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Frontiers of low-carbon technologies: Results from bibliographic coupling with sliding window

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A B S T R A C T

It is of great significance to quickly and accurately detect the current and future development trends of low-carbon technologies (LCT). However, there is a lack of detecting research fronts of low-carbon technologies based on the bibliographic data. This paper proposes a research framework integrating LCT domains and the bibliometric coupling with sliding window technique to explore the LCT research fronts in recent decade (from 2007 to 2016). Eleven research fronts matching the foresight given by LCT experts are identified, including carbon capture and storage (CCS) in power generation, technology transfer, technology diffusion, electrocoagulation, magnetic nanoparticles, critical metals application, electrocatalytic water oxidation, ionic liquids, mutually immiscible ionic liquids, electric vehicle (China), electric vehicle (UK and USA). Closer investigation of the evolution shows that CCS application in the power plants and hydrogen production from water electrolysis are two emerging fronts. Besides, bibliometric coupling with sliding window is an effective tool to detect the frontiers of low-carbon technologies. Finally, the implications of the research for LCT monitoring and development are discussed.

1. Introduction

In response to climate change, low-carbon technology innovation is getting more and more attention (Mi et al., 2015; Wang et al., 2017; Wei et al., 2017). At the same time, the innovation and diffusion of low-carbon technologies are also the important driving force for low-carbon economy development (Cong, 2013; Cong and Shen, 2014; Mi et al., 2017c). In addition, the development of low-carbon technologies and corresponding policy design play a vital role in the residential health and pollutant emission reduction (Kanada et al., 2013; Mi et al., 2017a, 2017b).

Given the importance of low-carbon technologies, it is of great significance to quickly and accurately detect the frontiers of low-carbon technologies. Some literature investigates energy issues, involving the research fronts of low-carbon technologies. In the visualization of international energy policy research, Wang et al. (2016) revealed the development trends of low-carbon technologies research. Sriwannawit and Sandstrom (2015) analyzed the development of diffusion research using the bibliometrics method, and their results included the research fronts of low-carbon technology transfer. However, from the perspective of publications, there are few studies on the frontiers of low-carbon technologies. An important research on this subject is from Albino et al. (2014) who used patent data to analyze the development trend of low-carbon energy technologies. Based on the researches above, this paper tries to explore the frontiers of low-carbon technologies in the recent decade based on the bibliographic data and bibliographic coupling technique.

Firstly, this paper obtains the highly-cited literature in the field of low-carbon technologies. Secondly, with the help of bibliographic coupling to extract the samples with the high coupling strength. Thirdly, categorizing the different research fronts of low-carbon technologies through the cluster analysis. Lastly, depicting the LCT frontiers evolution employing the sliding window technique (this technique through time interval overlapping and panning to obtain more information about the change). From the

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foregoing, some policy implications will be given according to the research findings. Generally, this study tries to answer two questions: (1) what are the research fronts of low-carbon technologies in recent years? (2) What are the evolution paths of LCT research fronts?

The remainder of this paper is structured as follows: in the following part, we highlight existing literature from three perspectives including low-carbon technologies, research front conception, and detecting methods of research fronts. In the third section, we present the research framework, methods and data. Next section are the results as well as the discussions. Finally, the conclusions and policy implications are discussed at the end of the paper.

2. Literature review

2.1. Low-carbon technologies

At present, there is no clear and unified definition of "low-carbon technology (LCT)", which is similar to the concept of "clean technology" and "environment-friendly technology" (Lv and Qin, 2016; Renewable and Society, 2010). Dechezleprêtre and Martin (2010) equated the concept of low-carbon technology with clean technology, both of which have significant potential to reduce greenhouse gas emissions. Gillingham and Sweeney (2012) defined LCT as a kind of technologies to decrease reliance on fossil fuels and reduce greenhouse gas emissions. Albino et al. (2014) recognized LCT as fundamental means to reduce the final cost of meeting environmental policy objectives and lower the cost of stabilizing atmospheric carbon dioxide concentrations. In the document *Catalogue of low carbon technologies promoted by the state (third batch)*, the national development and reform commission (NDRC) of the People's Republic of China (2016) defined LCT as follows, based on the clean and efficient use of energy and resources, these technologies were characterized by the capability to reduce or eliminate carbon dioxide.

Generally, the classification of low-carbon technologies has two main streams (NDRC, 2016; Renewable and Society, 2010). Firstly, according to the stages of the control process, low-carbon technologies are grouped into zero-carbon technologies, carbon reduction technologies and carbon storage technologies. On the other hand, according to the technical features of emissions reduction, low-carbon technologies are categorized by non-fossil energy technologies, fuels and raw materials substitution technologies, the Non-CO_2 reduction technologies in production processes, "carbon capture, utilization and storage" (CCUS) technologies, carbon sink technologies.

Although the definition of low-carbon technologies from different scholars have different details, there is a basic consensus: on the one hand, low-carbon technologies can reduce greenhouse gases in the atmosphere. On the other hand, low-carbon technologies are essential to sustainable development (Foxon and Pearson, 2008; Kennedy et al., 2016).

2.2. Research front conception

Research front is an important concept in the field of Scientometrics, which was firstly proposed by Price in 1965. Price (1965) defined the recently published and highly-cited literature as the research front. Based on the concept introduced by Price, the concept of research front has received wide attention and expanded meaning in recent years.

Small (1973) and Griffith et al. (1974) viewed that the clustering of co-cited articles represents the research front. Garfield (1989) pointed out that the research front includes co-cited articles and citing articles. Morris et al. (2003) explored the research front using the bibliographic coupling method. Shibata et al. (2008) proposed that the high cited clustering (Direct Citation Clusters) is the research front. Chen (2006) pointed out that the research front is a set of emergent concepts and their knowledge base. In the view of Persson (1994), cited literature is the knowledge base, and citing articles is the research front. Braam et al. (1991) also has a similar view. They defined research front as citing articles clusters with common knowledge base.

In addition, five stages of research fronts are proposed by Upham and Small (2010): emerging fronts, growing fronts, stable fronts, shrinking fronts and exiting fronts, which provides one way to depict the change process of fronts in a period. The categorizing is a useful tool to track the evolution of research fronts in a timely and accurate fashion.

2.3. Research front detection methods

The research front detection methods generally include two types: subjective and objective methods. Subjective methods mainly use the expert consultation and experience judgment, which are influenced by expert knowledge in the specific field. Objective methods refer to some data-driven tools, employing bibliographic data to reveal the performance of the research front, and including the following methodologies or their combination: direct citation, co-citation (Small and Griffith, 1974), bibliographic coupling (Morris et al., 2003), science network (Shibata et al., 2008), word frequency analysis (Kleinberg, 2003), co-word (Pottenger and Yang, 2001). In the era of big data, facing with massive data and complex decision-making environment, objective methods are more and more important and popular with the advantages of accurate detection, time-saving and cost-efficient.

In some specific fields, studies on research fronts show that bibliographic coupling has slightly better performance, compared with co-citation and direct citation (Boyack and Klavans, 2010; den Besselaar and Heimeriks, 2006; Shibata et al., 2009).

Relatively speaking, the highly-cited articles have better quality and higher research value, which are often used as important basis to recognize the research front. Many researches detect research fronts using bibliographic coupling based on highly-cited articles (Ho, 2014; Pislyakov, 2011; Small, 2006). To explore more details of the research fronts, research time are divide into different time frames, and sliding window are proposed to track the evolution process of research fronts. Besides, most studies take 5-year as a citation window (Small, 2006; Upham and Small, 2010).

3. Methodology

3.1. Research framework

To better understand the low-carbon technologies frontiers in the field of natural science in recent decade, this study retrieves the bibliographic data related low-carbon technologies articles from the *Science Citation Index Expanded (SCI-E) database* of *Web of Science database (WOS)*. Due to more standardized and consistent records than other database, *WOS* database has been widely used in related researches (other database can also be used to reveal new findings, but in this paper, we focus on the discoveries from SCI-E database). Bibliographic coupling method is employed to construct sliding window analysis, based on highly-cited articles. And then cluster analysis is utilized to reveal low-carbon technologies research fronts and its evolution trends (2007–2016). Based on the findings from data driven investigation, the paper proposes the policy implications for development of low-carbon technologies. The research framework is shown in Fig. 1.

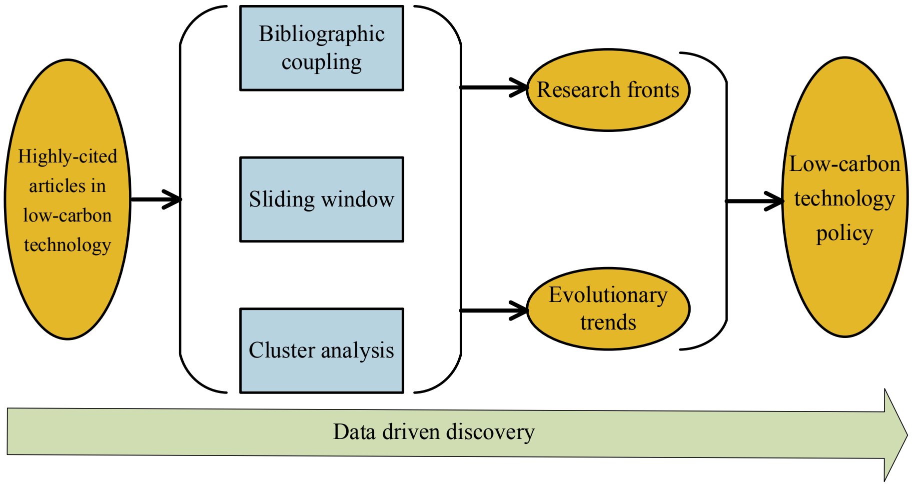


Fig. 1. Research framework.

3.2. Bibliographic coupling method

Bibliographic coupling, a common tool to detect research fronts, was first introduced by Kessler (Kessler, 1965, 1963a; 1963b). Kessler proposed the definition of bibliographic coupling: two articles have a common third article in their bibliographies. The coupling strength of the two articles is determined by the number of cited articles they share. And the higher coupling strength, the more correlation between the two articles. In this paper, bibliographic coupling is employed to effectively identify the low-carbon technology literature with high correlation. The steps of bibliographic coupling are shown in Fig. 2.

Step 1 Constructing the original citation network

In this paper, the object of bibliographic coupling is a set of literature in the field of low-carbon technologies. These documents (Citing articles) and its references (Cited articles) constitute the original citation network. For example, in the Fig. 2, the article 1 refers to six articles including A, B, C, D, E and F.

Step 2 Calculating the original citation matrix

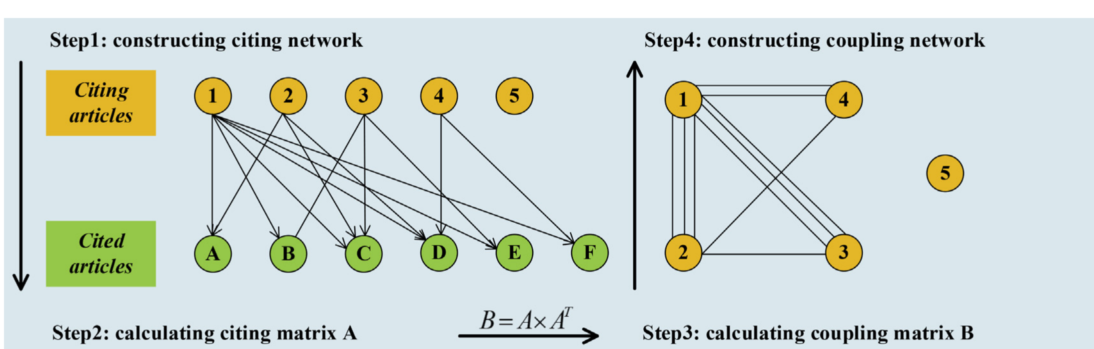
Based on the original citation network in the first step, the relationship between LCT citing articles and cited articles is expressed as matrix, namely the original citation matrix. For example, article 1 cites to article A. Then The element at row 1, column 1 of matrix is 1. If there is no citation relationship, the corresponding element value equals 0.

Step 3 Calculating bibliographic coupling matrix

The paper defines the original citation matrix as A, and calculates $B = A \times A^T$ to get the bibliographic coupling matrix B. The elements at rows and columns 1 of matrix are citing articles, and the elements value reflects the coupling strength between two citing articles. E.g. article 1 and article 2 refer to three common cited articles A, C, and D, so the element at row 1, column 2 of matrix B equals 3.

Step 4 Building bibliographic coupling network

Based on the coupling matrix B obtained in step 3, the coupling relationship between LCT documents (citing articles) is expressed as network form, namely bibliographic coupling network. For example, the coupling strength of article 1 and article 2 equals 3, so there are 3 links between the two nodes.



	Article A	Article B	Article C	Article D	Article E	Article F
Article1	1	1	1	1	1	1
Article2	1	0	1	1	0	0
Article3	0	1	1	0	1	0
Article4	0	0	0	1	0	1
Article5	0	0	0	0	0	0

	Article1	Article2	Article3	Article4	Article5
Article1	6	3	3	2	0
Article2	3	3	1	1	0
Article3	3	1	3	0	0
Article4	2	1	0	2	0
Article5	0	0	0	0	0

Fig. 2. Bibliographic coupling process.

3.3. Cluster analysis

Cluster analysis was first introduced to anthropological studies by Driver and Kroeber in 1932 (Bailey, 1994). Clustering is very popular in the field of data mining and knowledge discovery with the task of grouping a set of objects. Under the clustering process, objects in the same group (called a cluster) are more similar (in some sense or another) to each other than to those in other groups (clusters). To better understand the research fronts of low-carbon technologies, cluster analysis was employed to reveal the different research types from a mass of LCT documents.

In this paper, the association strength (namely similarity) between two LCT documents (nodes i and j) is given by:

$$L_{ij} = \frac{2hb_{ij}}{w_i w_j} \tag{1}$$

$$w_i = \sum_j b_{ij} \tag{2}$$

$$h = 0.5\sum_i w_i \tag{3}$$

where b_{ij} denotes the weight of the edge between nodes i and j, where $b_{ij} = 0$ if there is no link between two nodes. In this paper, all networks are undirected, and we always have $b_{ij} = b_{ji}$. w_i (w_j) denotes the total weight of all edges of node i (node j). And h denotes the total weight of all edges in the network.

Given the time-saving, better understanding, interactive and dynamic visualizations, smart local moving algorithm is utilized to assign the nodes to clusters by maximizing the function (van Eck and Waltman, 2014; Waltman and van Eck, 2013):

$$T(z_1, \ldots, z_n) = \sum_{i<j} \theta(z_i, z_j)(L_{ij} - \alpha) \tag{4}$$

where n denotes the number of nodes in the LCT documents network. z_i denotes the cluster to which node i is assigned. Where $\theta(z_i, z_j)$ equals 1, if $z_i = z_j$ and 0 otherwise. Parameter α (namely resolution, a non-negative value) is employed to adjust the number of clustering, reflecting the detail level of the cluster results. This study applies cluster analysis provided by VOSviewer.

To enhance the reliability and credibility of research results, the expert consultation process is introduced. After clustering process, two subject experts in low-carbon technologies field join the research to verify the titles, abstracts and keywords in the LCT documents and assist in assigning the research fronts to these clustering. After the evolution trends of LCT research fronts are obtained, consultation with fellow experts is also conducted to validate the results.

3.4. Data collection and processing

3.4.1. Low-carbon technology knowledge domains

This paper chooses the LCT definition from NDRC. In the document *Catalogue of low carbon technologies promoted by the state (third batch)* (National Development and Reform Commission (NDRC), 2016), the national development and reform commission (NDRC) of the People's Republic of China categorized the low-carbon technologies into three types, according to the stages of the control process, including zero-carbon technologies, carbon reduction technologies and carbon storage technologies. The LCT knowledge domains are shown as Fig. 3. As a process control technology, Carbon reduction technologies include energy-saving and efficiency technologies, raw material substitution or reduction of technologies, fuel substitution technologies and other emissions reduction technologies. Carbon storage technologies are used as the terminal control technology, including “carbon capture, utilization and storage” (CCUS) technologies, and carbon sequestration in biological engineering. Zero-carbon technologies are the source control technology, including renewable energy and civilian nuclear power technologies. On referring to the technology classification frame from IEA, renewable energy technologies include biomass energy technologies, geothermal energy technologies, hydro power generation technologies, ocean energy technologies, solar energy technologies and wind energy technologies.

Given the actual performance of the data set, some studies focus on the technology management in the LCT documents, “technology management” is added to the above knowledge domain frame.

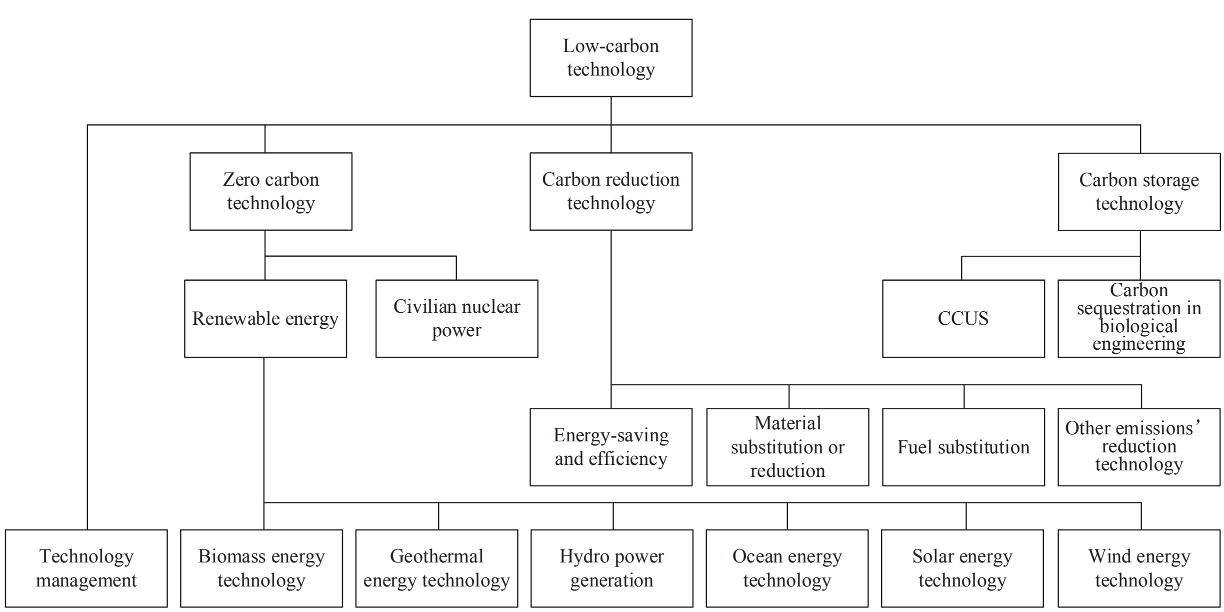


Fig. 3. Low-carbon technology knowledge domains chart.

Table 1
Low-carbon technology literature and highly cited articles (2007–2016).

Year	Original articles	Related articles (percentage)	Extracted articles	Times cited threshold
2007	63	43(68.25%)	20	19
2008	84	72(85.71%)	21	21
2009	85	70(82.35%)	22	19
2010	83	66(79.52%)	20	19
2011	85	70(82.35%)	22	10
2012	100	75(75%)	20	11
2013	117	84(71.79%)	22	11
2014	113	80(70.80%)	21	13
2015	123	99(80.49%)	21	6
2016	156	142(91.03%)	35	2
Total	1009	801(79.39%)	224	–

After identifying the relevant research fronts using sliding window technique, the research fronts are categorized into these domain classifications for future analysis.

3.4.2. Highly-cited documents of LCT

The highly-cited documents related to low-carbon technologies are the basis for exploring the evolution and trends in the research fronts. "Highly-cited documents" refers to the top 20 most cited articles in LCT field annually from 2007 to 2016. Documents with the same number of citations as the document ranked 20th are also included in this research. This paper allocates bibliographic coupling data files into five overlapping sliding windows: 2007–2012, 2008–2013, 2009–2014, 2010–2015, 2011–2016.

In this research, the search terms utilized in *SCI-E* database of *WOS* include "low carbon technology", "low carbon technologies", "low carbon energy technology", "low carbon energy technologies", "clean technology", "clean technologies", "cleantech", "Environmental technology", "Environmental technologies", "envirotech", "greentech", "Sustainable engineering", with the publication date set from 2007 to 2016, and the "Article" document type exclusively. This study completed raw data retrieval on April 22, 2017.

3.4.3. High coupling strength articles of LCT

Weakly correlated articles with lower frequency of coupling strength may lead to less meaningful results and bring some interferences (Culnan, 1986). To avoid meaningless results and interferences, this study concentrates on the highly-coupled articles. The paper follows the skills proposed by previous studies (Chen and Morris, 2003; Morris and Boyack, 2005; Yang et al., 2008), setting five as the ideal threshold of coupling strength. To better categorized the research fronts of low-carbon technologies, the clustering data files are compiled by filtering out the documents whose coupling strength less than 5.

4. Results and discussions

4.1. LCT-related documents and highly-cited articles

In this study, the number of LCT related articles and the number of highly-cited articles annually are shown as Table 1.

Based on the bibliographic data retrieved from *SCI-E* database in *WOS*, the total number of original papers in LCT field in the 10-year period amounts to 1009. After filtering by the titles, abstracts, keywords and authors' information, 801 LCT-related documents are identified, accounting for 80% of the original documents. According to the definition of highly-cited articles in this study, the articles with the top 20 cited times annually are extracted for further analysis. As shown in Table 1, noting that 20th high cited documents may exist more than one articles, apart from 2008 (21 documents), 2009 (22 documents), 2011 (22 documents), 2013 (22 documents), 2014 (21 documents), 2015 (21 documents), and 2016 (35 documents), the number of highly-cited articles annually is 20, with a total of 224 documents. In the process of extracting highly-cited articles, the highest threshold value of cited times is 21 in 2008, and the lowest threshold is 2 in 2016. Compared to the articles from earlier years, those published in 2016 are relatively recent, so the low threshold of cited times is reasonable.

4.2. Bibliographic coupling frequency analysis

This paper compiled the bibliographic coupling data files with 5 sliding windows: 2007–2012, 2008–2013, 2009–2014, 2010–2015, 2011–2016. The bibliographic coupling frequency results is shown as Table 2. The results present that the coupling frequency distribution of different sliding windows are relatively consistent. 0 frequency approximately accounts for 97%, and the articles with 1 pair of coupling strength is approximately 1.3%. There are small proportions of documents whose coupling frequency is greater than 1, with a fairly consistency of proportion distribution in different sliding windows.

To reduce the interferences from the articles with low coupling strength, the paper set five as the ideal threshold of bibliographic coupling strength for exploring. This study follows the strategy of clustering in previous research (Morris et al., 2003; Morris and Boyack, 2005; Yang et al., 2008), extracting the documents with the coupling strength greater than or equal to 5. Under this setting conditions, the results show that the highest 24 pairs in the first sliding window accounting 0.31% of the total. The fifth window have ten pairs highly-coupled documents with the lowest proportion 0.1%.

4.3. Research fronts of low-carbon technologies

After selecting the articles with bibliographic coupling strength greater than 5 for clustering, results are shown in Table 3. In this research, only a small number of highly-cited articles are suitable for each research front, which are the results from data-driven analysis. Through the results, we find that these clustering are meaningful and can be identified as different research fronts. The clustering results in the five sliding windows are shown in Table 3.

4.3.1. Research fronts of LCT in the first window (2007–2012)

Based on the smart local moving algorithm provided by VOS-viewer, clustering technique are employed to perform the data mining process for the highly-cited articles from 2007 to 2012. A total of seven research fronts are identified, as presented in Table 4.

The 7 research fronts include 25 documents which can be classified into three knowledge domains: technology management, fuel substitution, energy-saving and efficiency. Among these, the knowledge domains of fuel substitution have the largest number of

Table 2
Frequency of bibliographic coupling.

Bibliographic coupling frequency	2007–2012		2008–2013		2009–2014		2010–2015		2011–2016	
	pairs	percentage	pairs	percentage	pairs	percentage	pairs	percentage	pairs	percentage
0–4	7726	99.69%	7980	99.74%	7988	99.84%	7864	99.86%	9860	99.90%
0	7566	97.63%	7796	97.44%	7813	97.65%	7709	97.89%	9687	98.15%
1	86	1.11%	107	1.34%	114	1.42%	108	1.37%	130	1.32%
2	34	0.44%	40	0.50%	34	0.42%	32	0.41%	30	0.30%
3	32	0.41%	31	0.39%	19	0.24%	11	0.14%	9	0.09%
4	8	0.10%	6	0.07%	8	0.10%	4	0.05%	4	0.04%
5–9	19	0.25%	16	0.20%	9	0.11%	6	0.08%	6	0.06%
5	10	0.13%	7	0.09%	2	0.02%	0	0.00%	1	0.01%
6	5	0.06%	5	0.06%	3	0.04%	3	0.04%	3	0.03%
7	0	0.00%	1	0.01%	1	0.01%	2	0.03%	2	0.02%
8	1	0.01%	1	0.01%	1	0.01%	0	0.00%	0	0.00%
9	3	0.04%	2	0.02%	2	0.02%	1	0.01%	0	0.00%
10–14	3	0.04%	1	0.01%	1	0.01%	1	0.01%	0	0.00%
15–19	1	0.01%	3	0.04%	2	0.02%	2	0.03%	2	0.02%
20+	1	0.01%	1	0.01%	1	0.01%	2	0.03%	2	0.02%
total	7750	100.00%	8001	100.00%	8001	100.00%	7875	100.00%	9870	100.00%

Table 3
Cluster results for research fronts.

Cluster results	2007–2012	2008–2013	2009–2014	2010–2015	2011–2016
Articles	25	25	18	15	16
Clusters	7	7	6	6	6
Coupling Pairs	24	21	13	11	10
Coupling strength	193	182	126	131	116

Notes: (1) Compared to the articles from earlier years, those published in later windows are relatively recent, so, after extracting high coupling strength documents, the declining number of articles is reasonable. (2) based on the above reason, the total coupling strength has a decreasing trend over time windows.

Table 4
Research fronts 2007–2012.

Class	Knowledge domain (percentage)	Cluster ID	Number of articles	Research front
1	Technology management (24%)	1	2	Technology transfer
		3	4	Technology diffusion
2	Fuel substitution (60%)	2	9	Ionic liquids
		4	3	Mutually immiscible ionic Liquids
		6	3	Electric vehicle (China)
3	Energy-saving and efficiency (16%)	5	2	Electrocoagulation
		7	2	Magnetic nanoparticles

research fronts, containing ionic liquids, mutually immiscible ionic liquids and electric vehicle (related to China). Besides, fuel substitution ranks the highest with 60% of all documents. For this domain, the ionic liquids is the most prevalent research front, including 9 highly-cited documents.

4.3.2. Research fronts of LCT in the second window (2008–2013)

Based on the smart local moving algorithm provided by VOSviewer, clustering technique are employed to perform the data mining process for the highly-cited articles from 2008 to 2013. A total of seven research fronts are identified, as listed in Table 5.

The 7 research fronts include 25 documents which can be categorized into three knowledge domains: fuel substitution, technology management, energy-saving and efficiency. The domain of fuel substitution contains relative larger number of research fronts. Compared with the results from first window, electric vehicle (related to UK and US) is the research front newly added to the fuel substitution domain. Similarly, fuel substitution ranks the highest with 60% of all documents. For this domain, the ionic liquids is the most prevalent research front, including 9 highly-cited documents.

Table 5
Research fronts 2008–2013.

Class	Knowledge domain (percentage)	Cluster ID	Number of articles	Research front
1	Fuel substitution (60%)	1	9	Ionic liquids
		4	3	Electric vehicle (UK and USA)
		6	3	Electric vehicle (China)
2	Technology management (24%)	2	4	Technology diffusion
		3	2	Technology transfer
3	Energy-saving and efficiency (16%)	5	2	Electrocoagulation
		7	2	Magnetic nanoparticles

Table 6
Research fronts 2009–2014.

Class	Knowledge domain (percentage)	Cluster ID	Number of articles	Research front
1	Fuel substitution (66.7%)	1	6	Ionic liquids
		4	3	Electric vehicle (UK and USA)
		5	3	Electric vehicle (China)
2	Renewable generation (11.1%)	2	2	Critical metals application
3	Energy-saving and efficiency (22.2%)	3	2	Electrocoagulation
		6	2	Magnetic nanoparticles

4.3.3. *Research fronts of LCT in the third window (2009–2014)*

Based on the smart local moving algorithm provided by VOS-viewer, clustering technique are employed to perform the data mining process for the highly-cited articles from 2009 to 2014. A total of six research fronts are identified, as listed in Table 6.

The 6 research fronts include 18 documents which can be categorized into three knowledge domains: fuel substitution, renewable generation, energy-saving and efficiency. The domain of fuel substitution contains a relative larger number of research fronts. Compared with the previous windows, renewable generation is the new knowledge domain, with critical metals application as research front. Critical metals application is a promising research front, including 2 articles, accounting for 11% of the total in this window.

4.3.4. *Research fronts of LCT in the fourth window (2010–2015)*

Based on the smart local moving algorithm provided by VOS-viewer, clustering technique are employed to perform the data mining process for the highly-cited articles from 2010 to 2015. A total of six research fronts are identified, as listed in Table 7.

The 6 research fronts include 15 documents which can be classified into three knowledge domains: carbon capture, utilization and storage (CCUS), renewable generation, and fuel substitution. Compared to the third window, CCUS is a newly added domain with the CCS in power generation as a research front, including 13% articles. For the knowledge domain of renewable generation, electrocatalytic water oxidation is a new research front, containing two documents.

4.3.5. *Research fronts of LCT in the fifth window (2011–2016)*

Based on the smart local moving algorithm provided by VOS-viewer, clustering technique are employed to perform the data mining process for the highly-cited articles from 2011 to 2016. A total of six research fronts are identified, as listed in Table 8.

The 6 research fronts include 16 documents which can be categorized into four knowledge domains: Carbon capture, utilization and storage (CCUS), renewable generation, technology management, and fuel substitution. Compared with the fourth window, technology management has re-emerged to be a main domain. For this domain, technology diffusion is a popular research front, including four documents with the share of 25% in the total.

4.4. *Evolution of LCT research fronts*

This paper employs bibliographic coupling and sliding window technique to identify 11 research fronts. Based on the LCT knowledge domains proposed in Figs. 3 and 4 depicts the above research results in LCT research fronts distributing in 5 knowledge domains: renewable energy, CCUS technologies, energy-saving and efficiency technologies, fuel substitution technologies, technology management. After the process of validation with relevant studies and consultation with some LCT experts, we confirm that results in this study 100% accord with experts' opinions. Besides, research fronts identified from the data-driven process are all recognized as important frontiers in the field of LCT. This study also verifies that the bibliographic coupling is an effective tool to detect the research fronts of low-carbon technologies.

To better understand the changes and trends of LCT research fronts in the recent decade (2007–2016), we compare the research fronts from five sliding windows. Based on the research fronts categorization proposed by Upham and Small (2010), Fig. 5 tracks the evolution paths of research fronts in low-carbon technologies.

Emerging fronts are research fronts who appear in the latter sliding windows. In this study, two kinds of emerging fronts are identified: CCS in power generation and electrocatalytic water oxidation. **Growing fronts** are those with several documents that

Table 7
Research fronts 2010–2015.

Class	Knowledge domain (percentage)	Cluster ID	Number of articles	Research front
1	CCUS (13.3%)	1	2	CCS in power generation
2	Renewable generation (33.3%)	2	3	Critical metals application
		5	2	Electrocatalytic water oxidation
3	Fuel substitution (53.3%)	3	2	Ionic liquids
		4	3	Electric vehicle (UK and USA)
		6	3	Electric vehicle (China)

Table 8
Research fronts 2011–2016.

Class	Knowledge domain (percentage)	Cluster ID	Number of articles	Research front
1	CCUS (12.5%)	1	2	CCS in power generation
2	Renewable generation (31.25%)	2	3	Critical metals application
		6	2	Electrocatalytic water oxidation
3	Technology management (25%)	3	4	Technology diffusion
4	Fuel substitution (31.25%)	4	2	Ionic liquids
		5	3	Electric vehicle (UK and USA)

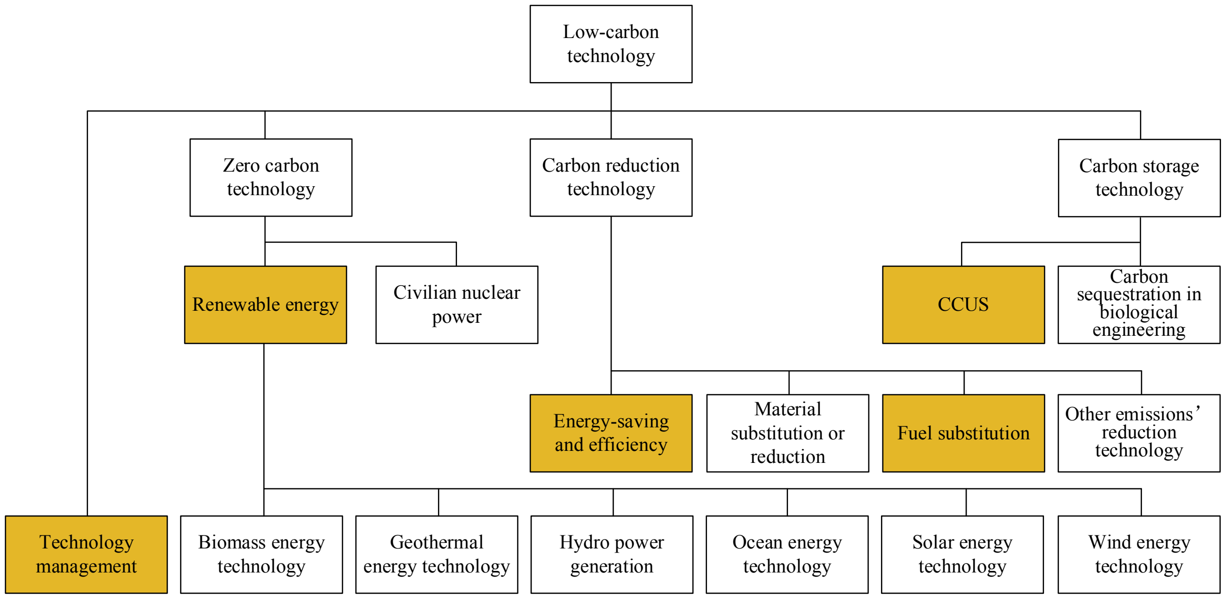


Fig. 4. Knowledge domain map of low-carbon technology research fronts.

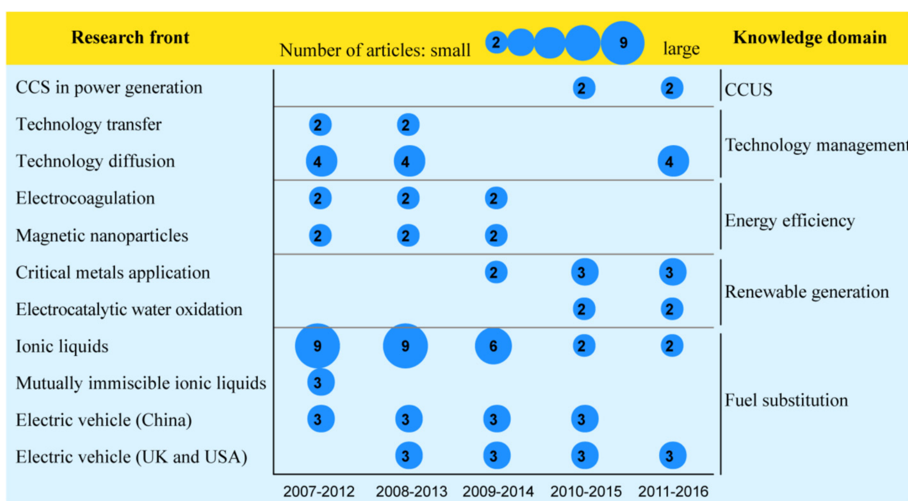


Fig. 5. Low-carbon technology research fronts evolution map.

continues to increase in latter windows. Critical metals application is the only research front in this category. **Stable fronts** are those who maintained the number of documents during the five sliding windows. Electric vehicle researches about China, UK and US fall under this category. In this type of research fronts, each sliding window contains 3 articles. **Shrinking fronts** are research fronts with decreasing numbers of documents throughout the five windows. In this study, ionic liquids is identified as a shrinking front. **Exiting fronts** are those that only appear in the former sliding windows. Four types of exiting fronts are detected in this paper: technology transfer, electrocoagulation, magnetic nanoparticles, mutually immiscible ionic liquids.

Technology diffusion is a re-emerging research front in this study. In the first, second and fifth sliding window, there are 4 articles in each window. But this research front disappears in the third and fourth sliding window. Compared with most research fronts, the research front of technology diffusion contains more documents. This type of evolution path reveals that technology diffusion is an important and fresh research issue with the emergence of new technologies.

In summary, five LCT knowledge domains are identified in this study. The domain of CCUS contains one emerging research front. The knowledge domain of technology management includes one exiting research front. And the domain of energy-saving and efficiency includes two exiting research fronts. The knowledge domain of renewable generation contains one growing and one emerging research fronts. The domain of fuel substitution contains one shrinking, one exiting and two stable research fronts.

5. Conclusions and policy implications

This paper proposes a research framework integrating LCT domains and the bibliometric coupling with sliding window technique to explore the LCT research fronts and its evolution in recent decade (from 2007 to 2016). The conclusions are shown as follows.

(1) **CCUS and renewable generation are promising domain in the low-carbon technology field.** It can be seen from the

Fig. 4 that five knowledge domains are identified in this paper: CCUS, technology management, energy-saving and efficiency, renewable generation, fuel substitution. Among these, the domain of CCUS and renewable generation include all the emerging and growing research fronts, which shows a promising future in these two areas.

(2) **CCS in power generation and hydrogen production from water electrolysis are emerging research fronts of LCT.** As shown in Fig. 5, the research fronts are explored in this study: CCS in power generation, technology transfer, technology diffusion, electrocoagulation, magnetic nanoparticles, critical metals application, electrocatalytic water oxidation, ionic liquids, mutually immiscible ionic liquids, electric vehicle. Among these, CCS in power generation and electrocatalytic water oxidation (mainly applied to generate hydrogen) belong to the type of emerging research fronts, showing that these two fields are the most cutting-edge sector in the LCT and are leading the trends for future research and development.

(3) **Bibliographic coupling is an effective tool to detect and track the research fronts of LCT.** To better identifying, the process is conducted in this order: extracting highly-cited articles, bibliographic coupling analysis, extracting highly-coupled articles with high coupling strength, clustering, finally interpreting the clustering results by subject experts' consultation. After verification and consultation, five knowledge domains and eleven research fronts are identified in this study. Based on the supports from qualitative and quantitative evidence, this research confirms that the data-driven discovery is highly consistent to the expert opinions, and bibliographic coupling is useful in research fronts detecting in the field of low-carbon technologies.

The policy implications of this paper are presented below.

(1) **Enhancing the research and development in the field of CCUS and renewable energy technologies.** In the future science planning and policy making, the strategy layout of CCUS and renewable energy technologies should be the focus, especially CCS (CCUS) applications in the power generation and hydrogen production from water electrolysis.

(2) **Developing an efficient and flexible system for frontiers detecting in the field of low-carbon technologies.** This study confirms that bibliographic coupling is an effective tool to identify the research fronts of LCT. For better accuracy and intelligence, co-citation, co-words, and patents mining et al. should be employed. Besides, it may be helpful to collaborate with proper mathematical predicting models and a team of experts in the designated field, to propose integrated detecting solutions combining qualitative and quantitative methods with high efficiency and flexibility and develop an integrated system for LCT frontiers detecting.

(3) **Establishing a long-term mechanism for monitoring global low-carbon technologies.** Timely identifying LCT frontiers, foresight analysis and strategic layout of these frontiers, are of great significance for a country to carry out sustainable development and enhance the competitiveness of energy science and technology. In most developed countries, such as US and European countries, monitoring and insight in the field of LCT are actively constructed. Especially, Japan has carried out 10 times science and technology survey (the 10th survey was completed in 2015) to explore and analyze the advanced clean energy technologies in deep. Even some developing countries are also paying attention to the development and layout in low-carbon technologies to follow the global trends. Therefore, it is most essential to establish a long-term mechanism for the LCT frontiers monitoring, to act as a forerunner for scientists and policy-makers. There are some constructive measures including regularly releasing LCT frontiers, depicting LCT long-term roadmap, and monitoring the relationship between LCT and economy development.

There are two expanded points for the further research. (1) exploring the fusion methods of patent data and bibliographic data of low-carbon technologies, to mine more multi-source and heterogeneous data. (2) based on the findings from this study, focusing on CCUS technology and hydrogen production from water electrolysis technology, to carry out the tech mining and monitoring.

Actually, these LCT fronts and its evolution are dynamic process. For example, these exiting fronts in this paper can be hot if there are some important innovations in the fields. Based on the limitation, we will monitor the LCT fronts in the further research to master the latest state.

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