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Way to accomplish low carbon development transformation: A bibliometric analysis during 1995–2014

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ABSTRACT

A bibliometric analysis of low carbon related publications is reported in this study in order to depict existing research activities and to identify future directions in this research field. These publications were retrieved from various databases such as: Science Citation Index (SCI), Social Science Citation Index (SSCI), Conference proceedings Citation Index-Science (CPCI-S) and Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH). There is a notable growth associated with the body of knowledge on low carbon research. A total of 5445 records were obtained from these four major academic databases. Journal articles and proceedings papers are two frequently used document types representing 93.24% (5077 records) of the records and English is the dominant language with 5250 records (96.42%). The most productive subject is Energy & Fuels (1282 records) and the most productive journal is Energy Policy (313 records). China has largest number of publications related to low carbon. However, the USA accounts for the highest H-index (50). The Chinese Academic of Science is the organization with the most records (100 records) and the highest H-index (15). Four clusters are identified according to the analysis of co-occurrence keywords. Topics from Cluster (I) (central nodes as "climate change" and "renewable energy") are still vital to the low carbon research. However, their relative popularities declined over the past decade compared to other topics. This indicates more diverse topics from Cluster (II) (central nodes as "low carbon economy"), Clusters (III) (central nodes focusing on "low carbon", "energy" and "sustainability"), and Cluster (IV) (central node as "smart grid" interrelate with Cluster (I)) will be foci of future research endeavor in the coming decade.

1. Introduction

Extreme weather conditions such as record-breaking heat waves, heavy rainfall along with strong winds, tornadoes and floods are now occurring more frequently and severely at the globe scale [1]. According to the Environmental Protection Agency (EPA), the average temperature of Earth will increase up to 11.5 °F in next few centuries if no actions were taken to control the carbon dioxide emissions. The "new" climate conditions with extreme weather will make the world an unsafe place for future generations.

At present, traditional fossil fuels still dominate the energy mix of many countries to satisfy human beings' demands. Hence, a large amount of GHG emissions derived from human activities is responsible for various environmental issues such as haze and acid rain [2–4]. Other critical issues include the changes in land-use such as deforestation [5]. More than 40% of the total emissions are from burning coal [6]. On the other hand, fossil fuel is depleting too severely to meet the long-term sustainable energy consumption requirement of the entire world.

Therefore, the concept of "low carbon" development has attracted an increasingly level of attention as a research focus over the last two decades. It is well recognized that the fossil fuel-driven Industrial Revolution is peaking and human-induced climate damages have motivated the whole society to transit toward a post-fossil carbon era. However, it is undeniable that, as the most crucial characteristic and the biggest target of post-fossil carbon society, low carbon development is considered as an efficient model to deal with global warming and energy crisis [7]. Low carbon development is a new model of development, from the perspectives of optimizing the economic structure, developing the low carbon energy technology, improving the

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energy structure and efficiency of energy utilization and so on [8–10]. It will not only change patterns of energy production and consumption, but also continue to change the approaches of social and economic development. The development path and mode need to be revisited due to complexity nature of low carbon development. Therefore, it is not a surprise that the total number of low carbon related publications has boomed.

Bibliometrics, firstly introduced by Pritchard [11], is a "statistical method of bibliography counting to evaluate and quantify the growth of literature for a particular subject" [12]. Content analysis and citation analysis are two most common bibliometric methods [13]. Bibliometric indicators are used in citation analysis to evaluate publications. Indeed, bibliometrics is a well-recognized method to measure the progress of various areas of science [14]. Compared to other methods, bibliometric analysis have advantages such as: (1) mathematically evaluating a specific research field for a certain period of time; (2) providing a scientific evaluation method to identify the knowledge generation nature of a system [15].

There is no lack of researchers related to low carbon. This is evidenced in the large number of publications in academic journal papers and conferences which cover various aspects of this research field. This calls for a systematic analysis of the fast growing body of knowledge related to low carbon. Bibliometric research has been undertaken in other related fields such as hydrogen energy and fuel cell technologies [16] and carbon cycling research [17].

This study aims to investigate the characteristics of topic of "low carbon" related literatures from 1995 to 2014 via by bibliometric analytical techniques. These include: type(s), language(s), general pattern(s), subject(s), journal(s), performance of countries/territories and institutions and distribution of co-occurrence keywords, etc. These findings provide a better understanding of hotspots in the research field of low carbon. Similarly, these findings provide useful inputs for identifying future research directions which could accomplish low carbon development transformation. Critical questions addressed in this study are:

- Q1: What basic performance and characteristics could be used as a reference for future research?
- Q2: What are geographic patterns in terms of the number of publications? Which country/territory and institution have made the greatest contribution to low carbon research?
- Q3: What main research fields based on the co-occurrence author keywords analysis were investigated in the past and what will be focuses of the future research?

2. Methodology

There are a number of phrases presented the same meaning as "low carbon" from different perspectives. Similarly, this study places focuses on climate-related "low carbon" rather than materials with lower carbon content. To conduct this research comprehensively and accurately, "low carbon" or "low fossil fuel" or "decarbonized" not "steel*" not "alloy*" were used as searching strategy in the database of the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Conference Proceedings Citation Index-Science (CPCI-S) and Conference Proceedings Citation Index-Social Science & Humanities (CPCI-SSH) on March 30, 2015. All publication characteristics (e.g. authors, title, document type and keywords) were imported into a spreadsheet in the first instance [17]. The documents were selected within the time span 1995–2014 where 5445 records were obtained. The initial screening shows that the most productive journals are all included in the four databases. We have also searched the Google Scholar and Scopus. However, the information collected is rather informal and complex to analyze, which likely lead to an inappropriate conclusion. Besides, these two databases are largely overlapping with SCI, SSCI, CPCI-S and CPCI-SSH. Therefore, the databases of SCI, SSCI, CPCI-S and CPCI-SSH were chosen in this study.

2.1. The Classical R/S method and The Mann–Kendall test

Through calculating the Hurst exponent H value, the Classical Rescaled-Range (CR/S) provides a useful tool to analyze the long-range dependence for non-stationary time series [18–20]. Different H values mean that the sequence have different future trends. Specifically, a value $0 < H < 0.5$ corresponds to anti-correlated data (anti-persistence behavior) which means the future trend in contrast with the past, the smaller of H value the stronger of the anti-persistence behavior. A value $0.5 < H < 1$ corresponds to correlated data (persistence behavior) which means the future trend in consistent with the past, the bigger of H value the stronger of the persistence behavior and the value $H=0.5$ corresponds to random data (uncorrelated behavior). In this study, the Classical R/S method was used to predict the paper quantity of time series.

The Mann-Kendall test originally due to Mann [21] and rephrased by Kendall [22] is an efficient tool for long-term sequence trend analysis which is widely used in test feature of the meteorology and hydrology fields of rainfall, runoff, temperature and water quality, etc [23–25]. For the Mann-Kendall test, a monotonic trend of increase or decrease is evaluated commendably of a non-stationary time series by means of the calculation of the Z value. If $Z > 0$, there is an upward trend, $Z < 0$ indicates a downward trend. If the absolute value of Z is greater than or equal to 1.28/2.46/2.32, the sequence trend has passed 90%/95%/99% significance test respectively. In this study, the Mann–Kendall test is applied to determine whether there was a positive or negative trend in the amount of annual low carbon publications during 1995–2014 and whether there was obvious trend of increase or decrease.

2.2. The impact factor

Statistical analysis has been considered as one of critical components of document research. Subjects of statistical analysis include subjects, research institutions and the collaborations. Two indicators were adopted in this study. The influence of countries/territories and institutes is measured by H-index. The influence of journals is assessed by the impact factor (IF). The impact factor (IF) is one of the most commonly used assessable technologies for the relative influence of journals. IF is calculated as "the average number of times articles from the journal published in the past 2 years have been cited in the Journal Citation Reports (JCR) year and calculated by dividing the number of citations in the JCR year by the total number of articles published in the two previous years" [26]. The Journal Citation Reports 2014 was the source of impact factors of identified journals. Similarly, H-index is one of common metrics for the impacts of a scholar on a specific research field. It is defined as: "A scientist has index H if H of his/her Np papers have at least H citations each, and the other (Np-H) papers have no more than H citations each," where Np is the number of papers published over n years [27]. The H-index is a single indicator which combines measures of quantity (number of publications) and impact (number of citations). This effectively solves the problem of evaluating results that only responds to quantity with poor quality. In this study, H-index and Impact Factor (IF) were employed to characterize the performance of countries/territories and institutions, and journals related to low carbon respectively.

2.3. Content analysis

Word frequency analysis is a useful and effective method of content analysis. It is a common approach that core words and expressions which indicate the core content of literature are taken as the research object [14,28,29]. As a result, author keywords reflect the research focus within a certain area which may suggest future science directions [30,31]. Furthermore, environmental issues are complex for both causes and implications, which could not be solved within one single aspect of the field. Therefore, the correlation of co-occurrence keywords of publications is analyzed in this study in order to identify the word clusters. Combining with keywords quantity analysis, the hot research contexts and its relevance are examined.

2.4. The social network

Social network analysis (SNA) provides a useful tool to analyze social relations [32]. In essence, SNA provides a quantitative assessment on the relationships between the social actors, either casual acquaintance or close bonds. In this study, SNA was adopted to analyze the collaborative relationships and groups among the top productive countries/territories and institutions. Bibexcel is a software tool to perform several bibliometric and network analysis [33]. Gephi is a software package which can visualize the cooperation or co-occurrence relationships between different objects with a map [34]. Thus, in this study, the SNA is undertaken to analyze the academic collaboration among different countries/territories and institutes by using the Bibexcel and Gephi. Gephi software was employed to draw the diagram on the basis of co-word matrices generated from Bibexcel.

3. Results

3.1. The characteristics of research publications

Characteristics of the low carbon publications during 1995–2014 are discussed as below. Of 5445 records, “articles” took the biggest share with 54.71% (2979 records), followed by “proceeding papers” with 41.95% (2284 records). The records of other types accounted for less than 10% such as review, editorial material, book review, meeting abstract, letter, book chapter, correction and software review. Environmental research with the participation of multiple stakeholders and have large-scale implications, therefore “proceeding papers” has great value for further analysis. Hence, only “articles” and “proceeding papers” were further analyzed in this study.

Low carbon related publications in the databases were written in 12 different kinds of languages. English was the dominant language, which accounted for 96.24%, followed by Chinese (3.21%). As English is a common medium of communication in scientific papers, relatively mass of Chinese articles make a clear demonstration of that China is doing a large amount of academic research compared with other non-English speaking countries. This is consistent with the analysis of national distribution.

Fig. 1 shows a set of characteristics of the low carbon publications between 1995 and 2014. For the Mann–Kendall test value $Z=5.84 > 2.32 > 0$ with 99% significance. This shows an obvious growing trend in the amount of low carbon related publications during the last two decades. The total number of publications rose dramatically from 66 in 2005 to 798 in 2011. This is arguably due to the introduction of the Kyoto Protocol in 2005, which attracted a lot of attention from academia. Since 2011, the total number of low carbon related publications grew steadily, despite a slight drop in 2014. This warrants further investigation as sustainable development remains a hot topic in recent years. The Hurst exponent value ($H=0.84$) was an independent variable of an exponential function relation calculated via the Classical R/S (CR/S) method. The R/S statistics were calculated from the annual amount of low carbon related publications during the last two decades as well as the exponential function relation ($1.0807*\times\hat{}0.84419$) (see Fig. 1). The value of Hurst exponent is greater than 0.5 and less than 1. This indicates that the future trend of amount of annual publications is in consistent with the past. Therefore, the amount of low carbon related publications is projected to gain notable growth in the future.

3.2. The distributions of subject categories and journals

All 5077 records are grouped according to 180 subject categories shown in four databases, i.e. SCI, SSCI, CPCI-S and CPCI-SSH. As shown in Table 1, the productive subjects in terms of the number of publications are: Energy & Fuels (1282 records) and Environmental Sciences (1158 records). The number of publications on low carbon analysis of other subjects is comparatively small. This indicated that low carbon as a concept related to many subjects with concentration on energy, environment and sustainable development, economics and engineering.

Fig. 2 shows the annual publications on the five most frequent subject categories in the low carbon research. Before 2005, the number of annual publications of these five subjects was small. However, the number of articles within top five subject categories soared from 2005 to 2009 and increased more dramatically since then, despite fluctuations in some years. It is interesting to note that unlike other categories, the number of publications related to subject category of economics begun to decrease since 2010. This is arguably due to the growing public awareness of implications of climate change and in turn their preference to assign higher priority to environmental issues rather than cost issues. Affordability of low carbon technologies and products are also well improved due to the technological innovations. Similarly, the subject of Environmental Sciences took the lead during

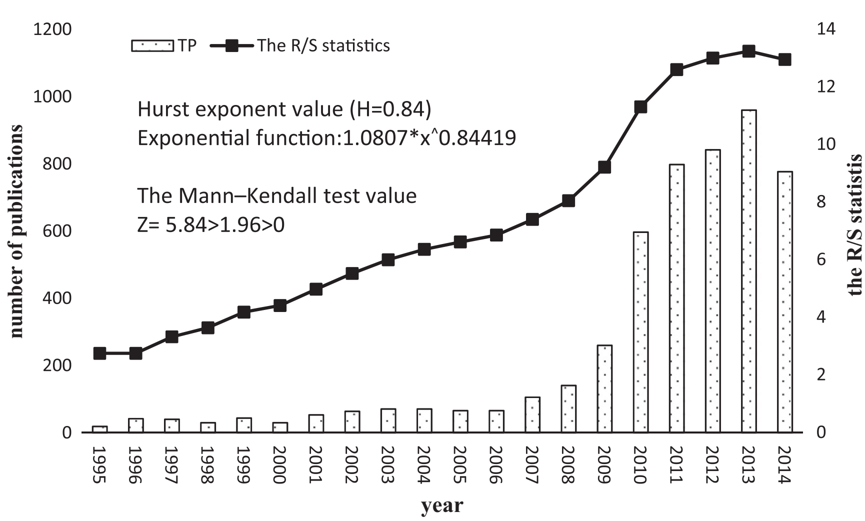

Fig. 1. The publication output performance. TP: the total number of publications.

Table 1
The 20 most productive subjects during 1995–2014.

Subject Categories	TP	%
Energy & Fuels	1282	25.45
Environmental Sciences	1158	22.99
Environmental Studies	848	16.84
Materials Science, Multidisciplinary	640	12.71
Economics	363	7.19
Engineering, Environmental	347	6.89
Engineering, Civil	322	6.39
Management	304	6.04
Engineering, Electrical & Electronic	269	5.34
Engineering, Chemical	241	4.78
Construction & Building Technology	238	4.73
Engineering, Mechanical	210	4.17
Urban Studies	163	3.24
Chemistry, Physical	153	3.04
Transportation Science & Technology	147	2.92
Physics, Applied	141	2.80
Business	137	2.72
Geosciences, Multidisciplinary	134	2.66
Operations Research & Management Science	132	2.62
Planning & Development	131	2.60

TP: the number of total publications.

the recent years. Therefore, the main research areas of low carbon are not only energy related aspects but also environmental science related aspects.

Each article contains information about the journal. Those articles on low carbon research (2979 records) were published in 1083 journals. These journals were further analyzed. Energy Policy is the most productive journal with 313 articles. The top 20 journals were listed in Table 2. It is worth noting that Journal of Power Sources has the highest IF value (6.217). Thus, both Energy Policy and Journal of Power Sources are amongst most influential journals on the research field of low carbon. Furthermore, most of these 20 journals are related to energy. These journals place focuses on the relationship between energy use and the greenhouse gas emissions, the contribution of the adjustment of energy structure for reducing greenhouse gas emissions, and the development of low carbon energy technology and low carbon energy strategy, etc.

Fig. 3 illustrates the publication patterns of the top 5 journals. It shows that all the top journals has few publications during the first decade. Since then, the low carbon related publications from core journals such as Energy Policy and Climate Policy have soared in first a few years and showed a slight drop in 2014. This indicated that research foci have shifted. As energy and its application are important in this field of research, low carbon related papers published in Energy and Apply energy continue to grow.

3.3. The contribution of the countries/territories

Address and affiliations of authors were supplied in each article. Accordingly, the contribution of different countries/territories and institutions can be examined. Only 5013 documents could be used to analyze the contribution of countries/territories and institutions as author addresses were not provided in some articles. Of these 5013 documents, less than 13% of publications involved international collaborations. From 1995 to 2014, 94 countries/territories have contributed to publishing documents on low carbon research. While this shows a great geographic breadth, the top 20 countries/territories are responsible for 89.85% of documents. This is in accordance with the “Pareto's Law”.

In Table 3 and Fig. 4, the 20 most productive countries/territories are ranked with respect to the total number of journal articles, the number and the percentage of articles without and with international collaboration, and the number of articles published by the first author as well as the corresponding author. In the top 20 countries/territories, there are two countries/territories from North America, six from Asia, ten from Europe, one country (Australia) from Oceania, and one country (Brazil) from South America. China was one of most productive contributors in the low carbon research with extremely large number of publications. However, the third placed USA has the highest H-index (50). This indicated that USA has highest level of academic attainments. Asian countries/territories have strong performance in terms of the total number of publications without international collaboration. This shows that the international cooperation with Asian scientists in the research field of low carbon is still relatively underdeveloped.

As shown in Fig. 4, the US took a leading position during the first ten years and then UK published articles rocked extremely rapidly since 2005. On contrary, articles published by Chinese scholars boomed since 2009.

The coauthoring relationships among the top 30 productive coun-

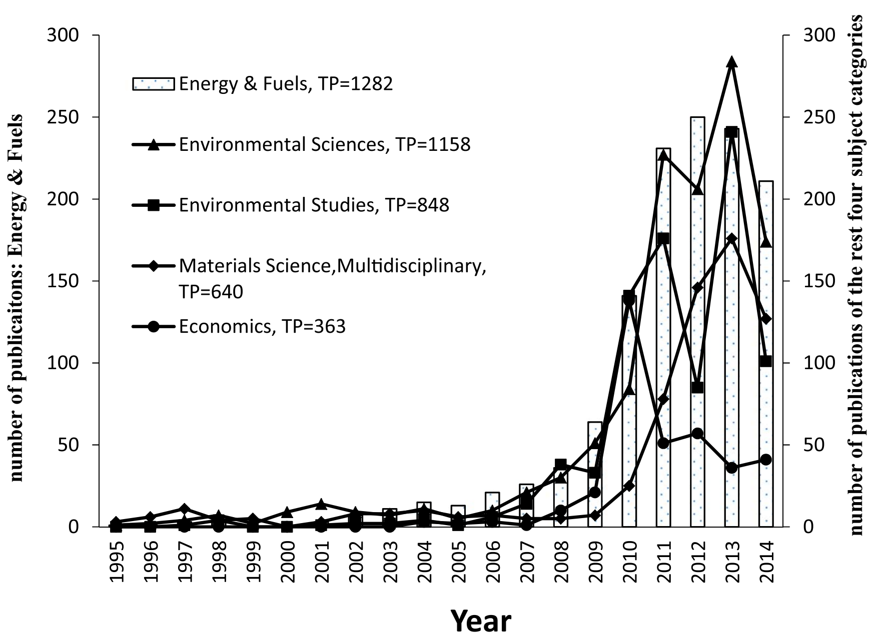

Fig. 2. The number of articles of the top 5 productive subject categories. TP: the total number of publications.

Table 2
The 20 most productive journals during 1995–2014.

Journals	ISSN	TP	IF2014	%
Energy Policy	0301-4215	313	2.575	10.51
Energy	0360-5442	68	4.844	2.28
Applied Energy	0306-2619	56	5.613	1.88
Climate Policy	1469-3062	55	1.703	1.85
Environmental Science & Technology	0013-936X	39	5.330	1.31
Building Research and Information	0961-3218	37	1.454	1.24
International Journal of Hydrogen Energy	0360-3199	37	3.313	1.24
Energy Economics	0140-9883	36	2.708	1.21
Journal of Cleaner Production	0959-6526	32	3.844	1.07
Climatic Change	0165-0009	29	3.430	0.97
Environmental Research Letters	1748-9326	26	3.906	0.87
Habitat International	0197-3975	25	1.746	0.84
Energy and Buildings	0378-7788	23	2.844	0.77
Renewable Energy	0960-1481	21	3.476	0.70
Sustainability	2071-1050	21	0.942	0.70
Energy Conversion and Management	0196-8904	20	4.380	0.67
Journal of Renewable and Sustainable Energy	1941-7012	19	0.904	0.64
International Journal of Greenhouse Gas Control	1750-5836	17	3.946	0.57
Journal of Power Sources	0378-7753	16	6.217	0.54
Global Environmental Change-Human and Policy Dimensions	0959-3780	14	5.089	0.47

TP: the number of total publications; R: the ranking; (%): the ratio of this journal's publications to the total number of publications during 1995–2014; IF: impact factor. Data source: http://www.medsci.cn/sci/.

tries/territories in the field of low carbon research were further analyzed via the social network analysis. Fig. 5 showed intuitively clear cooperative relationships among them and the thickness of these connecting lines demonstrated the intensity of cooperation. It is worth noting that countries/territories with similar geographical location worked more closely, especially in the Asia and Europe.

3.4. The contribution of the institutions

A total of 3140 institutions contributed to the subject of low carbon according to the 5013 articles with author addresses information. Less than 32% of these articles involved inter-institutional collaboration. The contribution of the 15 most productive institutes in low carbon research from 1995 to 2014 is shown in Table 4. Among the top 15 institutes, seven institutes are from China, seven from UK, and one from USA. The three productive countries appear in the list with great differences. This could be explained by the amount of publications and dispersion degree of institutes which UK is slightly lower than USA with similar number of articles. Chinese Acad Sci, China (100 articles) made the largest contribution with best performance in collaborative publications and the highest H-index (15). However, other institutions in China are in need of strengthening cooperation and improving the quality of articles. Most productive institutions in UK did well in collaboration with H-index around 10. Univ London Imperial Coll Sci Technol & Med (UK) ranked 4th. On contrary, Univ Calif Berkeley (USA) has 364 citations and H-index of 12 with a comparatively smaller total volume of publications.

The analysis is extended to the departments of the top institutes of 3 productive countries respectively (Chinese Acad Sci, China, Univ London Imperial Coll Sci Technol & Med, UK, Univ Calif Berkeley, USA). As shown in Table 5, Gradate University of Chinese Academy of Sciences is the most performing department in each of these top 3 institutes in terms of the number of low carbon related publications.

The publication pattern of the top 5 productive institutes over the last two decades is shown in Fig. 6. Prior to 2009, none of these top 5 productive institutes published more than 5 articles related to low carbon every year. Since then, the number of low carbon related publications from these top 5 productive institutes grew rapidly despite fluctuation in some years. Year 2014 saw a drop of low carbon related publications from two Chinese institutes, i.e. Chinese Acad Sci and Beijing Jiaotong University. This is arguably due to the wide concerns of researchers from other countries/regions on low carbon development.

The cooperative relationship among the 30 most productive in-

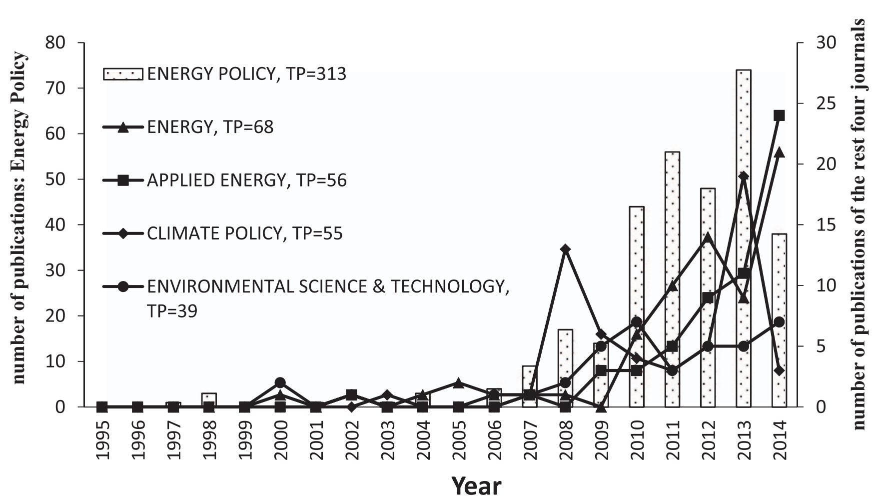

Fig. 3. The number of articles of the top 5 productive journals during 1995–2014. TP: the total number of publications.

Table 3
The top 20 productive countries/territories during 1995–2014.

Country	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	H-index
China	2169	1(43.27)	1(46.07)	3(24.1)	1(42.25)	30
UK	738	2(14.72)	2(13.05)	2(26.13)	2(13.01)	35
USA	622	3(12.41)	3(9.56)	1(31.92)	3(9.89)	50
Japan	229	4(4.57)	4(4.05)	6(8.14)	4(3.85)	16
Germany	222	5(4.43)	5(2.65)	4(16.59)	5(3.15)	29
Australia	139	6(2.77)	7(1.99)	6(8.14)	7(2.13)	15
France	130	7(2.59)	9(1.62)	5(9.23)	8(1.84)	27
South Korea	115	8(2.29)	6(2.19)	19(2.97)	6(2.15)	18
Canada	108	9(2.15)	10(1.46)	9(6.89)	10(1.6)	18
Netherlands	95	10(1.9)	13(1.05)	8(7.67)	12(1.32)	19
Taiwan	91	11(1.82)	8(1.92)	31(1.1)	9(1.8)	13
Italy	86	12(1.72)	12(1.1)	12(5.95)	13(1.28)	16
Spain	83	13(1.66)	13(1.05)	13(5.79)	11(1.38)	13
India	79	14(1.58)	11(1.23)	15(3.91)	14(1.24)	12
Sweden	71	15(1.42)	15(0.71)	11(6.26)	15(0.98)	14
Austria	59	16(1.18)	24(0.41)	10(6.42)	18(0.68)	13
Brazil	51	17(1.02)	15(0.71)	18(3.13)	16(0.78)	10
Switzerland	50	18(1)	29(0.37)	14(5.32)	21(0.54)	18
NORWAY	49	19(0.98)	18(0.57)	16(3.76)	18(0.68)	13
Malaysia	44	20(0.88)	15(0.71)	23(2.03)	17(0.74)	9

TP: the number of total publications; SP: the number of publications without international collaboration; CP: the number of publications with international collaboration; FP: the number of publications from the first author's country; R (%): the ranking, and the ratio of one country's publications to the total number of publications during 1995–2014.

stitutions in the field of low carbon research is also analyzed via the social network analysis. The corresponding cooperation network diagram shows that the Chinese Acad Sci (China) and the Univ London Imperial Coll Sci Technol & Med (UK) are particularly active in inter-institutional research on low carbon (see Fig. 7). It is noticeable that the research institutes in the same country collaborated closely. However, the Chinese Acad Sci (China) also collaborated with Natl Inst Environm Studies (Japan). It is worth noting that three China institutions did not appear in Fig. 7 which means these institutes did not cooperate with the rest of the top 30 productive institutions.

4. The main research fields

Keywords of a paper provide a fair indication of its focus. Therefore, keywords of low carbon related papers were analyzed in order to identify their patterns. A total of 10,982 individual keywords were used in journal articles retrieved from SCI, SSCI, CPCI-S and CPCI-SSH databases. Most of these keywords were not used frequently. 9000 (81.95%) keywords were only used once, which indicates a variety of research priorities. 178 keywords were used at least 9 times, indicating that they were related to main research streams of low carbon. In-depth analysis was undertaken to identify the major tendency of these studies. This paper selected the data of 1995–2014 and divided it into 4 stages to analyze the pattern of these keywords: the first stage (1995–1999), the second stage (2000–2005), the third stage (2006–2010) and the fourth stage (2010–2014). Each stage covers a gap of five years.

A total of 391 keywords (of which 371 keywords were used only once) had been studied in the first stage and "photosynthesis" ranked the first with 4 papers. Similarly, a total of 838 keywords (of which 790 keywords were used only once) had been studied in the second stage and "ethylene oligomerization" ranked the first with 8 papers. The small number of keywords during the first ten years indicates the field of low carbon was in its infancy and has not been studied further. Since 2005, as this research field has gained wide public attention, the total number of keywords presented an exponential growth. A total of 1820 keywords and 8801 keywords had been studied in the third and fourth stage which focused on "climate change" and "low carbon economy" respectively.

As shown in Table 6, "low carbon" ranked the 2nd in terms of the amount of total publications. There was no publication with keyword of "low carbon economy" within the first ten years but this keyword surged to 3rd in 2005–2009 to 1st in 2010–2014. This indicated that low-carbon-economy related topics were given an increasingly level of attention in last decade. Similarly, "sustainable development", "renewable energy", "low carbon city" and "carbon emissions" showed the same growth trend, suggesting that effective reduction of carbon emissions has become a common research field. "Energy efficiency" presented a stable and continuous growth, suggesting that improving energy efficiency has become one of primary research focuses on sustainability. Meanwhile, keywords relevant to measurement method and technique (e.g. "carbon footprint", "life cycle assessment", and "carbon capture and storage") sustained rapid growth during the last decade. This indicates that these low carbon techniques and measurement methods are becoming more popular and accessible to researchers in the field of low carbon. These low carbon techniques and measurement methods will likely be more frequently used to quantify carbon dioxide in atmosphere and reduce its emissions in the coming decade. "Industrial structure" is another keyword that received increasingly attention from 220th in 2005–2009 to 26th in 2009–2014

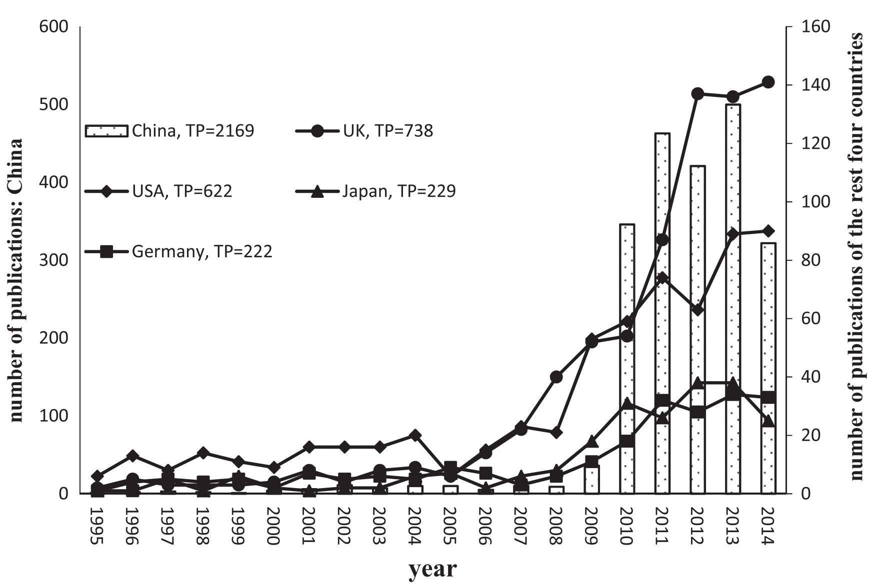

Fig. 4. The annual number of top 5 productive countries during 1995–2014. TP: the total number of publications from this country.

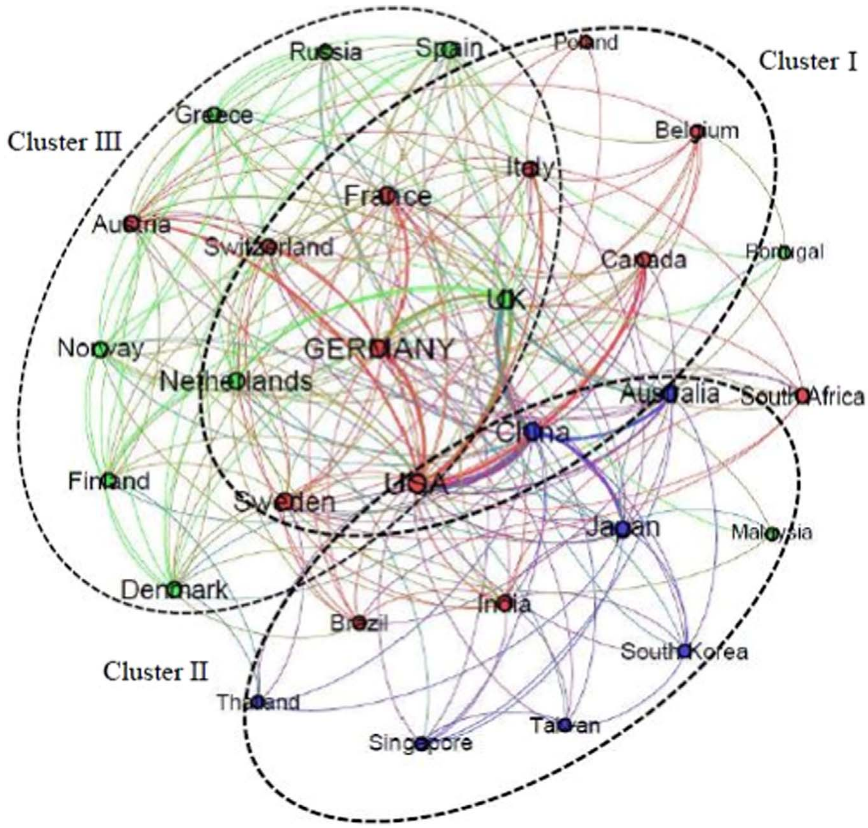

Fig. 5. The cooperation network of the top 30 productive countries/territories. The coauthor network (30 nodes, 4271 links). Nodes represent papers and links represent collaborative relationship between papers. Large nodes have more papers and thicker lines have closer connection. Cluster (I) central country was USA; Clusters (II) central country was China and it was composed of Asia countries/ territories; Clusters (III) central country was UK and it was mostly composed of European countries. Colors indicate the listed clustered groups. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

as there were more research papers focusing on the impacts of transformation of industrial structure as responses to low carbon development. "Policy" was a keyword which received a growing level of attention. Therefore, future research opportunities exist on policy related topics such as the impacts of policy instruments on low carbon development and establishment of market mechanism. By contrast, the ranking of "climate change", "renewable energy", and "energy" dropped. These relative declines are arguably due to the increasingly level of diversity in research focuses.

Cluster analysis was undertaken by using Gephi in order to identify main research streams. The bibliometric networks were visualized and clustered in order to highlight current focuses of low carbon related researches. The data displayed according to the Force Atlas2 Layout. As shown in Fig. 8, these clusters varied in size and partially overlapped.

As shown in Fig. 8, central nodes of the Cluster (I) and the Cluster (IV) was "climate change" and "smart grid" respectively. These two Clusters were strongly interconnected with "renewable energy", which is one of most important areas in low carbon research. Central nodes of the Cluster (II) focused "low carbon economy", such as "low carbon technology" "industrial structure" and "carbon trading". This is another core area in low carbon related researches. Central nodes of the Cluster (III) was "low carbon ", "sustainability" , "policy" and "supply chain".

Table 4
Top 10 productive institutions in the publication of low carbon area during 1999–2014.

Institute	TP	TP R (%)	SP R (%)	CP R (%)	FP R (%)	H-index
Chinese Acad Sci, China	100	1(1.99)	2(1.24)	1(3.66)	1(1.4)	15
Tsinghua Univ, China	70	2(1.4)	4(0.93)	2(2.44)	3(1.12)	10
Beijing Jiaotong Univ, China	65	3(1.3)	1(1.71)	0	2(1.24)	3
Univ London Imperial Coll Sci, UK Technol & Med, UK	57	4(1.14)	11(0.67)	3(2.18)	5(0.74)	13
Univ Leeds, UK	51	5(1.02)	15(0.61)	5(1.93)	5(0.74)	10
Univ Oxford, UK	42	6(0.84)	49(0.32)	4(1.99)	24(0.44)	12
Univ Manchester, UK	41	7(0.82)	15(0.61)	10(1.28)	8(0.62)	12
Univ Cambridge, UK	40	8(0.8)	36(0.41)	6(1.67)	15(0.52)	11
Shandong Univ Technol, China	40	8(0.8)	3(1.13)	0	4(0.8)	2
UCL, UK	39	10(0.78)	23(0.49)	7(1.41)	14(0.54)	9
Tianjin Univ, China	36	11(0.72)	5(0.75)	31(0.64)	7(0.66)	6
Tongji Univ, China	36	11(0.72)	5(0.75)	31(0.64)	8(0.62)	5
Beijing Normal Univ, China	35	13(0.7)	10(0.69)	23(0.71)	8(0.62)	8
Univ Calif Berkeley, USA	34	14(0.68)	42(0.38)	9(1.35)	18(0.5)	12
Univ Bath, UK	33	15(0.66)	8(0.72)	45(0.51)	12(0.58)	9

TP: the number of total publications; SP: the number of publications without international collaboration; CP: the number of publications with international collaboration; FP: the number of publications from the first author's country; R (%): the ranking, and the ratio of one country's publications to the total number of publications during 1995–2014.

Table 5
The top subordinates of the top 3 institutions.

Institution	Subordinate	TP
Chinese Academy of Sciences, China	Grad Univ (Univ Chinese Acad Sci)	25
	Inst Policy & Management	12
	Inst Geog Sci & Nat Resources Res	10
	Inst Appl Ecol	7
	Inst Urban Environm	5
	Dalian Inst Chem Phys	5
	Inst Coal Chem	4
	South China Sea Inst Oceanol	3
Univ London Imperial Coll Sci Technol & Med, UK	Ctr Environm Policy	12
	Ctr Energy Policy & Technol	11
	Dept Chem Engn	7
	Dept Mech Engn	5
	Dept Elect & Elect Engn	4
	Grantham Inst Climate Change	3
Univ Calif Berkeley, USA	Energy & Resources Grp	13
	Lawrence Berkeley Natl Lab	11
	Lawrence Berkeley Lab	6
	Goldman Sch Publ Policy	5
	Dept Agr & Resource Econ	3
	Renewable & Appropriate Energy Lab	3

TP: the number of total publications.

This cluster focused on countermeasures with a consideration of the complexity of environmental problems.

4.1. Clusters (I) and (IV)-climate change

4.1.1. Renewable energy

The keyword of “climate change” was usually considered as the biggest environmental problem confronting to human beings so far. The rapid growth in consumption of fossil fuels not only has accelerated its depletion but also discharged greenhouse gas directly which ultimately causing globe warming. The keyword of “Renewable energy” was mostly concerned by scholars in this field for its potential to the climate change mitigation and adaption. Lester pointed out that efforts are required to develop the renewable energy and transform the mode of economic development and structure of energy use in order to control the global warming [35]. The core of energy structure will turn from fossil fuels to renewable energy such as top ranked keywords of “hydrogen” (26th), “biomass” (34th), “nuclear power” (41st) and “wind power” (46th). Renewable energies are not constrained by resources, as several studies have shown that the solar resource and the wind resource have sufficient potential to power all human beings’ energy needs [36]. However, it has intermittent output in the context of varieties of natural environment condition. In addition, land demand and high initial cost will hinder its common usage as the primary energy. That is the reason a growing number of studies attempted to investigate how to achieve full renewable energy potentials [37].

Hydrogen production is one of best favorites in the low fossil fuel options in the higher energy case [38]. As a result, the proportion of hydrogen related publications to the total publications is reasonably high. It ranked 21st, 5th and 4th in the first three stages respectively, before dropping to 79th in the last stage (2010–2014). This is arguably due to the rapid expansion of the scale of low carbon research which covered a lot other areas than hydrogen. As a result, despite a reasonable number of publications (13), the proportion of hydrogen related publications to the total publications experienced a sharp decrease during 2010–2014. Meanwhile, the ranking of the keyword of hydrogen dropped to 79th. Electricity generated from new nuclear power stations will be competitive with alternative low carbon generation options, if the safety, efficiency and sustainability of nuclear power system could reasonably match its development and operational costs. Current UK Government support for nuclear power has in part been informed by highly competitive cost estimates [39]. The cost of wind power generation has become less steep as its technology improved in recent years. China's wind electricity generation was only behind coal and hydropower, accounting for 2% of total electricity consumption nationally. Although wind power experiences a rapid development in China, a number of challenges exist such as wind resource assessment and grid access [40].

4.1.2. Smart grid

The core keyword of Clusters (IV) is “smart grid”. It is a network system of digital information which can link up the renewable energies and end users of electrical equipment or other electrical facilities. With the assistance of energy storage, different forms of power generation could be accessed which helps to provide a more stable power supply and timely feedback. This greatly improves the practicability of the renewable energies. As the energy system needs radical transition for widely use of renewable energy resources, smart grid is the best

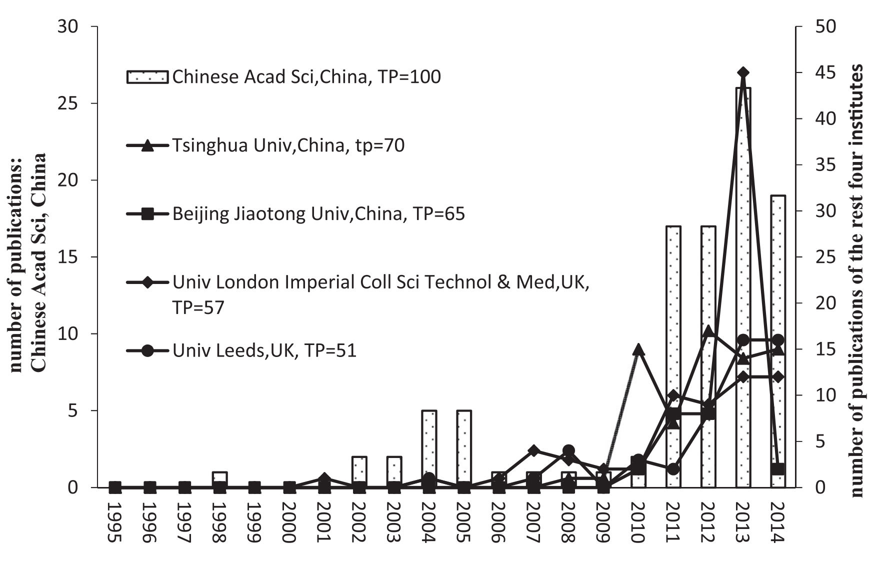

Fig. 6. The growth trend of the top 5 productive institutes during 1995–2014. TP: the total number of publications from this institute.

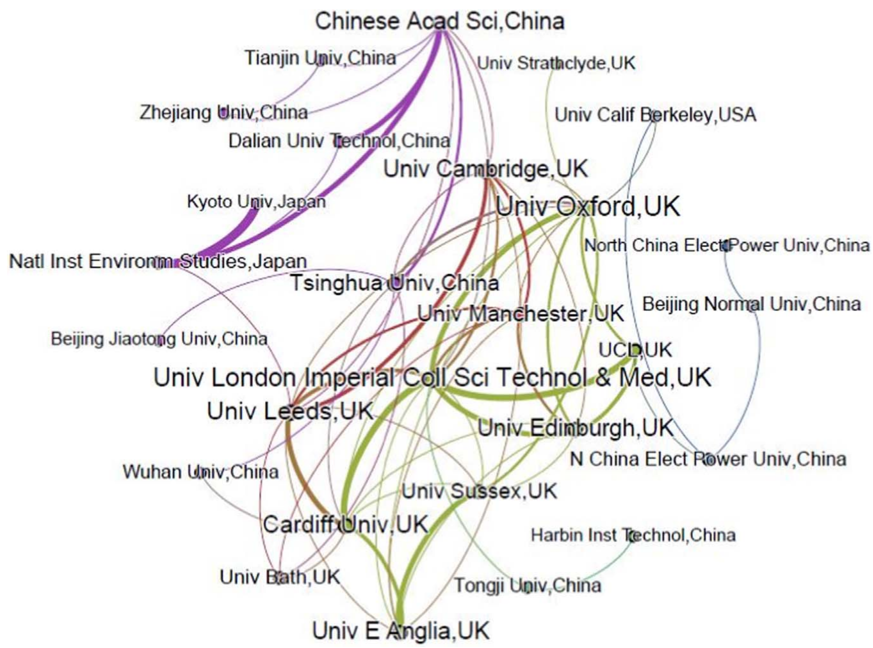

Fig. 7. The cooperation network of the top 30 productive institutions. The coauthor network (30 nodes, 4271 links). Nodes represent papers and links represent collaborative relationship between papers. Large nodes have more papers and thicker lines have closer connection. Colors indicate the listed clustered groups. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

platform [41]. Due to its apparent low carbon benefits, it has become crucial to improve and evaluate the smart grid. The other important area of research is the modeling and optimization of micro-grid and distributed power generation system [42,43]. In developed countries, there is a growing public awareness that smarter electricity networks play a critical role for smarter communities, smarter cities and a smarter country [44]. China faces the challenges of grid connection for development of renewable energy for power generation. Technological innovations allow devices and systems to support the formation of a more intelligent grid [45]. In the future, smart distribution grids will become the focus of development in China. It has the potential to integrate a growing amount of outputs from variable distributed renewable resources [46].

Table 6
The increasing trend of 30 hot topics during 1995–2014.

No.	Author Keywords	TP	95-14 R (%)	95-99 R (%)	00-04 R (%)	05-09 R (%)	10-14 R (%)
1	Low carbon economy	543	1(12.8)	0	0	3(3.51)	1(15.05)
2	Low carbon	291	2(6.86)	0	0	14(1.45)	2(8.13)
3	Climate change	208	3(4.9)	0	12(1.1)	1(9.09)	3(4.64)
4	Sustainable development	131	4(3.09)	0	0	20(1.03)	4(3.61)
5	China	111	5(2.62)	21(1.23)	49(0.55)	9(1.86)	5(2.86)
6	Renewable energy	98	6(2.31)	0	0	4(2.69)	6(2.43)
7	Energy	91	7(2.15)	4(2.47)	49(0.55)	4(2.69)	9(2.15)
8	Low carbon city	82	8(1.93)	0	0	88(0.41)	7(2.29)
9	Carbon emissions	79	9(1.86)	0	0	49(0.62)	8(2.17)
10	Energy efficiency	75	10(1.77)	21(1.23)	12(1.1)	13(1.65)	10(1.83)
11	Sustainability	72	11(1.7)	0	12(1.1)	17(1.24)	10(1.83)
12	Low carbon society	62	12(1.46)	0	0	2(4.13)	15(1.2)
13	Carbon emission	61	13(1.44)	0	0	49(0.62)	12(1.66)
14	Energy consumption	58	14(1.37)	0	0	49(0.62)	13(1.57)
15	Carbon	52	15(1.23)	2(3.7)	2(3.3)	7(2.48)	23(0.89)
16	Climate policy	50	16(1.18)	21(1.23)	12(1.1)	7(2.48)	20(1)
17	Energy policy	49	17(1.16)	0	12(1.1)	14(1.45)	17(1.14)
18	Carbon footprint	47	18(1.11)	0	0	88(0.41)	14(1.29)
19	Low carbon development	43	19(1.01)	0	0	49(0.62)	17(1.14)
20	Low carbon tourism	41	20(0.97)	0	0	0	16(1.17)
21	Low carbon technology	38	21(0.9)	0	0	20(1.03)	21(0.94)
22	Energy saving	38	21(0.9)	0	0	220(0.21)	19(1.06)
23	Greenhouse gas emissions	37	23(0.87)	0	49(0.55)	29(0.83)	22(0.92)
24	Life cycle assessment	35	24(0.83)	0	0	29(0.83)	23(0.89)
25	CO_2 emissions	31	25(0.73)	0	0	0	23(0.89)
26	Hydrogen	30	26(0.71)	21(1.23)	5(1.65)	4(2.69)	79(0.37)
27	Carbon capture and storage	30	26(0.71)	0	0	20(1.03)	29(0.72)
28	CCS	30	26(0.71)	0	0	88(0.41)	26(0.8)
29	Policy	29	29(0.68)	0	0	88(0.41)	28(0.77)
30	Industrial structure	29	29(0.68)	0	0	220(0.21)	26(0.8)

TP: the number of total publications. R (%): the ranking, and the ratio of one keyword's publications to the total number of publications during 1995–2014.

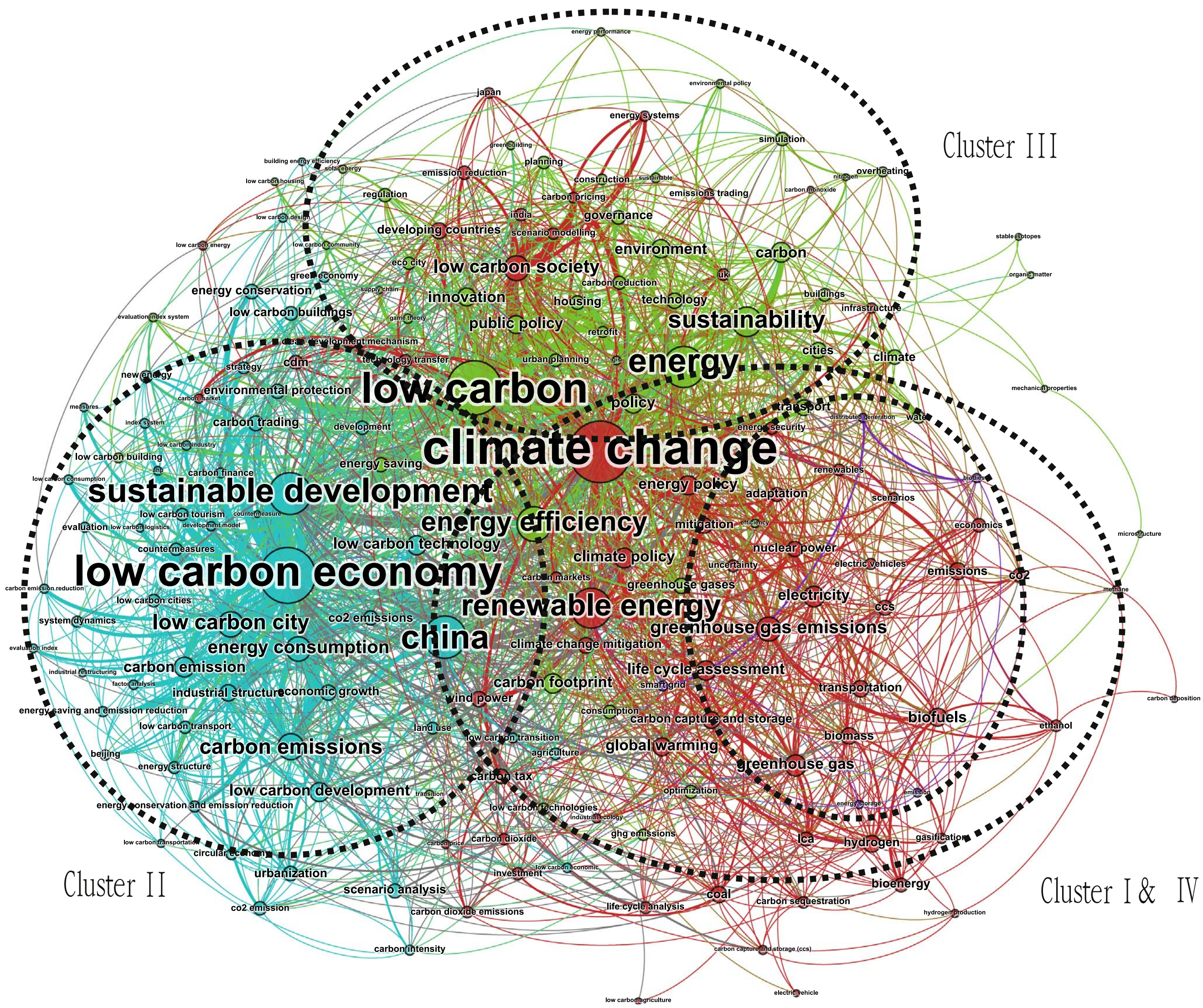

Fig. 8. The co-occurrence keywords network (177 nodes, 1931 links). Nodes represent papers and links represent shared reference between papers. Large nodes have more occurrence references. Approximate location of clusters are indicated with: the Cluster (I) (account for 36.72%) central nodes were “climate change” and “renewable energy”; Clusters (II) (account for 31.07%) central nodes was “low carbon economy”; Clusters (III) (account for 29.38%) central nodes focused on energy and its sustainability; Clusters (IV) (account for 2.82%) focused on smart grid area which has a strong relation to the renewable energy. Colors indicate the listed clustered topics. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

4.2. Clusters (II)-low carbon economy

This paper focuses on research documents which could accomplish transformation towards low carbon development. It is worth noting that low carbon economy is the most frequently used keyword in all publications retrieved from the databases. In 2003, the British government, for the first time, proposed the concept of low carbon economy in the Energy White Paper. It is well recognized that developing low carbon economy is the most effective way to deal with the challenges of environmental change. It can be observed from Table 6 that there were very few articles related to low carbon economy during the first two stages, and then the number increased rapidly. As the study of the whole area has entered into a stable development phase, the number of papers related to this hottest area began to decline. Low carbon economy is a kind of sustainable economic development pattern with characteristics of low carbon consumption, low carbon emission and low pollution. It affects transformation of all aspects of economic and social development. Similarly, “low carbon society” (12th), “low carbon tourism” (20th), “low carbon transport” (58th) and “low carbon buildings” (67th) received noticeable attention.

4.2.1. Industrial structure

The characteristics of the second industry are energy intensive with severe pollution, especially with the raw material processing industry and resource-intensive industry. Within the same size of development, carbon intensive industries cause deteriorating air quality and consume more energy than low carbon industries. Therefore, it is well recognized that the adjustment of industrial structure (the transformation from the second industry to the tertiary industry) and the change of industrial structure (from heavy to light) are main factors that lead to the reduction of energy consumption and energy intensity. Under the constraints of energy saving and emission reduction, the adjustment of industrial structure in the short term will lead to the reduction of industrial production. However, in the long run, the whole industry and environment will achieve a win-win outcome. However, some scholars argued that shifting to a low carbon industry oriented economy would entail a decrease in CO_2 emission intensity per unit of GDP but an increase in overall CO_2 emissions in absolute terms [47]. Therefore, effective measures to control final demand emissions and to adjust energy mix will become a focal point of low carbon studies.

4.2.2. Carbon market mechanisms

The three Kyoto flexible mechanisms: emissions trading, the clean development mechanism (CDM), and Joint Implementation (JI) have always been controversial [48]. Keyword of “emissions trading” (189) is essentially a dynamic mechanism and operating mechanism of development of low carbon economy. Emissions trading has incentives conducive to enterprises with spontaneous processes for the active carbon reduction effects can make profits through the carbon trading market. The research methodologies mainly concentrated on multi-agent modeling (ABM) and multi object optimization. In the context of low carbon development, an efficient market mechanism needs to be studied systematically in various aspects such as design, optimization and assessment of its impact. At the same time, future research should be undertaken on combining theoretical researches with the actual practice.

The location of “clean development mechanism” (CDM) (98th) indicated that it has closer relationship with carbon economy and its market. It is a mechanism that developed countries take the load of reduction emission of greenhouse gas as part of the fulfilled obligations required by the Kyoto protocol. This is through implementing projects which has the effect of reduction of greenhouse gas emission in the developing countries. On the one hand, developed countries could flexibly perform themselves obligations at a lower cost. On the other hand, developing countries could gain funds and technologies from developed ones to facilitate the sustainable development. van der Gaast proposed an approach to facilitate low-carbon energy technology transfer compatible with the energy development demands and priorities of developing countries, providing insights on improving the CDM for technologies [49]. Carbon trading market simply measures the profits in terms of the certified emissions reductions which in fact becomes a perverse incentives hampering energy CDM project development. The developing countries sell large quantities of carbon resources to developed countries without introducing advanced low carbon technologies. Consequently they have to fulfill their own emissions reduction obligations at greater expense. Since then, a lot of efforts have been made on exploring mechanisms to improve the CDM [50–53].

4.2.3. China

A lot of developing countries such as China (5th) are in the middle of industrialization and moving towards that of the developed countries for the electromechanical manufacturing sector in the second industry and the tertiary industry are growing. Environmental problems (e.g. haze and acid rain) are becoming increasingly severe in developing countries with fossil fuel dominated energy structure [54]. In China, the rapid urbanization and industrialization have resulted in the nationwide ambient fine particle pollution (haze episodes) in most urban areas [55]. Hence, it is not surprising that the total number of publications in China has rocketed since 2005 and Chinese scholars participated in writing almost 85% papers of which focus on the low carbon economy. This is arguably due to the fact that the Chinese government adopted the Renewable Energy Sources Act in 2006. China's research on low carbon yielded fruitful results also because of the promotion and guidance of laws, regulations and the 2010–2020 Renewable Energy Medium and Long-term Development Plan.

4.2.4. Low carbon technology

According to the Intergovernmental Panel on Climate Change (IPCC), global warming is very likely caused by human induced GHG emissions. Therefore, the development of low carbon technology as one of effective countermeasures has gathered considerable attention from a globe perspective. The keyword of “carbon capture and storage” (CCS) (27th) is widely recognized as one of effective technologies to reduce GHG emissions [56–58]. Raymond R. Tan used a simple graphical approach to determine the target of implementing the minimal extent of CCS retrofit that fulfills the sectorial carbon footprint target [59].

4.3. Clusters (III)-low carbon development

4.3.1. Policy

Due to the external effect of carbon emissions at the global scale, the policy intervention plays a critical role in emissions reduction. More attention has been paid to long-term alternatives in climate change related policies such as technological innovation for sustainable energy [60]. Furthermore, an individual's attitudes and subsequent behavior to engender mitigated behaviors of carbon emissions would be to introduce regulation that forces low carbon lifestyles [61]. A noticeable growing number of studies focused on making effectively government stimulus-encouraged policies. At present, carbon tax is widely adopted as policy instruments to deal with climate changes. Carbon tax can influence prices, consequently affect the use of energy to reducing the CO_2 emissions with less management cost and easier operation methods [62]. The revenues for climate change and starting as early as the 13th five-year plan period (2016–2020) would be preferable and realistic [63]. Moreover, carbon tax could enhance the public awareness of climate change [64]. However, enterprises will try to pass on the losses on to customers which are detrimental to the effectiveness of carbon emission reduction efforts. How to design the emission reduction policy system which conforms to the national development and status quo appears to be a new trend in this field of research.

4.3.2. Carbon footprint

An accurate and effective carbon emissions measurement is the foundation of low carbon research. At present, a common index is known as “carbon footprint” (18th). It is historically defined as “the total set of greenhouse gas (GHG) emissions caused by an organization, event, product or person”. Hence, it has been employed in a large number of studies as a tool to characterize and measure the performance of the carbon emissions range from energy sources to specified area of production [65–68]. A number of researches measure it by using life cycle assessment (LCA) methods which could calculate carbon footprint from the whole production process. In the context of climate change, LCA is commonly used to assess the environmental performance of low carbon techniques and products [69,70].

4.3.3. Low carbon supply chain

The low carbon development should be examined from the supply chain system's perspective. This supply chain consists of links and nodes (e.g. enterprises). The management of low carbon supply chain aims for the maximization of economic benefits and social welfare, the optimization of resource allocation and the minimization of environmental impacts.

The main achievements are two-folded: (1) the optimal design and evaluation of the low carbon supply chain. The design and placement of links and nodes of a supply chain will have a significant impact on carbon emissions. As a consequence, the evaluation system attracts an increasingly level of attention. In traditional evaluation system of supply chain, economy acts as the main factor. By contrast, the evaluation of low carbon supply takes other factors into consideration such as the carbon emissions, energy consumption and the degree of compatibility with the environment. Existing studies mainly focused on how to develop the evaluation index system and apply evaluation model to assess the performance of low carbon supply chain either qualitatively or quantitatively [71]. (2) The management measures of low carbon supply chain. Low carbon supply chain consisting of various enterprises is a typical complex system. To improve the entire system, strategies need to be in place. Existing studies pay more attention to management measures which could provide the theoretical basis for policy making [72].

5. Conclusions

Based on the databases of SCI, SSCI, CPCI-S and CPCI-SSH, this study investigated the characteristics of the low carbon literature from 1995 to 2014 by using bibliometric techniques. There were 5445 publications in total. Among them, articles and proceeding papers (5077 records) accounted for 93.24%, while English is the dominant language with 5250 records (96.42%). Based on the results of the Classical R/S analysis and the Mann–Kendall test, there is obviously and rapidly increasing trend of the total number of low carbon publications which will ensure a sustained growth in the future. The most productive subject is Energy & Fuels (1282 records) and the most productive journal is Energy Policy (313 records). China is the most productive country in the research field of low carbon, followed by UK and USA, however the USA, accounting for the highest h-index (50). The Chinese Academic of Science is the organization with the most records (100 records) and the highest H-index (15). According to the analysis of keywords four clusters were identified i.e. Cluster (I) (central nodes were “climate change” and “renewable energy”), Cluster (II) (central nodes were low carbon economy, Clusters (III) (central nodes focused on “low carbon”, “energy” and “sustainability”), and Cluster (IV) (central nodes interrelate with Cluster (I)). In conclusion, low carbon economy and its development path (e.g. the adjustment of industrial structure and of market mechanism) are the foci of low carbon researches during the last two decades. The application of renewable energy at a large scale such as smart grids is still vital to the low carbon research. Countries all over the world are paying more attention to reduce carbon dioxide emissions in order to mitigate global warming via preferential policies. Low carbon development related researches have gained a noticeable growth. In addition, measurement methods and low carbon techniques have become popular research topics. This indicates a growing diversity for the low carbon related researches. These findings provide useful references to researchers in the field of low carbon research such as the identification of low carbon field research hotspots as well as future research directions.

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