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Review

Bibliometric and Visual Analyses of Low Carbon Technology Innovations: Developments, Hotspots, and Trends

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Abstract

As low carbon globalization advances, low carbon technological innovation is attracting attention, and more efforts are being invested in technology-driven decarbonization of the economy. Low carbon globalization requires the optimal allocation of national scientific and technological resources on a global scale, which is the newest and fastest growing area of economic globalization, and therefore requires attention to low carbon technological innovation. In this paper, an in-depth bibliometric and visualization analysis based on 205 articles from the Web of Science core collection was conducted using Citespace and VOS viewer in order to analyze the knowledge structure, hot topics, and trend directions in the field. The study found that China has the highest number of articles published between 2012-2021 and is also the world's largest carbon emitter, suggesting that large amounts of carbon emissions drive low carbon technological innovation. Xiamen University, Beijing Institute of Technology, and Tsinghua University are the most active institutions. In addition, cooperation between authors tends to be grouped and has been frequent in recent years. The co-occurring articles and keyword analyses identified three hotspots of low carbon technological innovation: 'CO_2 emission', 'policy', and 'energy'. In addition, keyword emergence analyses indicate that renewable energy, developing countries, and technology innovation themes are emerging trends. Low carbon technology innovation and renewable energy innovation in developing countries will be promoted.

Keywords: Low carbon, green technologies, technological innovation, environmental policy, bibliometrics

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Introduction

It is commonly argued in the literature that a low carbon future will depend on a combination of technological innovation (improving the performance of technologies and systems) and more sustainable behaviors (e.g., less travel or less waste) [1]. As a response to climate change, low carbon development is receiving increasing public attention, and there is an urgent need to implement a low carbon economy through technological innovation in order to effectively reduce carbon emissions [2]. Technological innovation is increasingly becoming an important way to develop a low carbon economy [3]. However, literature assessing the technological and socioeconomic outcomes of policy instruments used to support the transition to a low carbon economy is neither readily available nor comparable and often provides conflicting results [4]. At the same time, ensuring technological diversity and spatial differentiation is critical to the speed of transition, and the challenge now lies in creating a field of horizontal competition for all technologies, taking into account the unique institutional advantages that their spatial differentiation may provide. The current field of low carbon technology innovation opens up a range of future research directions [5], and the rapid rate of change of research hotspots and the continuous increase in research results in this field in recent years indicate that technology innovation in low carbon development processes is attracting more and more attention. Therefore, in order to identify current research hotspots and predict potential future research directions, we need to make a full summary.

The fundamental principle underlying low carbon technological innovation is the reduction of energy consumption and carbon emissions through the optimization of energy management at all stages of production, consumption, construction, operation, and reuse/recycling. This is achieved through the improvement of system management and technology system integration. This encompasses the enhancement of energy efficiency, the promotion of energy-saving technologies, the reinforcement of monitoring and evaluation, the formulation of rigorous regulations and policies, the reinforcement of education and training, the integration of diverse energy-saving technologies, the encouragement of technological innovation, and the utilization of sophisticated information technology to achieve intelligent management. Many institutions and scholars are currently contributing to the field of low carbon technology innovation, but few studies have systematically reviewed and surveyed the field, making it difficult to effectively assess the major advances and insights in the field. Therefore, in order to effectively explore emerging trends in this field, there is an urgent need to analyze developments, hot spots, and trend directions in this topic, which must be done in a more systematic and comprehensive manner. There are many approaches to retrospective analysis, each with its own relative merits. Wong, CY et al. outline an integrated framework that brings together technologies with similar characteristics and analyzes the evolution of these characteristics over time, elucidates the sectoral composition and scope of specialization in selected economies, presents the specificities of low carbon energy technology innovation patterns in selected Asian emerging economies, and thus summarizes the science-based relative impact of low carbon energy technologies on areas of technological excellence [6]. Koasidis K. et al. review low carbon industrial transformation in the UK and Germany from the perspective of sectoral innovation and systemic failure. They observe existing and potential drivers or barriers to sustainable industrial technology diffusion based on a framework of sectoral innovation systems and systemic failure and analyze the impact of policies [7]. Hunter, GW et al. Human This paper uses a two-step triangulation approach for a structured overview of LCC (low carbon city) initiatives in China, with a data collection methodology that includes a comprehensive review of 238 articles on LCC to identify and categorize LCC components, and also uses discourse and frame analysis to develop and synthesize a conceptual framework [8]. In these several review methods, scholars follow traditional review methods to analyze a limited number of articles in a targeted and more flexible manner based on experience, but the perspective and analysis paths are often limited by factors such as region and industry, and the analysis results and summaries are somewhat limited, although partial reviews are achieved in specific segments. In the context of low carbon globalization, the field of low carbon technology innovation research needs to make full use of the few pieces of literature available to overcome barriers such as industry and country to obtain a more comprehensive and accurate quantitative analysis.

This study uses bibliometrics, which has been widely used as a quantitative analysis tool for identifying research trend detection, conducting author collaboration analysis, journal development, and innovation subject areas. The bibliometric analysis overcomes the artificial shortcomings of traditional review methods by collecting and organizing a large body of literature and distinguishing the main paths and indicators for analysis. The results of the bibliometric analysis help researchers find suitable partners, target collaborative groups, and assess hotspots and future directions. Citespace and VOS Viewer, as one of the few functional bibliometric software available, have become practical, recognized, and comprehensive in literature analysis and are widely used by researchers in various fields [9]. In order to provide effective support for subsequent research on low carbon technology innovation and to address the knowledge gaps that exist in bibliometric reviews of such topics, the main objectives of this study are to (1) provide an overview of research in the field of low carbon technology innovation from 2012 to 2020 in the context of low carbon globalization, (2) discuss popular research topics in the field and their characteristics, and (3) analyze potentially valuable research based on emerging trends analysis directions.

Methodology and Data

This section details the data collection, research methodology, and data analysis process used in this study.

Data Sources

Web of Science is a comprehensive multidisciplinary core journal database. In this paper, the Web of Science Core Collection [Science Citation Index Expanded (SCIE) and Social Sciences Citation Index (SSCI)] database is used as the data source, and the search formula is: [TI=("low carbon*") AND ("technological innovation*" OR "technology innovation* " OR " technical innovation*")] OR [AB=("low carbon*") AND ("technological innovation*" OR "technology innovation*" OR "technical innovation*")] OR [AB=("low carbon*") AND ("technological innovation*" OR "technology innovation*" OR " technical innovation*")]. The search period was from January 1, 2012, to December 31, 2021. A total of 223 documents were retrieved using this search formula, and the types of documents retrieved included papers, conference proceedings, conference abstracts, and reviews. To reduce errors and improve precision, duplicate literature, conference papers, and literature that did not match the research topic and the search formula were removed from the search results. A total of 205 documents were obtained after screening.

Research Methods

The bibliometric approach excels in exploring the underlying knowledge structures contained in the scholarly literature and integrating visualizations to further analyze the field. Bibliometric software can be used to quantitatively analyze large amounts of literature data and generate visualization and content analysis results. Citespace is multivariate, time-phased, and dynamic citation visualization analysis software that allows readers to visualize and understand the topic. The analysis methods used in Citespace include co-citation analysis, co-occurrence analysis, burst detection, and cluster analysis. Among them, co-citation analysis is an analysis of the co-citation relationship between two studies appearing in a third study. The higher the number of co-citations, the more similar the two studies are and the deeper the correlation. Cooccurrence analysis counts the number of occurrences of a set of keywords in the studied literature and measures the affinity between them by their co-occurrence. burst detection detects a decrease or increase in the use of specific keywords. Cluster analysis is based on the similarity of objects, and multiple clusters composed of sets of objects grouped by similar objects are analyzed. Citespace can also address connections or working relationships between papers, helping users reduce cognitive gaps and identify key points and future trends in the research field. VOS viewer is also a software tool for constructing and visualizing bibliometric networks. The resulting networks can include journals, researchers, or individual publications, and they can be constructed based on citations, bibliographic coupling, co-citation, or co-authorship relationships. vOS viewer also provides text mining capabilities that can be used to construct and visualize co-occurrence networks of important terms extracted from a large body of scientific literature. Therefore, in this study, Citespace and VOS viewer-based bibliometrics were used to analyze existing papers related to low carbon technology innovation. In addition, a critical reading was performed to allow a more in-depth analysis of key studies and to provide key insights into the topic.

Data Analysis

We used Web of Science to analyze the search results and store the retrieved documents in categories, and we used Excel to count the number of annual publications, countries, institutions, and authors of publications. We also used Citespace (6.1.R3) and VOS viewer (1.6.18) to extract important noun phrases from titles, abstracts, and keywords for co-word, co-occurrence, and emergent word analysis and used the above two software programs to map the development history and research hotspots of low carbon technology innovation. In Citespace, the time span was selected as 2012-2021, the time node was set to 1 year, the node type was selected as Country, Keyword, etc., the default node strength was Cosine, the threshold value was selected as TOP 20, the network cropping ribbon was selected as Minimum Spanning Tree for mapping analysis, and the time zone was selected for analyzing the keywords over time. VOS viewer was used to analyze keywords, authors, etc. The data type was selected from WOS, the counting method was set to full counting, and the word list was added to clean the data, and then the minimum frequency of occurrence of words was set to finally form the graph.

Results

This section provides a qualitative and in-depth analysis of selected data in the area of low carbon technology innovation. Trends in literature publication (Section Literature quantity analysis) and literature sources (Section journal, and author analysis) over the last 10 years are analyzed. In addition, the results of highly co-referenced articles and clustering information are explained in detail (Section Analysis of co-reference articles), and the top 20 co-referenced keywords and keyword bursts are elaborated (Section Analysis of Cluster).

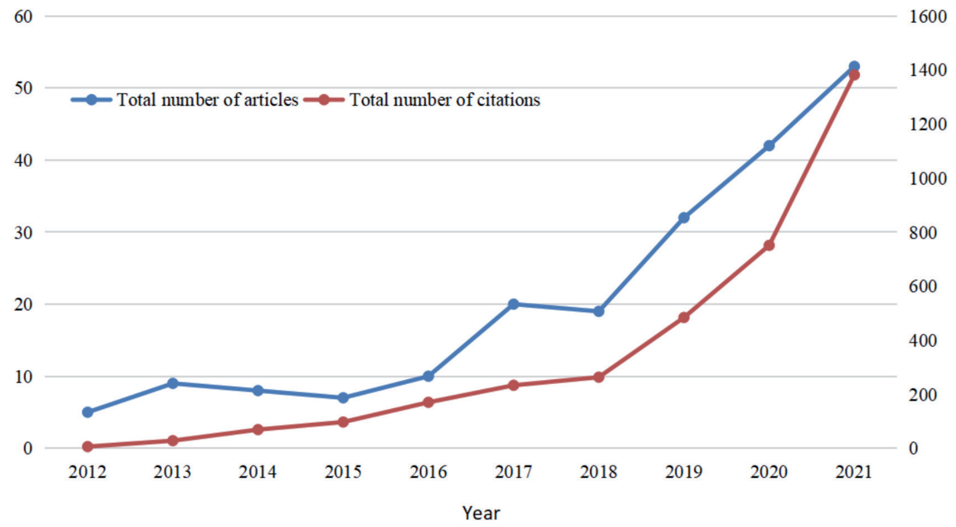

Fig. 1. Temporal evolution of the total publications in the WOS database.

Literature Quantity Analysis

The annual distribution of publications from 2012-2021 is shown in Fig. 1. Although the number of literatures on low carbon technology innovation has risen and fallen in different years, the number of literature issues has continued to increase over time. Prior to 2017, the annual number of publications was small and growing very slowly or not at all. However, a significant and continuous increase in the number of publications was observed from 2018-2021. The average number of publications was 20.5 and even reached 42.3 in the last 3 years. Although the number of studies in this field has not yet reached a high level, the work on low carbon technology innovation has grown rapidly.

Country, Institution, Cited Journal, and Author Analysis

In this subsection, the results of the literature analysis of countries, organizations, co-cited journals, and authors are presented one by one. The above analysis allows researchers to identify the countries, organizations, and journals with influential and cutting-edge achievements in the field and will make it easier to find partners in the same field. The relationship between each factor in each study can be observed from the visualization results.

Country

We selected the top 20 countries in terms of contribution for the analysis, and by looking at the size of the nodes and the thickness of the lines in Figs. 2 and 3, the contribution of each country and the cooperation between them can be clearly identified. Fig. 2 shows the geographical distribution of countries and their cooperation, and it can be seen that Europe is the continent with the highest density of contributing countries. China is the country with the highest contribution, with the highest number of publications on low carbon technology innovation literature (123), followed by ENGLAND (26), the USA (19), GERMANY (11), and JAPAN (10). As shown in Fig. 3, the study period was divided into 10 phases, and a total of 43 institutions (N/43) conducted research on low carbon technology innovation, and they collaborated with each other 74 times (E/74). China occupies a central position in this field and often collaborates with the United States, the United Kingdom, Germany, and Japan, with the latest research in three countries closely related to China between 2019 and 2021: Singapore, Pakistan, and Belgium. Furthermore, it is worth noting that China, as the world's largest carbon emitter, accounts for more than a quarter of global greenhouse gas emissions and that China's per capita emissions are about 40% higher than the global average. In this context, China's total literature accounts for 60% of the global research on low carbon technology innovation. Is there a close relationship between the two, which shows that intensive carbon emissions promote the level of low carbon technology innovation.

Institution

In Fig. 4, the literature between institutions and their inter-institutional collaboration over the past 10 years is visualized, with a total of 193 institutions (N/193) examining low carbon technology innovation, who collaborated with each other 143 times (E/143), and the top 20 most active institutions in terms of number of publications.

The top 20 institutions in terms of number of publications are shown in Table 1, with three universities, Xiamen Univ, Beijing Inst Technol, and Tsinghua Univ, tied for first place, all with 6 publications, followed by other institutions, each with close to the total number of publications. In the past 10 years, all institutions have

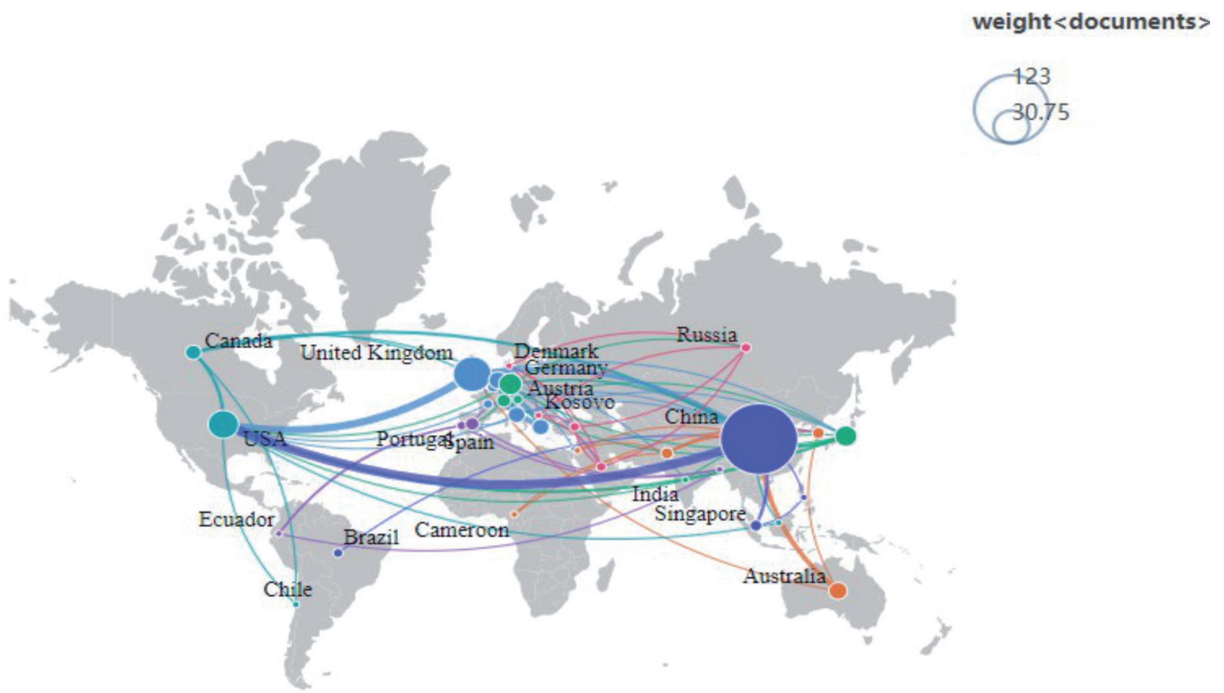

Fig. 2. Geographical distribution and cooperation of countries.

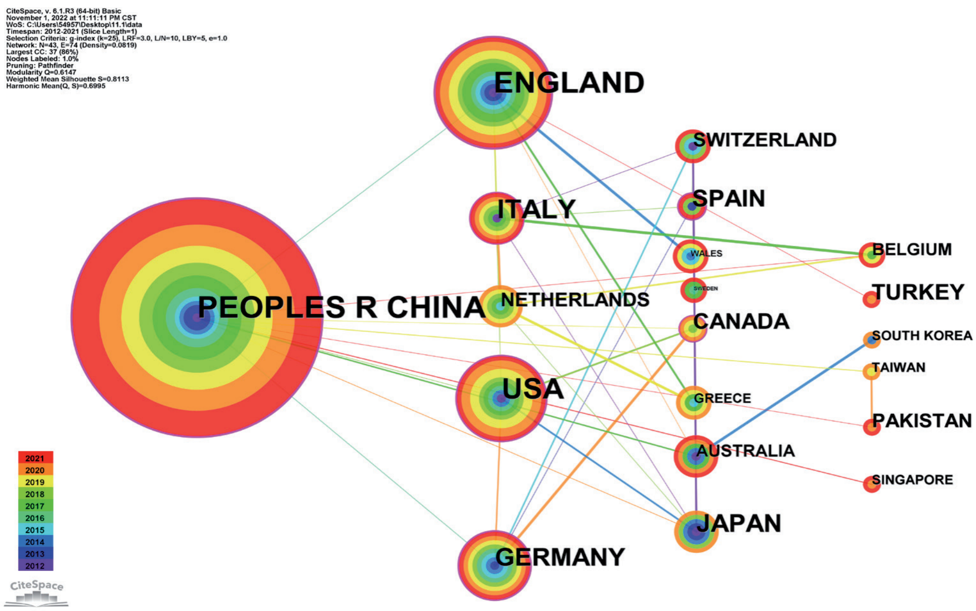

Fig. 3. Cooperation network of producing countries.

published no more than 10 articles. Among these 20 institutions, it is noteworthy that the top 10 institutions, such as Xiamen Univ, Beijing Inst Technol, and Tsinghua Univ, are all located in China, and all other institutions except 2 in the UK and 1 in Japan are also from China. With a large number of institutions, China's research in low carbon technology innovation further strengthens the cooperation between institutions and promises to form academic alliances, which can play a leading role in promoting the development of overall research. In addition, China's carbon subsidies and R&D investments are among the highest in the world, which shows that both government and corporate R&D investments are conducive to promoting innovation.

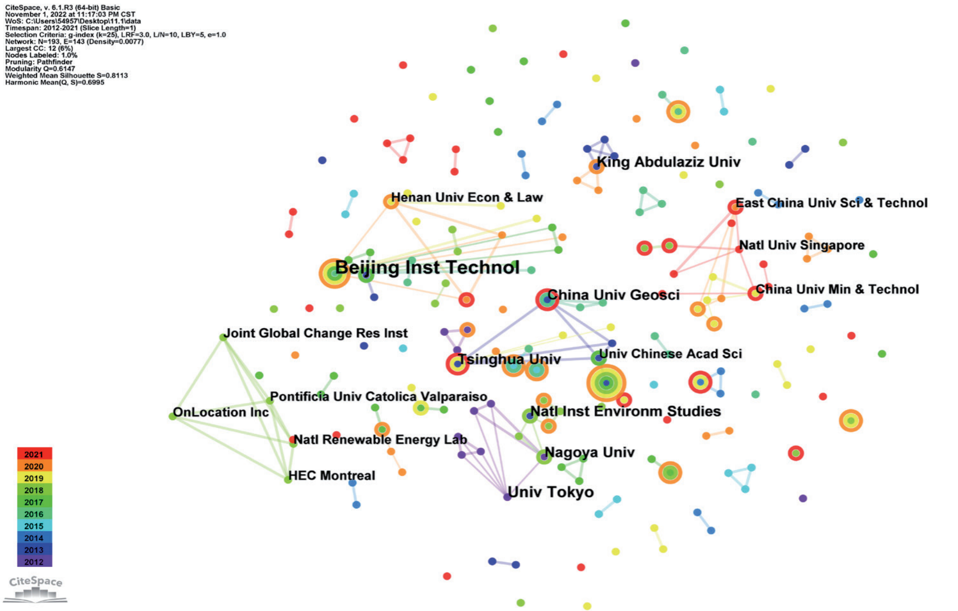

Fig. 4. Collaborative network of literature publishing institutions.

Table 1. Top 20 most productive institutions.

Count	Institution	Country
6	Xiamen Univ	China
6	Beijing Inst Technol	China
6	Tsinghua Univ	China
5	Harbin Engn Univ	China
5	North China Elect Power Univ	China
5	Chinese Acad Sci	China
4	Shanghai Jiao Tong Univ	China
4	Hohai Univ	China
3	Guangzhou Univ	China
3	Harbin Univ Sci & Technol	China
3	Natl Inst Environm Studies	Japan
3	Jiangsu Univ	China
3	Cardiff Univ	United Kingdom
3	Southeast Univ	China
3	China Univ Geosci	China
3	Shandong Univ	China
3	City Univ Hong Kong	Hong Kong,China
3	Imperial Coll London	United Kingdom
2	China Univ Geosci Beijing	China
2	Ocean Univ China	China

Cited Journals

The citations of the journals were analyzed to analyze the impact of different journals. Since the total number of articles published in different journals varies, statistical data analysis alone may not be sufficient to assess their impact. Co-citation analysis helps to visualize the internal relationships between journals and to understand the impact and position of journals in the field. Therefore, the choice was made to further analyze and obtain the results of the top 20 journals cited in this study. The results of the visual analysis were used to visualize the highly cited journals and the collaborative relationships between the various journals. Overall, 434 journals published papers in the field (N/434) and cited 2003 between them (E/2003).

Fig. 5 shows that almost all of the journals with high citations were cited in 2013. The size table of the nodes ENERG POLICY and JOURNAL OF CLEANER PRODUCTION are the most frequently cited journals. Based on the color of the lines between nodes, excluding a few journals, the majority of citations between journals occurred before 2018. Table 2 lists the top 20 most frequently cited journals in the field. The highest-ranked journal by citation count is the journal ENERG POLICY with 157 records, which is twice as many as the journal with the lowest citation count, ENERGY RES SOC SCI and the second highest-ranked journal is the JOURNAL OF CLEANER PRODUCTION with 124 records. Overall, the top 5 journals account for the top 20 journals with about 45% of the citations.

Author

As shown in Fig. 6, the majority of authors are more active in 2021. The number of authors in the field has

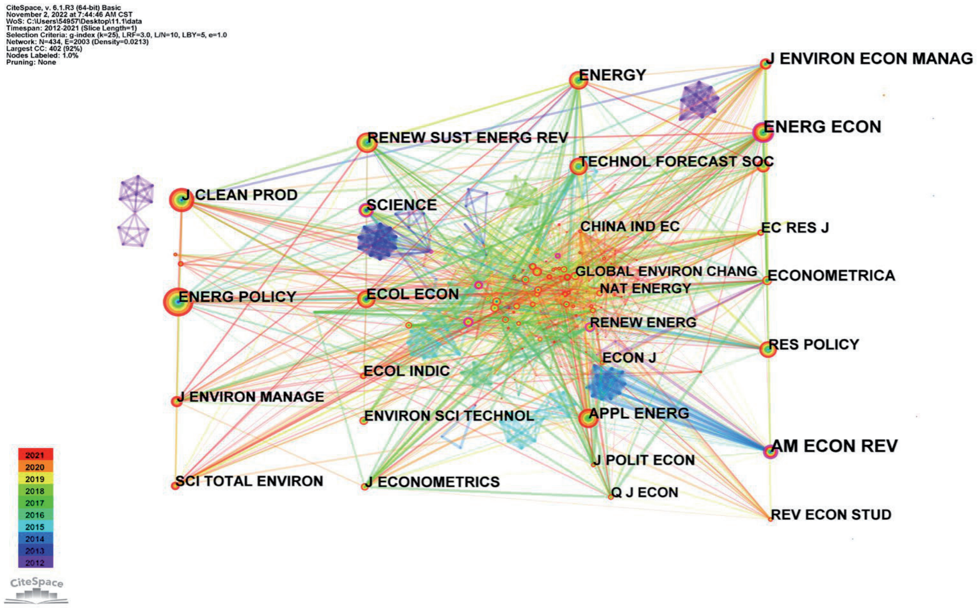

Fig. 5. Co-cited analysis of journals.

continued to increase over time, and the connections between authors have become more frequent. In addition, several authors form cliques based on the number of published authors (N/254) and collaborations (E/294). Although many scholars have focused on and conducted research on low carbon technology innovation, there is a relative lack of communication among them. In addition, Table 3 lists the top 20 authors with the highest number of publications. It should be noted that the top 2 to 6 authors have the same total number of publications, namely CHEN Z, CHEN SWANG L, WANG X, and WONG LT. Similarly, the top 7 to 11 authors have the same total number of publications.

Table 2. Top 20 highly cited journals.

Count	Cited Journals
157	ENERG POLICY
124	J CLEAN PROD
94	APPL ENERG
93	RENEW SUST ENERG REV
85	ENERG ECON
76	ENERGY
74	TECHNOL FORECAST SOC
68	ECOL ECON
63	RES POLICY
59	SUSTAINABILITY-BASEL
48	J ENVIRON MANAGE
42	J ENVIRON ECON MANAG
41	SCI TOTAL ENVIRON
36	SCIENCE
35	AM ECON REV
30	RESOUR CONSERV RECY
29	ENERGIES
27	ENVIRON SCI POLLUT R
27	ECOL INDIC
26	ENERGY RES SOC SCI

Analysis of Co-Reference Articles

Innovative and high-quality articles tend to be cited more frequently. The analysis of highly cited articles can provide the most valuable reference and information for researchers and readers interested in this field. According to Fig. 7, articles by Cheng JH, Wang H, and Zhang YJ were highly cited in the last 10 years, and according to the color of the lines in the nodes, most of the citations between the literature occurred in 2017. Table 4 lists the top 20 most frequently cited literature in the field. The highest ranked literature by citation count comes from the work of Cheng JH et al. with 7 records, followed by the work of Wang H and Zhang YJ et al. with 6 records for both, but overall, there is little difference in the number of citations for each literature.

Analysis of Cluster

The timeline of co-referenced articles can be viewed through Citespace for keyword co-occurrence and keyword clustering to get a clearer picture of the main research in the field of low carbon technology innovation. As shown in Fig. 8, the rows between

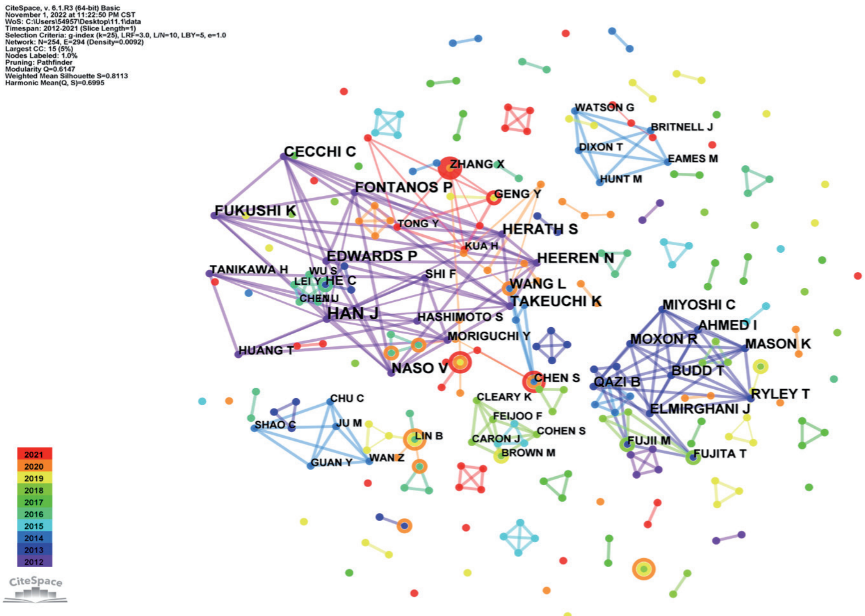

Fig. 6. Collaborative network of authors in the literature.

nodes refer to co-references, and the rank of the cluster is determined by the number of references. The type, number, and period of activity of highly cited references vary widely. The modularity Q = 0.6174 in Fig. 8 indicates a significant cluster structure that clearly defines the research direction of each cluster. The mean Silhouette = 0.8113 indicates good homogeneity between clusters. The co-citation between clusters has increased significantly in recent years, and, in general, research has begun to focus on several issues such as competition between different subjects for carbon low carbon technologies, carbon emissions, and renewable energy, which is consistent with the research hotspots reflected by the keywords.

Table 3. Top 20 most productive authors.

Count	Author
6	ZHANG X
5	LIN B
4	CHEN Z
4	CHEN S
4	WANG L
4	WANG X
3	ZHU J
3	GENG Y
3	WANG J
3	ZHANG H
3	CUI H
2	BROWN M
2	CHEN L
2	KUA H
2	LI Z
2	LI X
2	LI W
2	DU P
2	BI K
2	ZHAO X

The 10 keyword clustering tags obtained in the clustering of Fig. 8 are "#0 competition#", "#1 renewable energy", "#2 electric vehicles", "#3 carbon emission", "#4 multi-level perspective", "#5 5 emissions factor", "#6 transport sector", "#7 low carbon", "#8 sustainability", and "#9 energy technologies".

Among them, "Cluster #0#8" can be used as a theme. While governments in both developed and developing countries focus on policies related to low carbon development, the behavioral strategies of firms change in response to government policies, requiring governments to make some dynamic strategic adjustments to cope with shocks. evolutionary game theory model based on the interaction between carbon taxes and manufacturers and found that government-imposed carbon taxes are more effective in encouraging low carbon manufacturing than government subsidies for low carbon technologies [10]. Emissions trading systems have been increasingly adopted by countries and regions for carbon reduction, but their actual effectiveness depends on the specific procedural design and institutional context. Zhu, J. et al. found that the Chinese pilot increased low carbon innovation by 5-10% in ETS firms without crowding out other technological innovations in ETS firms. The increase in ETS firms accounted for about 1% of

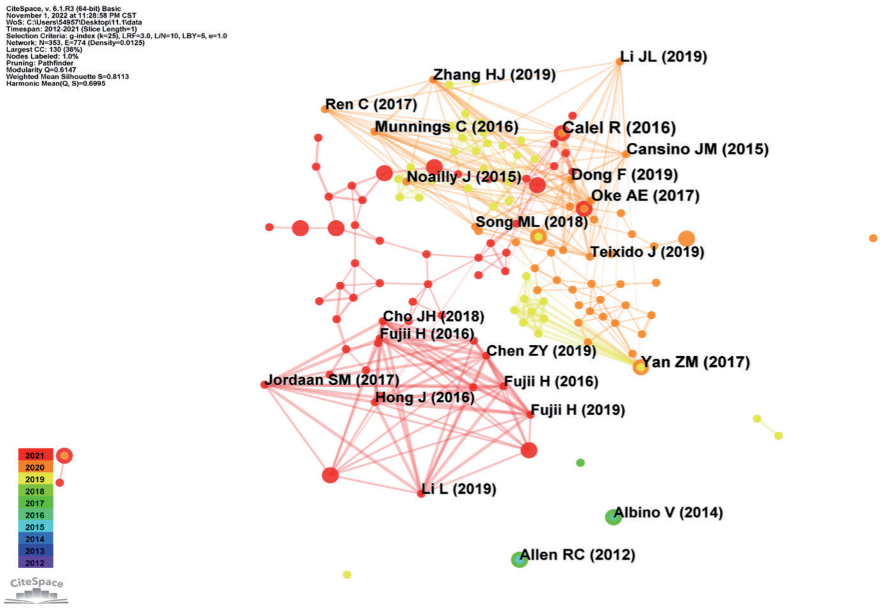

Fig. 7. Co-reference analysis of references.

Table 4. Top 20 highly cited journals.

Count	Cited References
7	2019, J CLEAN PROD, V231, P1158
6	2019, ENERG POLICY, V129, P930
6	2017, ENERG POLICY, V100, P18
5	2019, J ENVIRON MANAGE, V247, P66
5	2019, NAT COMMUN, V10, P0
5	2018, ENERGY RES SOC SCI, V37, P175
5	2020, RESOUR CONSERV RECY, V157, P0
4	2017, ENERG POLICY, V109, P499
4	2016, REV ECON STAT, V98, P173
4	2017, APPL ENERG, V185, P1919
4	2017, J ENVIRON ECON MANAG, V83, P121
4	2018, J CLEAN PROD, V201, P123
4	2017, J ENVIRON ECON MANAG, V81, P209,
4	2014, APPL ENERG, V135, P836
3	2019, J CLEAN PROD, V211, P171
3	2018, J CLEAN PROD, V170, P471
3	2018, MANAGE WORLD, V34, P43
3	2017, TECHNOL FORECAST SOC, V122, P4
3	2017, RESOUR CONSERV RECY, V126, P153
3	2015, ENVIRON INNOV SOC TR, V16, P51

the regional increases in low carbon patents, while the increase from similar increase from large non-ETS firms is also caused by ETS [11]. Establishing environmental regulations cannot always be a uniform application of static standards and a blind increase in regulatory intensity, but should take into account the characteristics and realities of different industries. Shen, N et al. analyzed the effects of technology gaps and pollution emissions on total factor productivity in Chinese industries and found that different types of environmental regulations had heterogeneous effects on ETFP in different industries; for example, in heavily polluting industries, too high environmental regulations can weaken firms' technological innovation [12]. While current emission reduction policies and the development of green technologies are costly, and research on innovation has focused on how to mitigate climate change by examining existing technologies and policies, Su HN et al. provide new insights on how innovation responds to changes in key climate change factors; for example, by shifting public funds to areas where innovation activities contribute most to the response to climate change [13]. Cheng, JH et al. used a difference-in-difference model to discuss the key to green growth and found that the effects from technological progress were significantly and consistently beneficial in terms of total factor productivity and that a better technological base was also more conducive to green growth, which also applies to cities in similar developing countries seeking to achieve economic transformation and green growth [14]. Low carbon technology innovation plays a crucial role in mitigating climate change. Yan, ZM et al. use patent data to study global trends in low carbon technologies and explore the convergence patterns of low carbon technologies across regions based on a nonlinear time-varying factor model, but they still

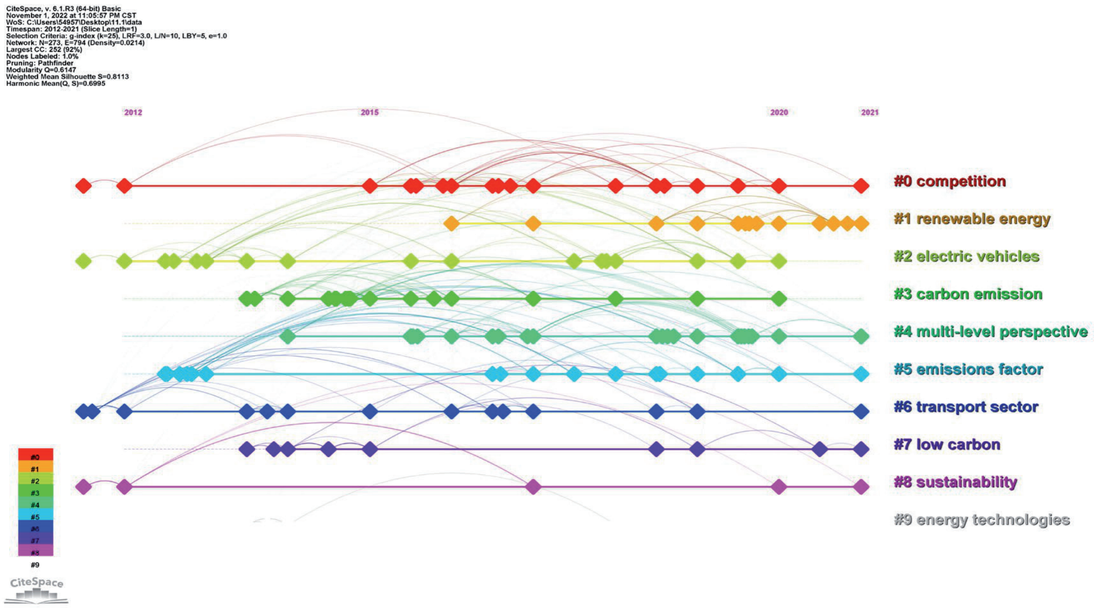

Fig. 8. Timeline visualization of the co-citation clusters.

cannot reject the convergence hypothesis for 19 OECD economies over the period 1960-2012. In addition, they emphasize the importance of global low carbon. Jin G et al. comprehensively observe the impact of government environmental regulation enforcement interactions on urban productivity growth and find that the simultaneous asymmetric bottom-up race and race-to-up environmental regulation enforcement interactions between geographically adjacent cities put productivity in geographically adjacent cities in different The bottom-up race and the race-to-up asymmetric environmental regulation enforcement interactions are found to result in different productivity growth patterns for geographically adjacent cities, while the race-to-up symmetric environmental regulation enforcement interactions result in a common productivity growth pattern for economically adjacent cities. In addition, there are firms that choose to relocate across locations rather than innovate locally, so long-term economic growth requires more targeted regulation and adaptive incentives for local government environmental regulation enforcement [15]. Bergek A et al. discuss technology innovation system (TIS) and context interactions and argue that the TIS framework can be further enhanced by a more detailed TIS context structure and conceptualization of TIS context interactions further enhanced, and examples are provided to illustrate how it can enhance our understanding of TIS drivers [16].

"Cluster #4#6" can be used as a theme. The core idea of Porter's hypothesis is that reasonably strict environmental regulation promotes firms' technological innovation and achieves a win-win situation for both the economy and the environment. Wang, H et al. used the propensity score Matching-Difference method to test the impact of China's carbon trading pilot system on the transition to a low carbon economy and found that under the given resource and environmental constraints, there is a certain degree of positive correlation, which can realize the win-win situation of environmental and economic benefits advocated by Porter's hypothesis, further verifying the applicability of Porter's hypothesis [17]. European low carbon patents under EU ETS regulation increased by almost 1%, and Calel, R et al. investigated its impact on technological change and found that EU ETS increased low carbon innovation by 10% in regulated firms but did not affect firms outside of regulation [18]. Albrizio, S et al. allowed for the impact of environmental policies in order to further test the Porter hypothesis. Using a new index of environmental policy stringency that allows the effect of environmental policy to vary across countries with the pollution intensity of industries and the technological progress of countries and firms, it was found that in the most technologically advanced countries, the tightening of environmental policy was associated with a short-term increase in industrial productivity growth, but this effect declined with the increase with global productivity [19].

"Cluster #1 #2 #9" could be a theme. Renewable energy not only ensures energy independence and security, but also supports the transition to a low carbon economy and society. In addition, technological innovation in renewable energy is an important factor influencing the development of renewable energy. Lin, BQ et al. analyzed the impact of each driver on technological innovation in renewable energy by considering CO_2 emissions as climate change and found that both government and corporate R&D investments contribute to promoting the level of innovation. Meanwhile, intensive CO_2 emissions promote the level of renewable energy technology innovation [20]. Green technology innovation is the key to achieving low carbon economic development and improving the efficiency of natural resources, and Miao CL et al. found that natural resources are at a high level of utilization efficiency with the addition of innovative green technologies, and the trend of change is enhanced [21]. Song, ML et al. explored the mechanism of its influence on urban eco-efficiency and found that the low carbon city pilot (LCCP) policy in China significantly improved ur ban eco-efficiency. In terms of the mechanism of action, the 2012 LCCP policy enhanced urban eco-efficiency only through the technological innovation pathway and did not enhance urban eco-efficiency through the advanced industrial structure or energy use efficiency pathway [22]. The current literature generally considers eco-innovation as a fundamental pathway for sustainable development, and to understand its mechanisms of action and drivers, Albino, V et al. provide a comprehensive overview of the evolution of low carbon energy technologies that play a key role in the current socioeconomic environment, thus revealing how specific situations such as environmental programs influence the development of low carbon energy technologies [23]. Economic development, policy change, and technological innovation are all prominent factors shaping the energy transition, but the existing literature is inconsistent in identifying and summarizing these factors. Cherp, A. et al. combine economics, sociology, and political science in an organizing principle to propose a meta-theoretical framework for analyzing national energy transitions, explaining them through a nested conceptual map of variables and theories. This framework elevates the role of political science compared to the existing literature, as the role of policy may become increasingly prominent [24].

"Cluster #3 #5 #7" could be a theme. How to quantify and certify its low carbon level is an urgent issue. Tan, S. et al. developed a framework of indicators to evaluate the LCC of low carbon cities in terms of economy, energy pattern, carbon, and environment. The same comprehensive evaluation method using the entropy weight factor method for LCC ranking was applied to 10 global cities and found that intensive human activities are a key aspect of low carbon management in cities [25]. Li, W et al. used a super-boundary function to comprehensively estimate and decompose the total factor carbon productivity of 36 industries in Chinese industry, analyzed its evolution with industry differences and dynamics, and found that the main factors of total factor carbon productivity growth are the change of economic development and the significant increase of green investment. In addition, low carbon high-tech industries are technology leaders, and technological innovation gradually plays a leading role in the growth of total factor carbon productivity in Chinese industry [26]. Gehrsitz, M. explored the impact of low emission zones on air quality and birth outcomes in Germany. This staggered introduction of policy measures creates a credible natural experiment and a natural control group for birth and air pollution measurements in cities that develop low-emission zones. I show that the adoption of the most stringent low emission zones reduces the average level of fine particulate matter by about 4%, reaching 8% in the highest pollution monitor of a city. The low-emission zone also reduced the number of days per year that the legal pollution limit was exceeded by 3 days. However, these reductions were too small to translate into substantial improvements in infant health. My results were not driven by changes in maternal or city-specific characteristics and were robust to changes in norms and selection of control groups [27]. Low carbon technology innovation is now recognized as an effective way to address environmental issues. Zhang, Y et al. used a systematic generalized method of moments technique to assess the impact of environmental innovation on carbon emissions in China and the impact of China's initial carbon trading scheme on carbon emission reduction and found that the impact of energy efficiency was most pronounced among environmental innovation measures and that innovation resources and knowledge innovation also played a prominent role in this regard. However, there is still a lack of research in the area of government environmental policies to curb carbon emission reduction [28].

Summarizing the popular research themes and the highly cited literature can identify the most active research directions in the field to explore the paths and knowledge explosion points in the evolution of the subject area. This can assist scholars understand the research history in the field of low carbon technology innovation, but the topic of low carbon technology innovation is still in a period of rapid development and change and is influenced by a variety of factors such as policy, economy, natural environment, etc. Fig. 8 examines the content of the literature during the decade 2012-2021, which requires continuous research and attention subsequently.

Analysis of Co-Occurrence Keywords

According to Fig. 9, each node in the co-occurrence analysis of keywords represents a keyword with the frequency of connections between them and the keywords with a frequency greater than 5 are shown in Fig. 9. Clearly, "Co2 emission", "energy", "impact", "policy", and "energy" are the common research themes. The top 20 most frequent keywords with the highest centrality are summarized in Fig. 10 and Fig. 11. Centrality refers to the impact of the keywords, i.e., keywords with centrality >0.1 are related to popular topics. "CO_2 emissions", "environmental regulation", "impact", and "policy" are hot topics with high centrality, indicating that policy research related to the impact of CO_2 emissions is a hot topic. In addition, some "technological innovation" caused by "system" in the process of low carbon technology innovation has been noticed, and the study of low carbon technology innovation from the perspective of system and innovation systems has also attracted more and more attention.

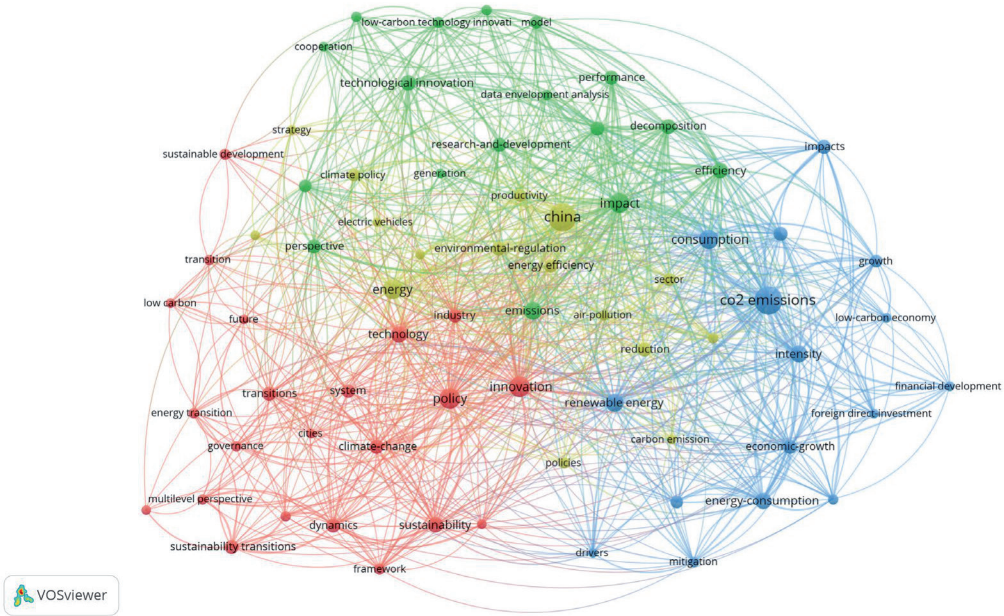

Fig. 9. Co-occurrence analysis of keywords.

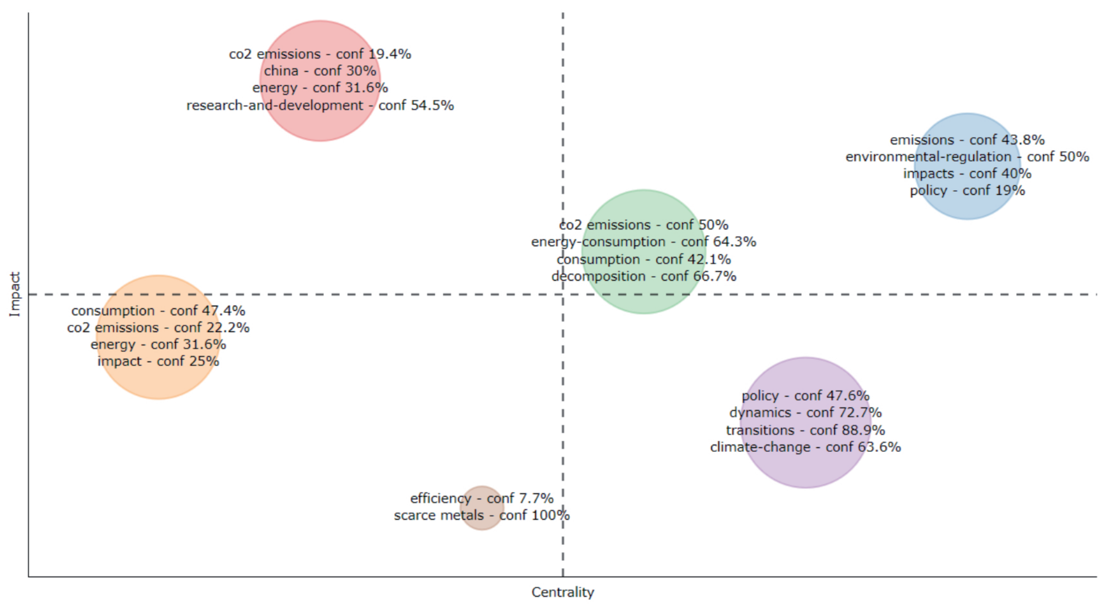

Fig. 10. Cluster analysis of keywords.

When using Citespace software for bibliometric review, the results of keyword burst analysis are unique. From the keywords with the strongest citation bursts, we can determine the keyword development and potential research themes. Table 5 shows the top 30 keywords with the strongest citation bursts. Excluding a few strong and long-lasting topics such as "energy" and "energy efficiency", most of the keywords burst after 2016, and all of them have very short cycles, especially the keywords "science" and "wind power" appear in this year and lose attention rapidly in this year or the following year. In addition, "technology", "low carbon technology", "technological innovation system", and "technological innovation" burst in different periods between 2016 and 2020, all of which are related to low carbon technology innovation. The frequent change of research hotspots from 2016 onwards indicates that the research hotspots in this field are changing rapidly and are in a period of high development and that scholars are active in researching such topics as low carbon technology innovation. In 2020, researchers start to focus on technology innovation in renewable energy, and low carbon technology innovation in developing countries also becomes a new research hotspot in the same year.

Keyword	Count	Centrality
co2 emission	43	0.19
impact	28	0.11
policy	25	0.15
energy	19	0.3
china	19	0.08
consumption	18	0.09
innovation	17	0.08
technology	16	0.14
energy consumption	16	0.05
emission	15	0.1
system	15	0.19
carbon emission	15	0.09
environmental regulation	14	0.09
climate change	14	0.07
renewable energy	13	0.01
intensity	13	0.01
transition	13	0.11
technological innovation	13	0
decomposition	12	0.05
efficiency	12	0.05

Fig. 11. Top 20 keywords in terms of frequency and centrality.

Discussion

low carbon technology innovation has attracted the attention of many scholars, and no review study has been conducted to summarize an outlook on this topic since the introduction of carbon peaking and carbon neutrality. The main drawbacks of following traditional methods for review studies are the reliance on the availability of journals and personal preferences, which makes the results biased and inadequate, and the incomplete coverage of key literature and important paths in traditional analysis methods. However, in this study, the bibliometric analysis used overcomes the personal subjective factor in traditional reviews, avoids missing key literature by completely covering all literature in the selected time period, and allows quantitative exploration of the knowledge structure, research hotspots, and trends in certain scientific fields. Therefore, this study used Citespace and VOS viewer software to conduct a bibliometric analysis of 205 articles in the Web of Science Core Collection database to obtain more objective and accurate results.

Through the bibliometric analysis of low carbon technology innovation, this study found that (1) the number of literatures in this field has continued to grow rapidly since 2017, and there was no sudden increase in particular years. This indicates that scholars in this field are increasingly focusing on low carbon technology innovation, and the number of publications is likely to continue the rapid growth trend in the coming years. (2) China is a major contributor to this type of research, publishing the largest amount of literature and having 17 of the top 20 institutions with the highest contribution. (3) Combining the high frequency and centrality of co-occurring keywords, "CO_2 emission", "impact", and "policy". The importance of "energy" and "China" has been indispensable in the field of low carbon technology innovation research. (4) The analysis of the keyword emergent results shows that the promotion of technological innovation in bioenergy, and thus low carbon technological innovation and development, is the most active and recurring research theme, while low carbon technological innovation in developing countries has also become a new focus.

The Chinese government has strongly supported the development of low carbon technologies through a series of policies and regulations, including clarifying the concept of green development and the goal of 'dual-carbon' in the 13th and 14th Five-Year Plans and setting a clear timetable and roadmap for low carbon technologies. The government has also set a clear timetable and roadmap for low carbon technologies and incentivized research institutes and enterprises to invest more in them. The government has lowered R&D costs and boosted innovation through financial subsidies, tax incentives, national key R&D programs, science and technology special projects, etc. It has also amended the Environmental Protection Law and introduced energy-saving and emission reduction regulations to provide legal safeguards for the promotion of low carbon technologies. Meanwhile, local governments have innovated regional policies through pilot demonstrations of low carbon cities and eco-parks to promote the localized application of low carbon technologies. The government also promotes the environmental awareness of the entire population through public participation and environmental education, creating a social atmosphere conducive to the promotion of low carbon technologies. These multilevel and multidisciplinary policy measures

Table 5. Top 30 Keywords with the Strongest Citation Bursts.

Keywords	Strength	Begin	End	2012-2021
Energy	2.26	2013	2018	
Science	1.33	2013	2013	
Low carbon	1.88	2014	2015	
Energy efficiency	1.67	2014	2017	
Future	1.32	2014	2018	
System	2.34	2015	2018	
Research and development	2.32	2016	2017	
Technology	1.91	2016	2018	
Diffusion	1.33	2016	2019	
Wind power	1.3	2016	2016	
Policy	1.63	2017	2017	
Perspective	1.57	2017	2017	
Sectoral system	1.24	2017	2017	
Low carbon technology	1.24	2017	2017	
Model	2.23	2018	2019	
Sector	1.62	2018	2018	
Sustainability	1.53	2018	2019	
Performance	2.6	2019	2019	
Strategy	1.68	2019	2021	
Technological innovation system	1.56	2019	2019	
Intensity	1.55	2019	2021	
Industry	1.38	2019	2019	
Sustainability transition	1.38	2019	2019	
Innovation system	1.26	2019	2021	
Consumption	2.7	2020	2021	
Renewable energy	2.43	2020	2021	
Technological innovation	2.43	2020	2021	
Driver	1.83	2020	2021	
Developing country	1.37	2020	2021	
Growth	1.3	2020	2021	

provide a guarantee for China's research in the field of low carbon technology innovation.

In addition to analyzing and discussing the results of this study, a critical review was conducted to better illustrate the research themes. According to the results of the co-referenced articles as well as the cluster analysis, the often influenced by competition in the process of low carbon technological innovation, in addition to technological innovation in renewable energy and technological innovation to reduce carbon emissions, are among the most critical studies. The results of the keyword emergent analysis 2016-2021 show that the cycles of relevant research hotspots in the field of low carbon technology innovation have been short in recent years, and scholars frequently change to new research topics, which indicates that scholars in this field are very active, especially the importance of systemic and systematic in low carbon technology innovation is gradually gaining more attention. Although research on the topic of low carbon technology innovation has been growing, most of the research institutions and researchers are from China, which leads to the fact that developing countries are also emerging as new hotspots. Therefore, more research and continuous observation of this topic is needed to see if research institutions and researchers from different countries have deeper and more cutting-edge insights on such topics. This means that despite these encouraging results of the present study, problems remain. The results of the study are limited by at least two limitations. First, due to the relatively small amount of literature available in the field, the results of the bibliometric analysis are limited and may not fully describe all aspects of the research area. In addition, due to the design of the software, it is difficult to represent the newly published high-level literature in the results of the visual analysis compared to older studies. In the future, we will continue to improve these shortcomings to improve the accuracy of trend prediction.

Conclusions

In order to fill the gap in systematic research in the field of low carbon technology innovation, a novel bibliometric approach was used to elucidate the developments, hot spots, and trending directions of this research and to allow a more efficient identification of the main advances and new insights in the field. The results indicate a surge of research interest in low carbon technology innovation. The analysis of highly cited references, quantitative reasoning on keyword frequency and centrality, and critical reading of recent and highly respected articles proved to exclude the use of the terms "Co2 emission", "impact", "policy", and "energy". Research has shifted to more sustainable behaviors such as improving the performance of technologies and systems and renewable green energy. Possible future research directions are identified through a combination of keyword emergent analysis and influential critical reading of references. First, research approaches and research directions on policies related to low carbon technology innovation will increase. Second, further research should focus more on innovation systems and systems for low carbon technology innovation. Third, the results of this study may also encourage scholars to continue to focus their efforts on efficient energy use, research on renewable energy, and green sustainable development. Finally, in the case of China, more regional carbon emissions will drive low carbon technology innovation, while state subsidies and inputs will also drive corresponding low carbon technology innovation, which indicates that low carbon technology innovation is similar to other traditional technology innovation in terms of development patterns. This study makes a contribution to low carbon technology innovation and provides a basis for in-depth research in this area. This study is based on 205 articles analyzed in the Web of Science Core Collection, and there may be limitations in the source of the data, resulting in a lack of comprehensive understanding of the field of low carbon technology innovation. Strict environmental regulatory policies can promote technological innovation by enterprises, thus achieving a win-win situation for both the economy and the environment. Therefore, the government should strengthen the implementation of environmental policies and encourage enterprises to adopt more environmentally friendly production methods. In addition, green technological innovation is the key to realizing the development of a low carbon economy. The government can encourage enterprises to increase their investment in green technology innovation by providing financial support, tax incentives, and R&D subsidies. The carbon emissions trading system is one of the most effective ways to reduce carbon emissions. The government can draw on the experience of other countries and regions to establish a sound carbon emissions trading system to promote low carbon innovation and technology development. Different industries respond differently to environmental policies. In formulating environmental policies, the government should take into account the characteristics and realities of different industries and avoid adopting a one-size-fits-all standard, so as to promote the sustainable development of various industries. Finally, low carbon technological innovation is a global challenge that requires the joint efforts of all countries. Governments should strengthen international cooperation and share technology and experience in order to promote the development of global low carbon technological innovation.

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Conflict of Interest

The authors declare no conflict of interest.

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