand model using the Low Emissions Analysis Platform to explore the effects of various energy efficiency and environmental emission reduction policies. Kypreos et al. [89] employed the global MARKAL model to investigate the effects of internalizing external costs in electricity generation. Furthermore, Swan et al. [53] provided a comprehensive review of various techniques for modeling energy consumption in the residential sector, covering top-down and bottom-up approaches.

In the second stage, the cited references are mainly organized into five clusters: #5 Building Sector (AY: 2011.2), #4 Energy Consumption (AY: 2012.6), #10 Embodied Carbon (AY: 2013.1), #2 Life Cycle Assessment (AY: 2013.5), and #3 Residential Building (AY: 2013.7), covering the period approximately from 2010 to 2015 (AY: 2012.9). Based on the clustering results and literature analysis, the primary research focus during this stage is on conducting the LCA of energy consumption and carbon emissions in the building sector, particularly in residential buildings. For instance, Gustavsson et al. [90] performed an LCA of a residential building's energy use and carbon dioxide emissions, with results indicating that the operational phase of the building had the highest share of life cycle energy use, and its influence increased with the building's life span. Another study by Basbagill et al. [30] proposed the application of LCA in early stage architectural design decisions, employing sensitivity analysis to generalize the method across various building shapes and design parameters, and formulated impact allocation schemes to achieve maximum embodied carbon reduction.

Moving on to the third stage, which spans from 2015 to 2023 (AY: 2017.2), the literature focuses more on building decarbonization and deep decarbonization strategies, with a particular emphasis on commercial buildings and an extension to the broader construction industry. Cluster #8 Construction Industry (AY: 2015.5), #0 Carbon Reduction (AY: 2016.8), #1 Deep Decarbonization (AY: 2017.3), and #6 Commercial Building Operation (AY: 2019.3) can be classified under the third stage, spanning from 2015 to 2023 (AY: 2017.2). Shi et al. [62] utilized the China TIMES model to simulate the building industry's energy consumption and carbon emissions in China until 2050. The study analyzed the impact of technological advancements and renewable energy in the building industry and measured the energy-saving and emission reduction potential in this sector. The modeling results indicated that building energy consumption is expected to grow to around 41.6EJ in the reference scenario in 2050. Furthermore, the study proposed that the adoption of renewable energy can significantly contribute to carbon reduction in the building sector. In particular, citing articles and cited articles at the third stage include ways to achieve decarbonization, such as building energy efficiency and renewable energy use. Aburas et al. [91] reviewed the effectiveness of thermochromic smart window technologies in improving energy efficiency in buildings. Yu et al. [92] conducted a techno-economic analysis of heating systems in Europe and found that electrifying heating systems with heat pumps can reduce household heating costs and the reliance on natural gas in European cities. In addition, building envelope retrofits can also be effective in improving energy efficiency. It also provides policy recommendations for building retrofitting and heating electrification in Europe.

Madurai Elavarasan et al. [93] conducted a review of various decarbonization policies in Europe, identifying effective strategies. They emphasized the potential of bio- and geothermal-based combined heat and power and district heating systems to reduce carbon emissions in the heating sector. Additionally, they highlighted the significant role of 3D printing in lowering building lifecycle emissions, while also promoting hydrogen utilization and carbon capture storage and utilization technologies to achieve climate neutrality in challenging-to-decarbonize sectors.

Overall, the above work addressed the fourth question in Section 1 by analyzing the co-citation network of the cited literature, revealing key documents and evolving trends in building decarbonization.

4. Conclusions

This study conducted a bibliometric analysis of the building decarbonization field from 1995 to 2023 using CiteSpace and VOSviewer visualization tools. The analysis encompassed the number of published papers, distribution of research forces, keywords, and co-citation of cited references. The primary focus was to review the current status of collaboration, hot topics, and overall evolution in the building decarbonization field. On the basis of the analysis results, the following conclusions were drawn:

(1) Overall, the field of building decarbonization has experienced rapid growth in publications, with a continuous increase in the number of publications (average annual growth rate: 33.2%). Early research in this area was spearheaded by the United Kingdom (UK) and the United States (US). Conversely, as an emerging force, China started relatively late but has made remarkable progress and achieved fruitful results. Furthermore, the analysis indicated that the *Journal of Cleaner Production* and *Applied Energy* holds significant influence in this field.

(2) Regarding research strength and collaboration, China, the US, and the UK dominated, accounting for 60.5% of the total publications. However, the distribution of research strength was uneven. Collaborative teams have been formed, but due to regional, language, and cultural differences, research teams primarily consist of authors from the same country (mainly from China), and international collaboration was relatively infrequent. In the future, institutions and authors from different countries should foster stronger exchanges and collaboration. Decarbonization represents a global responsibility that requires collaborative efforts across nations. Despite being major carbon-emitting countries, India and Japan have shown few institutions and authors engaged in building decarbonization research. Future efforts should be directed to increase this critical domain.

(3) The research hotspots in the field of building decarbonization primarily revolved around evaluating energy consumption and carbon emissions in the building sector through methods such as life cycle assessment, decomposition analysis, scenario analysis, and input–output analysis. The research also emphasized building energy efficiency, environmental impacts, electricity, and renewable energy. Keyword co-occurrence analysis identified carbon storage, optimization, and cost as prominent topics in 2021, signifying recent hotspots and cutting-edge directions of building decarbonization research. The varying economic levels and developmental stages among countries lead to differing research levels in building decarbonization. While the current research hotspots deserve attention from all researchers, past areas should not be overlooked, particularly for economically less developed countries, as they hold valuable reference significance.

(4) Early literature in this field covered relatively small and scattered research topics, mainly focusing on energy and modeling approaches. Around 2015, a significant number of key milestone papers emerged, distributed in clusters between the second and third stages. These research results laid a solid theoretical and methodological foundation for the rapid development of the field. Research topics became more specific and influential, leading to the development of more models and analysis

methods, and gradually forming a trend of interdisciplinary integration, including energy, environment, economics, engineering technology, and policy.

However, this study does have limitations. The study only utilized the WOS core database, neglecting other databases, such as Scopus and CNKI (a Chinese academic website), which may lead to incomplete data. Overall, this research serves as a valuable reference for future scholars engaged in related studies.

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