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A Study on the Evolution of Carbon Capture and Storage Technology Based on Knowledge Mapping

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Abstract: As a useful technical measure to deal with the problem of carbon dioxide (CO_2) emissions, carbon capture and storage (CCS) technology has been highly regarded in both theory and practice under the promotion of the Intergovernmental Panel on Climate Change (IPCC). Knowledge mapping is helpful for understanding the evolution in terms of research topics and emerging trends in a specific domain. In this work knowledge mapping of CCS technology was investigated using CiteSpace. Several aspects of the outputs of publications in the CCS research area were analyzed, such as annual trends, countries, and institutions. The research topics in this particular technology area were analyzed based on their co-occurring keyword networks and co-citation literature networks, while, the emerging trends and research frontiers were studied through the analysis of burst keywords and citation bursts. The results indicated that the annual number of publications in the research field of CCS technology increased rapidly after 2005. There are more CCS studies published in countries from Asia, North America, and Europe, especially in the United States and China. The Chinese Academy of Sciences not only has the largest number of publications, but also has a greater impact on the research area of CCS technology, however, there are more productive institutions located in developed countries. In the research area of CCS technology, the main research topics include carbon emissions and environmental protection, research and development activities, and social practical issues, meanwhile, the main emerging trends include emerging techniques and processes, emerging materials, evaluation of technological performance, and socioeconomic analysis.

Keywords: carbon capture and storage; knowledge mapping; technological evolution; CiteSpace

1. Introduction

1.1. The Significance of Carbon Capture and Storage Technology

As one of the most significant components of long-lived anthropogenic greenhouse gases (GHGs), carbon dioxide (CO_2) may contribute to long-term global warming. During the period of 1959–2008, on average, the CO_2 emissions were about 43% of the total emissions every year. In order to control global warming, it is essential to achieve the stabilization of CO_2 concentrations [1]. To capture and sequestrate the carbon dioxide which is called carbon capture and storage (CCS) technology, has been regarded as an effective way to reduce the emissions of CO_2 [2]. CCS technology is really a set of technologies, which normally consists of four elements, which are capture, compression, transportation, and storage. This significant technology can not only decrease emissions of carbon dioxide generated from the utilization of fossil-based energy by more than 65% [3], but also provide an increasingly-important hedge for fossil fuels energy; moreover, this technology can responsible for about 16.67% of total reductions of carbon dioxide emissions required by 2050 [4]. As a promising technology to deal with global warming, CCS technology will be of great importance to decrease the CO_2 emissions [5].

Since at least 2005, when a special investigation on CCS technology was released by the IPCC [6], international institutions (International Energy Agency, IEA) and some developed countries in North America (i.e., the United States and Canada) and Europe (i.e., the United Kingdom and Norway) have begun to invest in and deploy CCS projects, and these projects include eight large-scale integrated projects around the world in 2013 and 14 large-scale projects in 2015 [7].

1.2. The Importance and Application of Knowledge Mapping

Against the backdrop of the knowledge economy, knowledge has become the most valuable parts of intangible assets for most entities [8], since the effective management of knowledge will be favorable to the development of science and technology [9]. Organizations constantly utilize their own knowledge to seek chances to improve their innovative activities. Knowledge management can be an effective measure to deploy knowledge assets [10]. The capabilities of knowledge management could help a firm improve its efficiency in using resources and the performance of technological innovation [11]. Knowledge management can contribute to understanding the situation and gaps of different researchers/research institutions, and define agendas for future research [12].

However, there is usually a knowledge gap between the knowledge what has been already known and the knowledge in practical application, and this gap is particularly important and should be faced when a company wants to develop a new product or process [13]. It is necessary for companies to know the mechanisms whereby knowledge is created and how knowledge can be used at different levels, such as technological R&D, institution and policy, and more. Therefore, knowledge mapping could help researchers or companies to know the situation and trends of knowledge flow and identify the existing gaps [14]. Knowledge mapping, also called knowledge representation, is a process in which a schematic representation of knowledge is created [15]. During the activities of knowledge management in an organization, knowledge mapping is a starting point of knowledge management. It can be a significant tool to obtain and communicate the explicit knowledge, meanwhile, it also can serve as a pointer to the organizations who own the implicit knowledge [16]. In recent years, knowledge mapping has shown increasing interest in the topic of knowledge management [8].

Scientometrics is one of the ways to realize knowledge mapping. It is a quantitative analysis about a process, as well as input and output of scientific and technological activities to understand the knowledge mapping of scientific fields and developing statuses in relevant scientific and technological domains based on the methods of computing technology and social statistics [17]. In recent years, knowledge mapping has been investigated using scientometrics. Mercuri et al. [18] applied the scientometric approach to show the global distribution of microbial fuel cell technology and uncover the scale of application of the technology. Montoya et al. [19] used bibliometric analysis techniques to investigate the current situation and future trends, as well as dynamic changes in the energy field in Spain. Konur [20] assessed the main developing trends and problems in the technological field of the algae and bio-energy based on an investigation of scientometric analysis.

According to the existing literature the number of publications in the CCS research area has experienced a continuous and stable growth. Meanwhile, given the great importance of knowledge mapping, it is urgent and necessary to acquire a correct understanding of the current situation and developing trends, as well as the hot spots and fronts of CCS research area by using the analysis tool of knowledge mapping, which is the objective of this paper. This paper will be organized as follows: Section 2 describes data collection and the knowledge mapping research software, Section 3 analyzes the results. The discussion is described in Section 4. Section 5 summaries the conclusions, and finally, Section 6 presents the research limitations.

2. Methodology

2.1. Knowledge Mapping and CiteSpace

With the rapid popularity and development of Information Technology (IT), is has become of great significance in knowledge management activities [21]. In this paper, CiteSpace was employed as a useful tool to obtain the information about knowledge mapping of CCS technology. CiteSpace is a freely available Java application software, developed by the Chen research group at Drexel University (V. 5. 0. R7, SE, 32-bit, Philadelphia, PA, USA). It was designed as an effective tool for mapping the knowledge of scientific literature and helping researchers to find the critical points in a specific area. Furthermore, some special analysis functions related to concepts of centrality of CiteSpace, such as detection analysis of bursts and in-between centrality analysis [22], will be used to visualize knowledge mapping of CCS technology, including analyzing the distribution of documents, identifying the research frontiers, detecting the emerging trends and abrupt changes, and more.

Since CiteSpace became available on 13 September 2004, not only the software service provider [23], but also many other researchers have used CiteSpace to carry out studies regarding knowledge management and knowledge mapping. Yu and Xu [24] used CiteSpace to study the status quo and developing trends in the research area of carbon emission trading. Chen and Guan [25] applied CiteSpace to investigate general development and research performance of emerging nano-biopharmaceuticals. Based on CiteSpace, Lin, Wu, and Hong [26] studied hotspots and future trends of ecological assets research.

2.2. Data Collection

To investigate the evolution of CCS technology from the perspective of knowledge mapping of CCS studies is the major objective of this paper. Literature collection is the essential basis for knowledge mapping. The bibliometric data were searched from the Web of Science in this study. The bibliometric search strategy can be described as follows. The timespan was "all years", the database was "Web of Science Core Collection", the topic was "carbon capture and storage technology". As seen in Figure 1, there are two groups of keywords in the search terms. "Group 1" is the keywords related to "CO_2", including "carbon", "CO_2" and "carbon dioxide". "Group 2" is the keywords related to "capture and storage", such as "captur*", "storag*", "sorbent", "transportation", "adsorption", "separation", and "adsorbent". The literature will be considered as our research sample if its title includes any keyword in both "Group 1" and "Group 2". All the studies were converted into a specific format to meet the requirements of CiteSpace software. It should be noted that, taking the accuracy and relativity of the sampled literature into account, this paper only collected literature using the "title", but not the "abstract" or "keywords". However, it should be admitted that the research studies, to some extent also reflected the research situation of CCS technology and had the academic value of their own in the research area of CCS technology if their "abstract" or "keywords" appeared the retrieval terms of this research topic. However, these articles had little impact on the study results.

Under the retrieval conditions and strategy described above, a total number of 10,180 CCS publications were searched on 26 January 2018. There are 12 various literature types in the final database, such as articles (9686), meeting abstracts (610), proceeding papers (533), reviews (385), news items (190), editorial materials (167), and corrections (56), as well as letters (44), and more. Among them, the major literature type is article, which accounted for 94.74% of the total literature. Taking into account the validity and representation of the literature, and in order to eliminate the "information noise" of the database, articles were included in further investigation and the other types of literature were excluded. The flow diagram of sample literature selection process is presented in Figure 1.

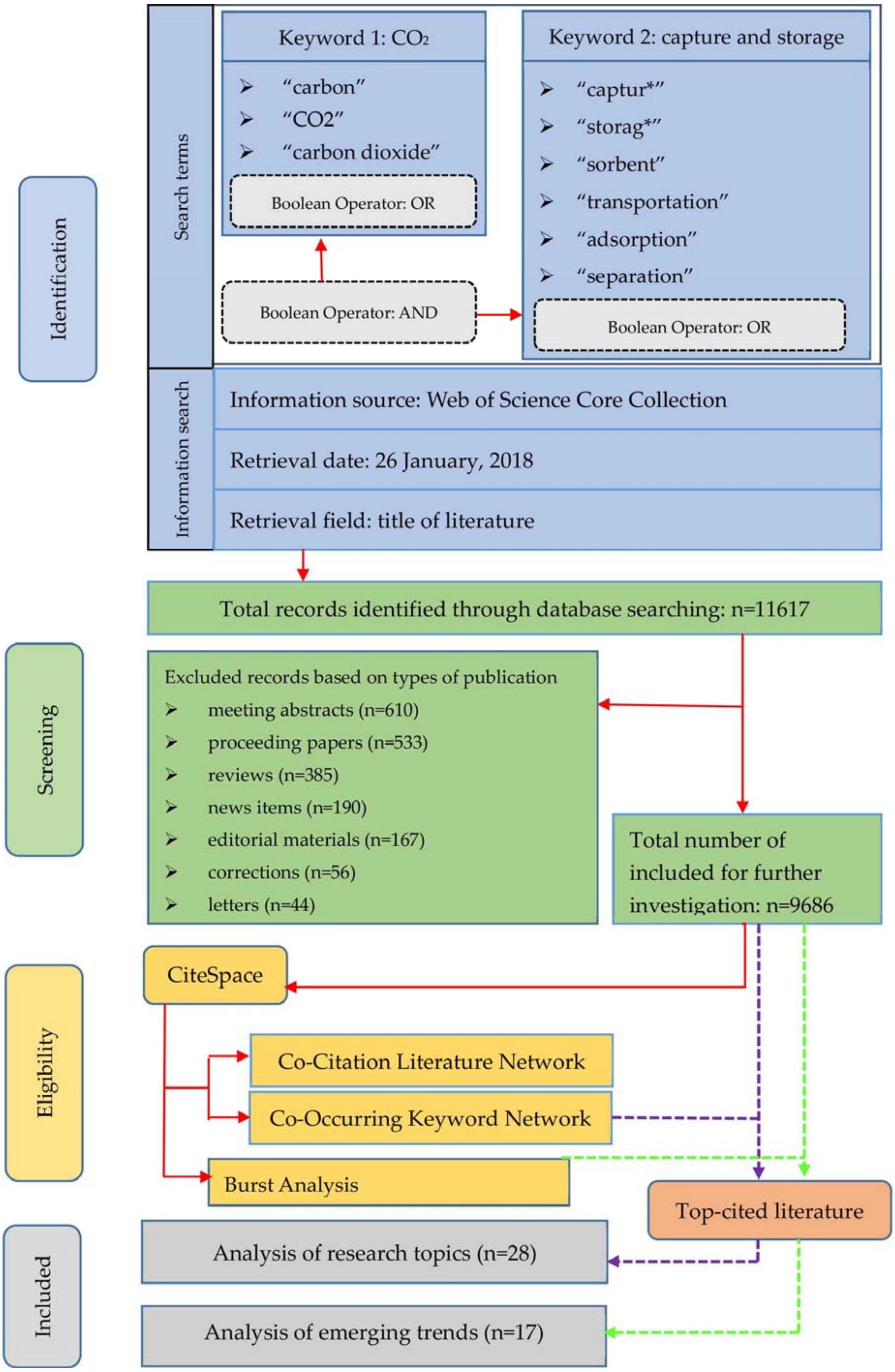

Figure 1. Process of literature retrieval and selection.

3. Analyses and Results

3.1. Basic Analysis of Publication Outputs

3.1.1. Annual Trend Analysis

The annual total publications during the study period is shown in Figure 2. The annual number of articles in the study area of CCS technology increased steadily from 60 in 2000 to a peak of 1372 in 2016. Additionally, a polynomial regression equation was employed to describe the relationship between literature publications and the year of publishing. The regression equation is $y = 1.6511x^2 + 25.187x$, where x represents the number of year since 2000 and y represents the publication number. During the given time period, the number evolution of published articles can be split into two parts. The first period is before 2006. The annual number of documents in the research area of CCS technology increased gradually and fluctuated during this time. Correspondingly, the second period is after 2006, and the annual number of publication in the research field of CCS technology increased rapidly. It should be noted that, because the terminal date for downloading literature was 26 January 2018, and there is a time lag for literature to be indexed by a database, the data for 2017 and, especially, 2018 would be incomplete.

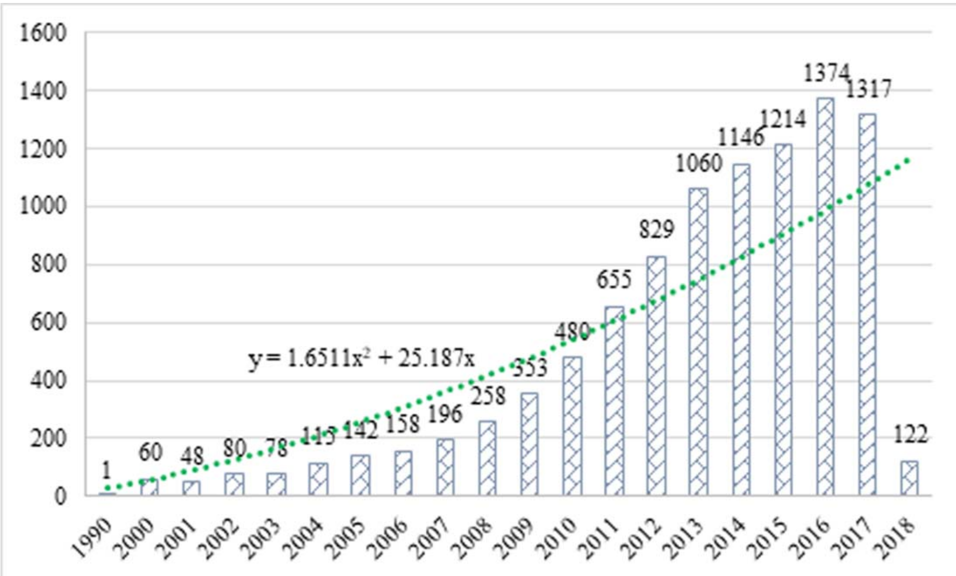

Figure 2. Annual number of publications in the carbon capture and storage (CCS) technology area.

3.1.2. Country Analysis

The different number of publications in every country reflects to some extent the different degrees of concern regarding the research on CCS technology. Table 1 lists the top 20 most productive countries in the research area of CCS technology. It can be seen that China ranked first, with 2455 articles, accounting for 25.356% of the total publications, which was followed by the USA with 2197 articles accounting for 22.682% of the total. Other productive countries included the UK (655), South Korea (600), and Australia (578), as well as Canada (509). Moreover, among the top 20 countries, there are nine European countries, seven Asian countries, two North American countries, one South American country and one Oceania country.

Table 1. Top 20 most productive countries in carbon capture and storage (CCS) research area.

Countries	Number of Publications	Percentage of Total Number	Countries	Number of Publications	Percentage of Total Number
China	2455	25.356%	Japan	322	3.324%
USA	2197	22.682%	Italy	306	3.159%
UK	853	8.807%	Norway	301	3.108%
South Korea	600	6.195%	Netherlands	292	3.015%
Australia	578	5.967%	Sweden	201	2.075%
Canada	509	5.255%	Iran	198	2.044%
Germany	476	4.914%	Poland	152	1.569%
Spain	437	4.512%	Malaysia	152	1.569%
France	381	3.934%	Singapore	146	1.507%
India	328	3.386%	Brazil	141	1.456%

Note: the number of publications of China contains 155 articles from Taiwan and the number of publications of the UK contains 198 articles from Scotland.

3.1.3. Institution Analysis

The main researchers and their research capabilities in a specific domain can be identified from the statistical and analytical perspectives of publications. Table 2 lists the top 20 most productive institutions in the research field of CCS technology. What can be seen is that the Chinese Academy of Sciences of China (CAS of China) had the most CCS articles, with 514 publications, followed by another Chinese institution, Tsinghua University, with 122 publications, and the third and fourth places are the institutions from the United States, the University of California, Berkeley (UC Berkeley, 118) and the U.S. Department of Energy (DOE, 105). Among the most productive institutions listed in Table 2, there are six institutions from China, five institutions from the U.S., and three institutions from the United Kingdom.

Table 2. Top 20 most productive institutions in the CCS research area.

Institution	Country	Number of Publications	Freq.	Centrality
Chinese Academy of Sciences	China	514	431	0.35
Tsinghua University	China	122	121	0.06
University of California, Berkeley	USA	118	109	0.15
U.S. Department of Energy	USA	105	100	0.05
Tianjin University	China	99	92	0
Georgia Institute of Technology	USA	98	92	0.02
University of Texas at Austin	USA	98	94	0.05
Zhejiang University	China	98	92	0.02
Consejo Superior de Investigaciones Cientificas (CSIC)	Spain	96	84	0.01
Norwegian University of Science and Technology	Norway	95	87	0.03
National University of Singapore	Singapore	93	88	0.03
Monash University	Australia	87	86	0.04
University of Queensland	Australia	87	79	0.01
The University of Edinburgh	UK	86	78	0.08
Imperial College of Science, Tech & Medicine	UK	86	80	0.08
University of Nottingham	UK	82	76	0.02
Oak Ridge National Laboratory	USA	80	63	0.08
The University of Melbourne	Australia	78	67	0.03
Huazhong University of Science and Technology	China	77	75	0.01
Southeast University	China	76	68	0

Note: the number of publications of Chinese Academy of Sciences contains 78 articles from the University of Chinese Academy of Sciences.

In terms of frequency, the CAS of China is at the top with 431, and then comes Tsinghua University (121), UC Berkeley ranks the third with 109. These institutions with high cited frequency had a greater impact on the research field of CCS technology. In terms of centrality, the top five institutions were the Chinese Academy of Sciences (0.35), the University of California, Berkeley (0.15), and the University of Edinburgh (0.08), the Imperial College of Science, Tech & Medicine (0.08), and Oak Ridge National Laboratory (0.08). Institutions with high centrality means that these institutions are significant in

CCS research area. It is worth noting that the institutions from developed countries have a higher value in both cited frequency and centrality, which implies that the institutions of developed countries discovered more significant technologies and have stronger innovative capabilities in this specific domain. Generally speaking, the institutions listed in the table paid more attention to the research on CCS technology, obtained more scientific works, and had a relative better research foundation. Figure 3 shows the co-occurring network of institutions in the domain of CCS technology. The different size of circle nodes represent different number of documents published by each institution and, the larger the note size of the institution, the more literature it published, for example, the circle nodes of CAS of China, DOE of the U.S., Monash University and CSIC, etc., are obvious larger in the figure, and these institutes also published more articles in the domain of CCS technology. Moreover, it also can be seen that among the most significant institutions, they were linked tightly each other, which led to more important notes (institutions) having a higher centrality. This reflects, not only the structure and position of research institutions in the domain of CCS technology, but also the collaboration pattern for productive institutions.

Figure 3. Mapping on the co-occurring network of institutions.

3.2. Research Topics Analysis

3.2.1. Co-Citation Literature Network

Literature analysis is one of the primary contents of knowledge mapping. The literature references can be analyzed from the perspective of visualization. The network of the literature co-citation in the research area of CCS technology can be developed using CiteSpace, which is shown in Figure 4. The nodes are the literature topics and the lines illustrated as various colours in the figure represent that the co-citation frequency of lines reached the threshold. What is shown that the important publications were tightly linked, which means that those studies concerned about similar research topics. Some previous studies represent the major research contents in this specific domain, while the core research concepts received a progressive and continuous development. Furthermore, the nodes separated from the core literature represent some new research branches, especially the new technical means and practice of this particular area.

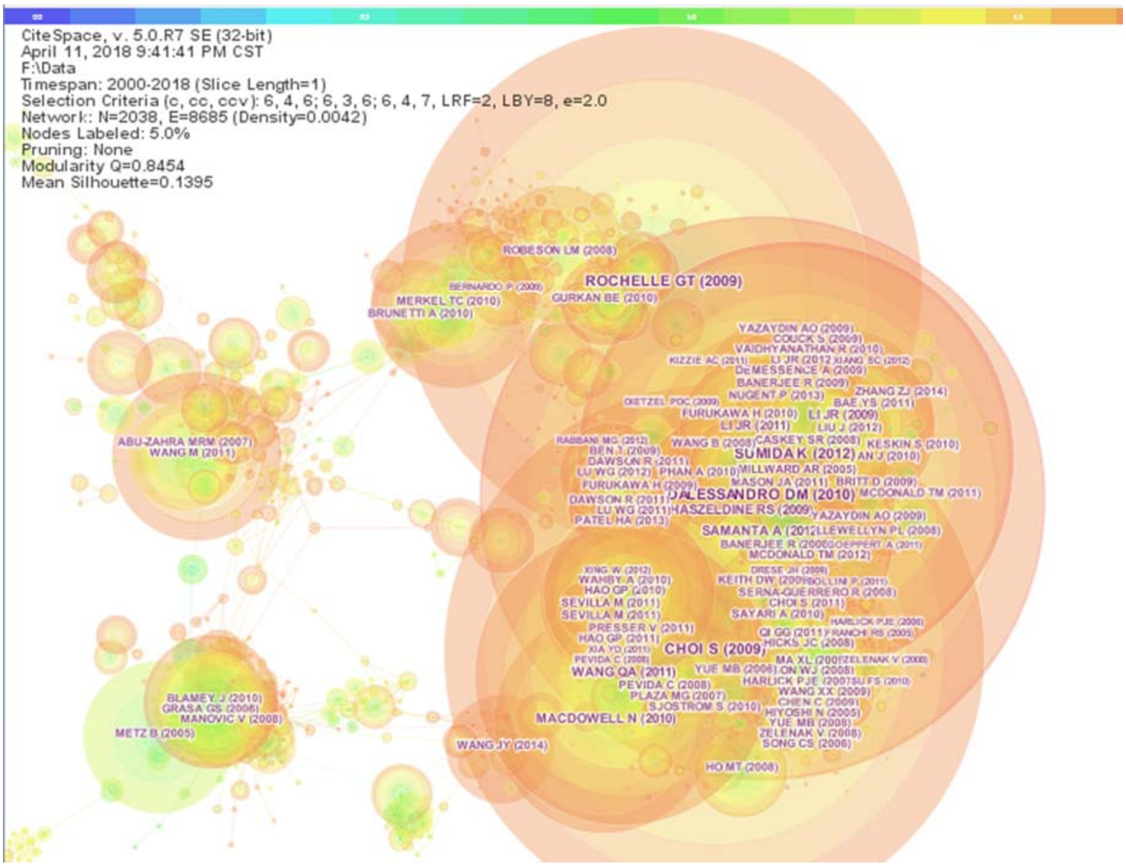

Figure 4. Co-citation literature network of CCS research area.

Table 3 lists the Top 20 references in CCS research area according to their frequency of citation. They were selected for analysis by CiteSpace. It can be seen that the literature was the most frequently-cited article and the frequency was 656, in which latest advances and developing trends in CO_2 separation were discussed, and a particular attention was also paid on advances in the technical area of metal-organic frameworks [27]. Then, the literature ranked 2nd has a frequency of 625, in which CO_2 adsorption behaviors were described while the current available CO_2 adsorbents and their significant features were also presented [28].

In terms of the source of the highly cited literature in the research area of CCS technology, there were three documents published in *Energy & Environmental Science* (Impact factor: 29.518). In addition, there are two documents published in *Science*. One of the references was published in *Science*, with a frequency value of 603, in which the process and solvent improvements of amine scrubbing to separate CO_2 from coal-fired power plants were investigated [29]. The other article published in *Science* has a frequency value of 272, in which several hurdles, such as technology, commercialization, and politics related to CCS technology were addressed [2]. There is one paper published in *Nature* with frequency value of 180, in which the technological applications about the metal-organic materials (MOMs) were reported [30]. The only one book listed in the table is edited by Metz B. [31] and published in 2005. This book has important influences on both academic and practice in CCS domain. It not only described the situation and challenges of carbon dioxide emissions, analyzed the technological contents of CCS, but also discussed the problems related to the technical applications of CCS.

Table 3. Top 20 references in the research area of CCS technology.

Authors	Literature Information	Freq.	Year
D'Alessandro DM	Angew Chem Int Edit, V49, P6058	656	2010
Choi S	Chemsuschem, V2, P796	625	2009
Rochelle GT	Science, V325,P1652	603	2009
Sumida K	Chem Rev, V112, P724	505	2012
Wang QA	Energ Environ Sci, V4, P42	347	2011
Figueroa JD	Int J Greenh Gas Con, V2, P9	329	2008
Samanta A	Ind Eng Chem Res, V51, P1438	299	2012
Yang HQ	J Environ Sci-China, V20, P14	278	2008
Haszeldine RS	Science, V325, P1647	272	2009
Macdowell N	Energ Environ Sci, V3, P1645	245	2010
Li JR	Coordin Chem Rev, V255, P1791	225	2011
Li JR	Chem Soc Rev, V38, P1477	209	2009
Millward AR	J Am Chem Soc, V127, P17998	195	2005
Merkel TC	J Membrane Sci, V359, P126	192	2010
Wang M	Chem Eng Res Des, V89, P1609	191	2011
Caskey SR	J Am Chem Soc, V130, P10870	190	2008
Hao GP	Adv Mater, V22, P853	190	2010
Boot-Handford ME	Energ Environ Sci, V7, P130	187	2014
Nugent P	Nature, V495, P80	180	2013
Metz B	Book	180	2005

Note: Taking the large number of literature into account, we just selected the Top 20 references for analysis.

3.2.2. Co-Occurring Keyword Network

The keywords can reflect the important concepts or core contents of a document. The research topics and hotspots can be detected using the keyword co-word analysis of CiteSpace [32]. The position, collaboration, and connection of the keywords of the references in the research area of CCS technology can be investigated using a keyword co-occurring network map. Figure 5 shows the co-occurring network using keywords as "node type".

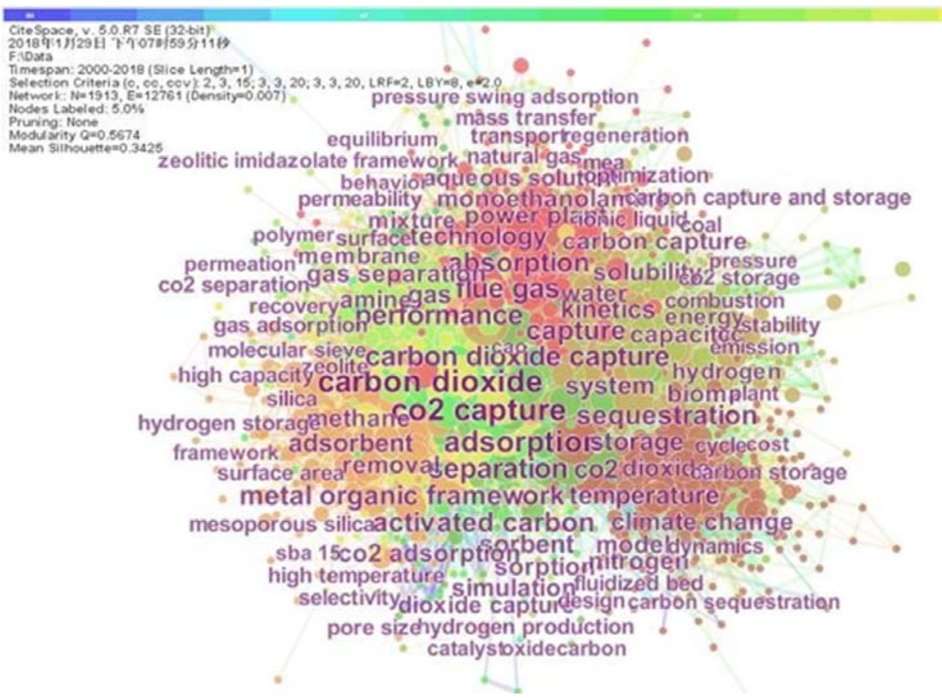

Figure 5. Co-occurring keyword network of CCS research area.

It can be seen that most of the keywords are closely connected to each other. Therefore, it can be concluded that the main studies in the field of CCS technology were interlinked, the core keywords in this specific domain includes "carbon dioxide", "CO_2 capture", "adsorption", "separation", "performance", "metal organic framework", and "activated carbon" as well as "adsorption", and more. It means that these keywords represent the research topics in the field of CCS technology. In addition, some keywords, such as "hydrogen storage", "membrane", "polymer", "permeability", "pressure", and "carbon sequestration", have become the important research branches in the research area of CCS technology. Although these keywords have a weaker correlation with core keywords, they may also, to some extent, represent novel theories or practical requirements in the field of CCS technology.

In order to investigate the popular research topics in the discipline of CCS technology and their evolution over time, the keywords that appeared more than 300 times were collected and listed based on years in Table 4. A total of 35 keywords are listed in the table. Because the purpose of this analysis is to investigate the changes in centrality over time, words/phrases with the same meaning were not merged in this study. As seen in the table, in terms of frequency, "carbon dioxide" appeared most frequently of all the keywords, followed by "CO_2 capture", "adsorption", "separation", and "carbon dioxide capture".

Table 4. Main research topics by year.

Year	Keyword	Centrality	Freq.
2000	Carbon dioxide	0.06	1921
2001	CO_2 capture	0.11	1866
2000	Adsorption	0.1	1375
2000	Separation	0.07	1055
2009	Carbon dioxide capture	0.01	1048
2006	Performance	0.03	847
2002	Flue gas	0.04	813
2009	Metal organic framework	0.03	800
2003	Capture	0.07	736
2002	Absorption	0.03	729
2000	Activated carbon	0.05	682
2000	Sequestration	0.11	670
2000	CO_2	0.17	621
2005	Adsorbent	0.02	582
2007	Technology	0.01	533
2000	Temperature	0.08	531
2000	System	0.08	514
2002	Storage	0.04	488
2001	Kinetics	0.12	485
2005	Sorbent	0.03	458
2002	Gas	0.04	452
2000	Dioxide	0.1	438
2000	Removal	0.03	421
2000	Water	0	390
2001	Sorption	0.02	388
2005	CO_2 adsorption	0.02	373
2010	Carbon capture	0	371
2003	Power plant	0.02	367
2004	Simulation	0.04	367
2002	Gas separation	0.04	348
2002	Capacity	0.03	315
2004	Amine	0.01	313
2006	Solubility	0.07	309
2000	Climate change	0.04	305
2007	Monoethanolamine	0	303

The studies represented by keywords with a highly-cited frequency have been concerned by many institutions/scientists. Therefore, these keywords can represent the research hotspots in the research area of CCS technology. In addition, it also indicates that the academic researches on CCS technology are mainly due to people's attention to the problems of CO_2 and climate change. Some specialized disciplines included in the table, such as "kinetics", "flue gas", "adsorbent", "power plant", and "metal organic framework", reflect the continuous development of CCS technology and the expansion of its application areas.

In terms of centrality, "CO_2" is the most important keyword with a centrality of 0.17, which is quite a high centrality value among all the keywords listed in the table. It is followed by "Kinetics" with a centrality of 0.12, and then "CO_2 capture" and "sequestration", both of which have a centrality of 0.11. This means that the researches represented by the keywords with high centrality have a greater impact on the research area of CCS technology, therefore, they represent the core contents and important sectors in this specific domain of technology.

The valuable information from the changes of keywords over time also can be analyzed. In order to illustrate the developing trends in CCS research area, the keywords listed in Table 4 can be divided into two periods, 2000–2005 and 2006–present. It can be seen that there are 28 keywords in the period of 2000–2005, which accounts for 80% of the total keywords and seven keywords in the period of 2006–present. The keywords "Carbon dioxide capture" in both of the two periods were cited frequently. It can be considered that the research contents represented by the keywords have not changed for a long period and became the foundation of the research field of CCS technology. Some keywords, such as "performance", "metal organic framework", "technology", "solubility", and "monoethanolamine", did not appear in the period between 2000–2005, but they appeared in the period from 2006–present, which shows that these keywords may represent new research topics related to practical applications in the domain of CCS technology in recent years.

3.2.3. Main Contents of Important Research Topics

(1) Representative significant research contents related to "Carbon dioxide" or "CO_2" (2000).

In the study by Hobbie et al. [33], they believed that although arctic and boreal area is of significance in current carbon circle, carbon sequestration activities within northern soils have not been understood very well, to explore the special properties of soil carbon in the systems of high latitude can improve current knowledge about carbon fluxes and even be helpful for evaluating the impacts of these systems on climate changes in the future. Schimel et al. [34] used the historical climate data to invest the impacts of CO_2 and climate on the carbon sequestration in the U.S. ecosystems. Treseder et al. [35] discussed that it is very important for evaluating the effect of world climate change on the circling of mycorrhizal carbon to investigate the decomposition of hyphal under the conditions of elevated carbon dioxide and nitrogen. Ravikovitch et al. [36] considered that carbonaceous adsorbents can play significant roles in practice application, therefore, they tried to investigate a special method to obtain the feature of pore size of micro-porous carbonaceous substances. Ding and Alpay [37] carried out an experiment and found that the complexities of carbon dioxide adsorption on hydrotalcite could change the adsorption efficiency of the material.

(2) Representative significant research contents related to "kinetics" (2001).

Sobkowski and Czerwiński [38] reported the kinetics of carbon dioxide adsorption by using the technical method of radiometry. They found that the adsorption feature of carbon dioxide is because the surface reaction on the electrode, the adsorption rate will raise if the electrode is set under a specific range, the concentration of surface will not be affected by the temperature and carbon dioxide concentration. Nugent et al. [30] examined how, in order to purify the products (i.e., fresh water and gases) in the industrial field, the expenditure of energy utilization could account for about 15% of energy output worldwide, and the request for the products is expected to increase three times by the year 2050. They described that the metal-organic materials with special technical properties offered an unprecedented carbon dioxide sorption selectivity over nitrogen, hydrogen and methane. Ding and Alpay [37] reported that, since the 1950s, the kinetics of carbon dioxide adsorption by different kinds of adsorbents had been examined broadly, while carbon dioxide adsorption capacity on hydrotalcite have been present recently. Serna-Guerrero and Sayari [39] reported that greenhouse gases have serious implications for our environment and ecosystem, lots of initiatives and new technologies were developed to deal with the emissions of carbon dioxide, and therefore, they tried to simulate the CO_2 adsorption kinetic model in their study. Ochoa-Fernandez et al. [40] described that, how to remove the carbon dioxide from waste gases is increasingly important during the activities of energy utilization, therefore, it is necessary for materials to regenerate a stable sorption capacity and improve the kinetic properties in the steps of both sorption and desorption.

(3) Representative significant research contents related to "CO_2 Capture" (2001).

Johnson and Keith [41] discussed that CCS technology has been regarded as an important technical measure to solve the contradiction between fossil-based electricity production and environmental issues related to climate changes, the adoption of CCS technology can contribute greatly to decreasing the economical expenditure of dealing with carbon dioxide emissions in electric sector. Huang et al. [42] described that there are two steps for current carbon storage technology, firstly, to use an amine to separate and capture the CO_2, and then, to pressurize the gas to supercritical carbon dioxide liquid. They found that the Dual Alkali Approach technique could be significant to enhance the efficiency in separating and capturing the carbon dioxide.

(4) Representative significant research contents related to "sequestration" (2000).

White et al. [43] reported that, as one of the most urgent and severe issues in the area of the environment, global warming has become a worldwide issue and need to be confronted and solved by every nation. They described that carbon storage refers to sequestrating the carbon dioxide in a designated location for a long term, therefore, it has become an effective technical means to mitigate the problem of global warming. Nowak and Crane [44] illustrated that CO_2 is an important part of greenhouse gases, a larger utilization of fossil-based energy production would be responsible for the emissions growth of CO_2, and urban forests can be tremendous useful for the decline of carbon dioxide in atmosphere, however, urban trees would also have negative effects on ecosystem. Stewart and Hessami [45] described that the sequestration of CO_2 was not yet mature, it is turned out that the techniques—no matter whether geologic or oceanic injectionare—still not sustainable, therefore, they present a possible technical measure to minimize the emissions of GHGs. Chu [46] reported that the energy production of fossil-based fuel leads to the growth of CO_2 emissions and causes severe climate change problems, and it is important to drastically decrease the CO_2 emissions in order to avoid possible environmental risks in the future. Herzog [47] examined the technical means related to carbon storage which involve processes of removing the GHGs and storing them in a selected reservoir. He described that, once a large quantity of carbon is captured, it would be ideal to achieve its commercial use, however, it also have some limitations in large-scale applications, therefore, as to a larger amount of captured carbon, it may be better to store it in geology or ocean.

(5) Representative significant research contents related to "solubility" (2007).

Suekane et al. [48] reported that, as to residual carbon dioxide stored in geology, solubility trapping is significant important in aquifer storage, some of the CO_2 stored in geology will dissolve and mix in the geological formation water. As to carbon storage technology, solubility trapping and residual gas can help improve storage capacity and efficiency. Keppler et al. [49] described that carbon solubility in olivine will be useful for capturing the dynamics of carbon dioxide exchange. They found that carbon solubility in olivine is unexpected low, which is fundamentally different from previous studies. Mitchell et al. [50] investigated the potential of microorganisms for improving the capacity and efficiency of CCS technology by using the techniques of solubility trapping and mineral-trapping.

(6) Representative significant research contents related to "performance" (2006).

Rubin and colleagues [51] reported that technological performance and economic expenditure are significant influencing factors in policy analysis of CCS technology. They found that, the emissions of carbon dioxide produced by power plant would be greatly reduced by CCS technology. Davision [52] evaluated the performance and costs of three main technologies for carbon capture employed in power plants, and found that, the economical expenditure of electricity would be expected to reduce by 18% under their designed technical conditions, and the advances in carbon dioxide capture technology would contribute to the reduction of economical expenditure. Abu-Zahra et al. [53] evaluated that to deploy CCS technology in a generating station will increase the expenditure of its electricity production, and the improvement and optimization of process will contribute to reducing the entire expenditure of carbon capture technology.

(7) Representative significant research contents related to "metal organic framework" (2009).

Sumida et al. [54] reported that CCS technology can efficiently capture carbon dioxide emitted from industrial sources, however, it can play an important role until the energy infrastructure has been modified greatly. They analyzed that, in order to decrease the cost related to CCS technology, it is essential to pay attention to the influencing factors related to the performance of carbon capture technology. And then, they described that metal-organic frameworks can be employed in carbon capture technology as an emerging and ideal materials. Millward and Yaghi [55] also analyzed several benefits of metal-organic frameworks for carbon storage technology. Li et al. [56] reported that, taking cost into account, to identify the emerging materials will become a significant issue in the research area of CCS technology. They examined that, because metal-organic frameworks have advantages in the cost and efficiency of synthesis, they can be greatly developed in the area of carbon capture technology as a separation material.

(8) Representative significant research contents related to "Monoethanolamine" (2007).

Freguia and Rochelle [57] reported that carbon storage technology has become an important technical means to cope with the environmental problem of global warming. They also described that, as an effective solvent for carbon capture, absorption with aqueous monoethanolamine has achieved practical application status. Strazisar and White [58] described that, in the technical process of CCS, how to separate carbon dioxide is one of the most critical parts, besides, they also analyzed that, as an effective and mature technology, monoethanolamine-based chemical absorption techniques have been widely practiced in the industry.

3.3. Analysis of Evolution and Emerging Trends

3.3.1. Burst Analysis and Research Evolution

Burstness value changes over time reflect when an abrupt change of frequency occurs in a specific duration [59]. In other words, an entity with a frequency burst value implies that its frequency has suddenly changed during a period of time [60]. As one of burst detection methods, citation burst can be considered as an important criterion to identify the most active area in a certain research field. A keyword node with a strong citation burst would represent the emerging trend of a specific research, and both the citation burst and occurrence burst can be supported by CiteSpace [61]. The burst means a major variable change in a given time period. This type of change is considered as an effective method to detect the emerging trends or academic frontiers in a particular research domain [62]. Several types of nodes, such as author, institutions, and keywords can be analyzed by burst detection. If applied for the node type of keywords, it will illustrate the fast-growing topics in the field being studied [61]. Therefore, the analysis of burst keywords is employed to investigate the emerging trends and their changes over the time in the research area of CCS technology. The top 300 keywords, whose citation burst value are relatively stronger, were selected for the analysis.

To identify the general situation of research trends and frontiers of CCS technology, the number distribution of burst terms in different years is analyzed and shown in Figure 6. It can be seen from the trend line of the polynomial equation that the annual number of burst keywords in the research field of CCS technology is somewhat similar to a "Smiling Curve". The evolution as a whole can be divided into three stages: A decline before 2005, stable growth between 2006 and 2013, and a rapid rise after 2014. It can also be estimated that the number of burst keywords will continue to increase over the next two years.

There are some severe challenges on issues of environmental protection and climate change in this 21st century [63]. As an effective technical means, CCS technology has attracted a great deal of attention from both academic and industrial fields, and it has become one of the most important research trends in the discipline of environment at the dawn of the new millennium. Especially, after an investigation on CCS technology was released by the IPCC in 2005, endeavours from relevant international organizations and countries also caused CCS technology to receive great attention during the 2nd stage. However, at this stage, academic research was also affected by some realistic factors, such as immaturity of the technology, technological risks, and the expensive costs. At present, as demonstration projects of CCS technology turn into practice, the relevant research has to be carried out in a comprehensive way. It can be concluded that there will be more branches and new developments in the research field of CCS technology in the next few years.

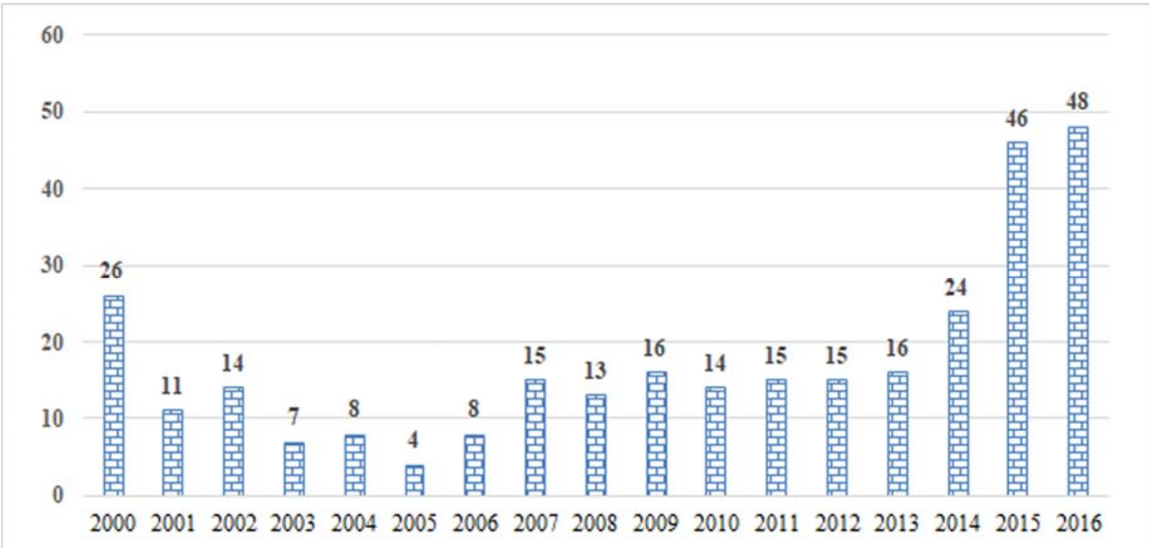

Figure 6. Annual distribution of TOP 300 burst keywords.

The citation burst of research literature represents when particular attention is paid to a specific domain of technology. The emerging trends in a particular research area can be identified by the analysis of literature with a stronger citation burst [64]. There are many pieces of literature with citation bursts and the top 20 pieces of literature are listed in Table 5. These research studies, not only have a stronger burst strength, but also have an active impact (the burst duration is lasting until the present) on the research area of CCS technology.

Among the top 20 pieces of literature, the articles written by Boot-Handford [65] and published in *Energy & Environmental Science* ranked at the first place on the list with a burst strength value of 30.447, in which the leading technologies of carbon capture were reviewed, meanwhile, the technological feasibility and the economic and legal of CCS technology were also discussed. The reference with the second strongest citation burst was written by Wang [66] and was also published in *Energy & Environmental Science*. In that paper, the authors felt that it is essential to update the materials of carbon capture in time. Besides, the authors also described how to organize the carbon dioxide sorbents according to different working temperatures. There is one reference published in *Nature* with a burst strength of 17.12; this paper provided a mechanistic framework, which is designed as a highly efficient adsorbents for removing the CO_2 [67]. In addition, there is also one reference published in *Science* with a burst strength of 10.3454. In that study, Furukawa et al. [68] focused on several aspects of metal-organic framework (MOF) chemistry, including its key developments and the impacts on practice. It can be considered that the literature studies listed in the table are the most influential works in the research area of CCS technology in recent years. They can represent the recent advances of CCS technology and meanwhile, the topics of these pieces of literature can represent the emerging trends and latest developments of CCS technology.

Table 5. Top 20 literature with strongest citation bursts.

Reference Information	Year	Strength	Begin	End
Boot-Handford ME, 2014, Energ Environ Sci, V7, P130	2014	30.447	2015	2018
Wang JY, 2014, Energ Environ Sci, V7, P3478	2014	29.6231	2016	2018
Leung DYC, 2014, Renew Sust Energ Rev, V39, P426	2014	22.3315	2016	2018
Mcdonald TM, 2015, Nature, V519, P303	2015	17.12	2016	2018
Zhang ZJ, 2014, Energ Environ Sci, V7, P2868	2014	16.1407	2015	2018
Dutcher B, 2015, Acs Appl Mater Inter, V7, P2137	2015	13.9032	2016	2018
Chowdhury FA, 2013, Ind Eng Chem Res, V52, P8323	2013	13.2412	2016	2018
Kenarsari SD, 2013, Rsc Adv, V3, P22739	2013	10.7725	2015	2018
Thommes M, 2015, Pure Appl Chem, V87, P1051	2015	10.4521	2016	2018
Li YJ, 2015, Appl Energ, V145, P60	2015	10.4521	2016	2018
Furukawa H, 2013, Science, V341, P974	2013	10.3454	2015	2018
Shekhah O, 2014, Nat Commun, V5, P	2014	10.1986	2015	2018
Yu Ch, 2012, Aerosol Air Qual Res, V12, P745	2012	9.281	2016	2018
Goto K, 2013, Appl Energ, V111, P710	2013	9.0674	2016	2018
IPCC, 2014, Climate Change 2014, V, P	2014	9.0578	2016	2018
Sethia G, 2015, Carbon, V93, P68	2015	9.0578	2016	2018
Dai Zd, 2016, J Membrane Sci, V497, P1	2016	9.0578	2016	2018
Liang Zw, 2015, Int J Greenh Gas Con, V40, P26	2015	9.0578	2016	2018
To Jwf, 2016, J Am Chem Soc, V138, P1001	2016	8.7093	2016	2018
Fracaroli Am, 2014, J Am Chem Soc, V136, P8863	2014	8.5977	2015	2018

Table 6 lists the top 10 keywords with stronger citation bursts in different periods of time, the research topics and their changes in the research area of CCS technology are presented in the table. In order to investigate the burst strength of different keywords, keywords with the same meaning, but expressed by different words/phrases, for example carbon dioxide and CO_2, would not be merged. The table shows the first time that each keyword appeared and its duration. What should be noted is that the line illustrated by blue color in the table means the whole study period of time (2000–2018) and the red line represents the duration of the citation burst. In addition, in order to understand more exactly the emerging trends in the research area of CCS technology and their changes over time, the research period is divided into three parts.

It can be seen that the top 10 burst keywords in different time periods were essentially different. During the time period from 2000 to 2005, "carbon dioxide" is at the first place in the list with a burst strength value of 52.5794 and the second keyword was "CO_2" with a burst strength of 45.0923. During the time period from 2006 to 2010, "high capacity" had the strongest citation burst with a strength of 15.9928, followed by "Monte Carlo simulation" (14.5793), and "calcium oxide" (11.5709). Furthermore, during the time period of from 2011 to present, "methane" had the strongest citation burst with a strength of 10.672, followed by "post-combustion CO_2 capture" (9.9749) and "carbide slag" (7.6256). The keywords listed in the table reflect the CCS research characteristics, such as hotspots, emerging trends and new developments in different periods.

Table 6 also shows the different burst durations of each keyword in different periods of time. This duration reflects the length of keywords' influence in the research area of CCS technology. As is shown, most of the keywords in the research period of 2000–2005, such as "dynamics", "CO_2", "hydrogen", "carbon storage", "forest", "bioma", and "disposal" had a longer burst duration than the keywords in the second and the third research periods. It is safe to assume that the studies related to these keywords can be regarded as the research pioneers in the domain of CCS technology. They can serve as important and fundamental sources for technological development and new research branches, so that the research studies embodied in these keywords have a longer influence on the advancements in this technological domain.

Table 6. Top 10 keywords with strong citation bursts in different periods.

Period	Top 10 Keywords	Strength	Begin	End	2000–2018
2000–2005	Carbon dioxide	52.5794	2001	2008	
	CO_2	45.0923	2001	2010	
	Nitrogen	21.3001	2000	2008	
	Hydrogen	20.7827	2003	2012	
	Ecosystem	20.6307	2000	2008	
	Carbon storage	20.2215	2000	2009	
	Forest	19.5339	2000	2009	
	Bioma	17.2279	2000	2009	
	Disposal	16.4679	2002	2011	
	Dynamics	16.4412	2000	2010	
2006–2010	High capacity	15.9928	2009	2013	
	Monte Carlo simulation	14.5793	2006	2011	
	Calcium oxide	11.5709	2006	2010	
	CaO	11.5081	2007	2010	
	Gas	11.0606	2006	2010	
	Combustion	10.2953	2008	2010	
	Calcination	9.9176	2007	2010	
	SBA 15	9.832	2007	2011	
	Reactor	9.4293	2007	2011	
	Carbonation	9.2963	2008	2012	
2011-present	Methane	10.672	2011	2012	
	Post-combustion CO_2 capture	9.9749	2016	2018	
	Carbide Slag	7.6256	2016	2018	
	Gas Storage	7.5231	2014	2016	
	Fabrication	7.2958	2016	2018	
	Graphene	7.252	2015	2018	
	Ambient Condition	6.899	2016	2018	
	Sulfation	6.8989	2012	2013	
	Facile Synthesis	6.701	2016	2018	
	Expanded Mesoporous Silica	6.4517	2011	2013	

Furthermore, the keywords in the research period of 2011–present, such as "post-combustion CO_2 capture", "carbide slag", "fabrication", "graphene", "ambient condition", and "facile synthesis", can represent the new topics, emerging trends, and even the major frontiers in the research area of CCS technology, because their burst durations have lasted until the present. The studies related to these keywords may have a continuous impact on the development of CCS technology.

3.3.2. Main Contents of Important Emerging Trends

(1) Representative significant research contents related to "postcombustion CO_2 capture" (burst strength: 9.9749; burst duration: 2016–2018).

Abanades et al. [69] described that CCS technology can be considered as one of the significant technical means to cope with climate change, and it is necessary to analyze the economical expenditure to explore the potential paths of utilizing carbon capture technology. They analyzed that the most common form of the cost estimation of carbon capture is incremental expenditure in power and the expenditure in removing the CO_2. Veltman and colleagues [70] evaluated the impacts of carbon capture technology on the environment and human health. It is indicated that if the scrubbing techniques based on amines are adopted in carbon capture technology, the toxicity to the freshwater ecosystem will increase 10 times, and the toxicity of terrestrial ecosystems will also suffer a minor increase. Plaza et al. [71] made a study on two different carbon adsorbent approaches and found that both of the techniques can be used to produce the adsorbents with a better CO_2 adsorption efficiency, meanwhile, they also considered that nitrogen functionalities can contribute to enhancing the carbon dioxide adsorption efficiency, especially under the condition of low partial pressures.

(2) Representative significant research contents related to "carbide slag" (burst strength: 7.6256; burst duration: 2016–2018).

Li et al. [72] introduced the sources and properties of carbide slag, and then, they investigated a new synthetic sorbent by using the combustion synthetic techniques and variety of materials, including carbide slag, and found that porous structures can be used to increase the capabilities of synthetic sorbenta, moreover, the capabilities of synthetic sorbenta will be beneficial to capture carbon dioxide. Li et al. [73] investigated that, in order to decrease and eliminate the carbon dioxide, the calcium looping technology is regarded as a valuable and feasible techniques for capturing carbon dioxide, and then, they concluded that, comparing with limestone or Hy-CaO, carbide slag have advantages in final carbonation conversion under the same technical conditions. Sun et al. [74] reported that, integration of a carbide slag disposal and a calcium looping system can contribute to decreasing the expenditure of transporting the raw sorbent materials. Thus, they described that the pelletization of carbide slag is very important for calcium looping process, in order to avoid appreciable loss of CO_2 sorption, it is also essential to control the calcination temperature.

(3) Representative significant research contents related to "fabrication" (burst strength: 7.2958; burst duration: 2016–2018).

Yu and colleagues [75] reported that, although amine baths are the commonly used techniques for CCS technology in practical application, the process itself also has some obvious disadvantages. Thus, in order to overcome the disadvantages, they fabricated bimodal mesoporous silica hollow spheres and considered that the CO_2 adsorption efficiency may depend on the temperature of adsorption and the specific surface areas of the sample. Qin et al. [76] analyzed that the process of carbon capture contributes about 75% of the total cost in CCS technology, however, in fact, only a few of the proposed technologies can be technically feasible and cost-effective in industrial practice, and currently, amine scrubbing is the only technique that is relatively mature and has commercial application possibilities. Therefore, they intended to find an efficient and low-cost fabricating and sorbent technology using the method of extending wet mixing and a cheaper insoluble precursors. Sun et al. [77] reported that, at present, the separation of carbon dioxide from N_2 and CH_4 has attracted increasing attention, the common method to eliminate carbon dioxide is "wet scrubbing," however, this process itself has several inherent shortcomings. Therefore, they designed a particular reaction to fabricate porous polymer networks. Liu et al. [78] presented a versatile fabrication strategy to conquer the defects of hierarchically porous carbon materials in industrial application.

(4) Representative significant research contents related to "graphene" (burst strength: 7.252; burst duration: 2015–2018).

Chandra et al. [79] reported two commonly used technologies and their technological limitations, and then, they considered that, as a promising and emerging technology, graphene can have several obvious advantages in the area of carbon absorption technology. Therefore, they examine how to synthesize one kind of porous carbon using graphene. Garcia Gallastegui et al. [80] reported that graphene itself has several very good technical properties, so graphene is receiving intense attention, and has been explored in various application fields. Besides, layered double hydroxides (LDHs) are also useful materials for carbon dioxide adsorbents. Therefore, in their study, they described that graphene oxide is helpful for improving the adsorption efficiency of carbon dioxide of LDH.

Li et al. [81] reported that graphene oxide is a good nanofiller in mixed matrix membranes (MMMs). Thus, they developed a novel multi-permselective MMMs in their experiments and found that the polyethylenimine-functionalized graphene oxide nanosheets has a positive role in promoting membrane properties. Shen et al. [82] reported that graphene oxide is a promising technology in membranes for molecular separation, and then, they proposed the membranes with carbon dioxide transportation channels of graphene oxide laminates.

(5) Representative significant research contents related to "facile synthesis" (burst strength: 6.701; burst duration: 2016–2018).

Li et al. [83] described a synthesis of hierarchical mesoporous carbon nitride spheres, and then, they investigated the carbon dioxide sorption performance of the products and found that, because of the capillary condensation effect, the micropores and mesopores can improve the capture properties of carbon dioxide. Lu and Zhang [84] reported that, because nanoporous organic polymers has many very good technical properties, they are regarded as a valuable and emerging material in the area of CCS technology, however, it is important for improving the adsorption efficiency to determine the porosity parameters of porous polymers. Kim and colleagues [85] reported that, the adsorbents for capturing the carbon at a higher temperature have attracted lots of attention in recent years. Thus, they tried to synthesize macroporous Li_4SiO_4 by using the method of solid-state transformation, which can significantly enhance carbon dioxide adsorption performance compared with conventional Li_4SiO_4.

4. Discussion

Knowledge mapping can provide us with valuable information about the status and trends of a certain field. It is turned out that CiteSpace is a useful tool for knowledge mapping. Literature mining and analysis is not only useful for researchers to find new research directions, but also benefits potential inventors/governmental agencies who intend to invest in mature technologies [86]. In this study, a comprehensive investigation about the research evolution and developing trends of CCS technology is provided using the CiteSpace software, based on retrieving the research literature from Web of Science. Some valuable conclusions can be illustrated from the perspectives of basic analysis, research topics analysis, and emerging trends and new development.

At present, there are growing concerns about reducing CO_2 emissions, so it is necessary to adopt emerging technologies in addition to the utilization of low carbon and renewable energy sources [87]. Among many possible technical means to cope with global warming, CCS technology is regarded as an effective technical means for removing carbon dioxide [88,89]. CCS technology is an integrated suite of technologies which can capture and store CO_2 at a selected place and prevent CO_2 from being emitted directly to the atmosphere, so that, many endeavors for the promotion of CCS technology have been initiated recently [90]. According to the report released by the IPCC in 2005, over 60% of global carbon dioxide emissions come from point sources that could apply carbon capture technology. CCS technology can contribute up to 20% of needed carbon dioxide emission reductions over the coming century [31]. In 2007, the United Nations Climate Conference was held and an agreement on the commitment of countries' carbon reduction and responsibility was promoted through a meeting of the Bali Road Map [91]. In December 2009, the Copenhagen Accord was drafted to reaffirm the goal of carbon reduction. The global CCS patent applications increased rapidly after 2006, the organizations from the U.S., China and some European countries, filed more patents [92]. Therefore, as one of promising technologies to combat climate change, CCS technology has received extensive attention, and the technological innovation activities in this particular technological domain have been promoted greatly since 2005.

In the CCS research area, there are more studies published in countries from Asia, North America, and Europe, especially in China and the U.S. These two countries are not only participating countries of the Copenhagen Accord, but also the main two sponsors of the accord. In the United States, carbon capture and storage technology has been regarded as an important consideration in U.S. climate policy discussions, and the funding for the research and demonstration of CCS technology has experienced a sharp increase in the new century [93]. In China, as the world's biggest emitter of GHGs and consumer of energy production, the government has provided active support, including finances and policies, for promoting the development of CCS technology in China [94]. In 2015, the advancements in CCS technology has even been proposed in National Medium and Long Term Development Plan of Science and Technology of China [95]. Moreover, in Japan, a long-term research program was formulated for CCS technology. In Europe, the first international conference on CCS technology was held in 1992 in Amsterdam [47]. According to an investigation made in 2006 about CCS technology from 28 European countries, 75% of the European energy stakeholders thought that it was "definitely" or "probably necessary" to widely deploy CCS technology to reduce the CO_2 emissions in their own countries [96]. Moreover, in order to deal with the challenges of sustainable energy and external energy dependency, the European Union has also developed some legislative initiatives, such as "European 2020", "Energy Roadmap 2050", and so on [97].

5. Conclusions

As CCS technology has a significant role in controlling CO_2 emissions, many countries have started to deploy CCS technology. With the vigorous support and push of governments, a multitude of research studies were carried out and the number of research articles increased in these countries correspondingly. In addition, the most productive institutions in the research area of CCS technology were identified in this study. There are several institutions from China. The CAS of China not only has the largest number of publications but also has the largest number of cited frequency and centrality. However, among all the most productive institutions, more institutes from developed countries have significant roles and greater impact on CCS research. In addition, among the main institutions, they linked closely with each other, which means that most of them paid more attention to cooperating and exchanging with each other in the scientific research of CCS technology.

In the research area of CCS technology, "carbon dioxide", "CO_2 capture", "adsorption", "separation", and "adsorption" are the major research topics while "hydrogen storage", "membrane", "polymer", and "carbon sequestration" are the research branches. "CO_2", "Kinetics", "CO_2 capture", and "sequestration" are the core research contents and "carbon dioxide capture" is the important research foundation while "performance", "metal organic framework", "technology", "solubility", and "monoethanolamine" are the new research topics. The important pieces of literature related to the research topics mentioned above and their citation network were also investigated. The significant findings of the research topics were summarized by reviewing the most cited literature related to the keywords with higher value of "centrality". The contents of the main research topics in the CCS technology include at least the following aspects: (1) Carbon emissions and environmental protection. The impact of carbon emissions on environment is addressed in the whole research period [33,34,39,43], it could be concluded that this topic would be continuous. Therefore, in order to cope with the severe problems posed by climate change and global warming, it is necessary for us to develop green and efficient technologies [35,36]. (2) Research and development of CCS technology. This topic focuses on several issues, such as experiment of carbon adsorption or sorption [36,37,40,46], new process for carbon capture or storage [42], porous materials (metal organic framework or metal organic materials) for carbon adsorption or separation [30,54], applications of monoethanolamine in carbon capture [57,58], applications of solubility trapping in carbon storage technologies [48–50], and so on. (3) Social practical issues of CCS technology. This topic reflects the degree of development or feasibility of CCS technology in practice. This topic includes not only the assessment of technological capabilities [48,50], but also the cost analysis and economic performance of CCS technology [41,51–53].

The keywords, such as "carbon dioxide", "CO_2", "high capacity", and "methane" represented emerging trends of CCS research areas in different periods of time and the keywords, such as "post-combustion CO_2 capture", "carbide slag", "fabrication", "graphene", "ambient condition", and "facile synthesis" may be new developments and possibly the major frontiers of the emerging trends in the research area of CCS technology. Similarly, important literature studies related to emerging trends were also stated. The valuable information about the latest advances and developments of the research frontiers of CCS technology has been analyzed using the burst analysis of keywords and literature. Specially, the important findings of the emerging trends were summarized by reviewing the most cited literature related to the keywords whose burst duration last until the present (2018). The contents of the main emerging trends in the CCS technology include at least the following aspects: (1) Emerging techniques and processes. With the development of science and technology, relevant techniques and processes have been developed and applied in CCS technology, such as postcombustion [69,70,98], combustion synthetic method [72], calcium looping technology [73,74], amine-functionalized solids and amine-scrubbing technique [75,76], facile nucleophilic substitution reaction [78], and so on. (2) Emerging materials. In order to increase technological efficiency, some new materials, including graphene [79–82,99] and nanoporous organic polymers [84], are employed in the innovative activities of CCS technology. (3) Evaluation of technological performance. Technological performance corresponds to the capabilities of firms to exploit the potentialities of the prevailing technology, and it can evaluated by the productivity level of firms [100]. In recent years, in the research area of CCS technology, technological performance is assessed from several aspects, such as performance of carbon capture [83], adsorption capability of carbon [71,75,80,85], performance of carbon sorbent [72] and performance of carbon membranes [81,82], and so on. (4) Socioeconomic analysis. This research trend is related to cost of carbon capture [70], cost of carbon transportation [74], economic performance of CCS technology [76,101], human health and environment [70,102].

6. Research Limitations

Generally speaking, the knowledge mapping of CCS technology is explored in this study. It can provide researchers or practitioners with explicit information about the research situations and emerging trends of CCS technology. With the continuous development of CCS technology, the research topics in this particular research area also changing. The main contents of research topics in the field of CCS technology involve at least following three aspects: carbon emissions and environmental protection, research and development (R&D) activities, and social practical issues. Additionally, as CCS technology tends to be gradually mature and its important role in mitigating climate change is being realized, which not only promotes the further development of CCS technology, but also inspired some emerging trends in the research area, such as emerging techniques and processes, emerging materials, evaluation of technological performance, and socioeconomic analysis, and more. However, it also should be noted that there are still some limitations in this study. First of all, the studies were collected from the Web of Science. As is known, the Web of Science is one of the most important bibliographic database in the world. Certainly, the dataset used in this study can represent the situation, hotspots, trends, and frontiers of the research area of CCS technology, but not all publications/journals are indexed by the database, especially in non-English speaking countries, and this case would be especially true. There are always some important publications published in the languages of these countries. Therefore, these publications would be excluded by this study. In addition, when it comes to CiteSpace, this software has some requirements about the data format, which would have an impact on the scope of data collection and analysis. These limitations should be carefully considered in any future relevant research.

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References

1. Quéré, C.L.; Raupach, M.R.; Canadell, J.G.; Marland, G.; Bopp, L.; Ciais, P.; Conway, T.J.; Doney, S.C.; Feely, R.A.; Friedlingstein, P.F.P.; et al. Trends in the sources and sinks of carbon dioxide. *Nat. Geosci.* **2009**, *2*, 831–836. [CrossRef]
2. Haszeldine, R.S. Carbon capture and storage: How green can black be? *Science* **2009**, *325*, 1647–1652. [CrossRef] [PubMed]
3. Benson, S.M.; Bennaceur, K.; Cook, P.; Davison, J.; de Coninck, H.; Farhat, K.; Ramirez, C.A.; Simbeck, D.; Surles, T.; Verma, P.; et al. Carbon Capture and Storage. In *Global Energy Assessment—Toward a Sustainable Future*; Cambridge University Press: Cambridge, MA, USA, 2012; pp. 993–1068, ISBN 9781 10700 5198.
4. IEA. *Technology Roadmap: Carbon Capture and Storage 2013*; International Energy Agency: Paris, France, 2013. Available online: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapCarbonCaptureandStorage.pdf (accessed on 2 February 2018).
5. Broecks, K.P.F.; Egmond, S.V.; Rijnsoever, F.J.V.; Berg, M.V.D.; Hekkert, M.P. Persuasiveness, importance and novelty of arguments about Carbon Capture and Storage. *Environ. Sci. Policy* **2016**, *59*, 58–66. [CrossRef]
6. Intergovernmental Panel on Climate Change, Carbon Dioxide Capture and Storage. Available online: http://www.ipcc.ch/pdf/special-reports/srccs/srccs_wholereport.pdf (accessed on 30 January 2018).
7. Kern, F.; Gaede, J.; Meadowcroft, J.; Watson, J. The political economy of carbon capture and storage: An analysis of two demonstration projects. *Technol. Forecast. Soc.* **2016**, *102*, 250–260. [CrossRef]
8. De Souza, E.F.; de Almeida Falbo, R.; Vijaykumar, N.L. Knowledge management initiatives in software testing: A. mapping study. *Inf. Softw. Technol.* **2015**, *57*, 378–391. [CrossRef]
9. Powell, W.W.; Snellman, K. The Knowledge Economy. *Annu. Rev. Sociol.* **2004**, *30*, 199–220. [CrossRef]
10. Lyu, H.; Zhou, Z.; Zhang, Z. Measuring Knowledge Management Performance in Organizations: An Integrative Framework of Balanced Scorecard and Fuzzy Evaluation. *Information* **2016**, *7*, 29. [CrossRef]
11. Darroch, J. Knowledge management, innovation and firm performance. *J. Knowl. Manag.* **2005**, *9*, 101–115. [CrossRef]
12. Centobelli, P.; Cerchione, R.; Esposito, E. Knowledge Management in Startups: Systematic Literature Review and Future Research Agenda. *Sustainability* **2017**, *9*, 361. [CrossRef]
13. Hall, R.; Andriani, P. Managing Knowledge for Innovation. *Long Range Plan.* **2002**, *35*, 29–48. [CrossRef]
14. Ebener, S.; Khan, A.; Shademani, R.; Compernolle, L.; Beltran, M.; Lansang, M.; Lippman, M. Knowledge mapping as a technique to support knowledge translation. *Bull. World Health Organ.* **2006**, *84*, 636–642. [CrossRef] [PubMed]
15. Fisher, K.M. *Overviee of Knowledge Mapping//Mapping Biology Knowledge*; Springer: Dordrecht, The Netherlands, 2002; pp. 5–23. Available online: https://link.springer.com/content/pdf/10.1007/0-306-47225-2_2.pdf (accessed on 28 January 2018).
16. Vailiii, E. Knowledge Mapping: Getting Started with Knowledge Management. *J. Inf. Syst. Manag.* **1999**, *16*, 16–23. [CrossRef]
17. Mingers, J.; Leydesdorff, L. A review of theory and practice in scientometrics. *Eur. J. Oper. Res.* **2015**, *246*, 1–19. [CrossRef]
18. Mercuri, E.G.F.; Kumata, A.Y.J.; Amaral, E.B.; Vitule, J.R.S. Energy by Microbial Fuel Cells: Scientometric global synthesis and challenges. *Renew. Sustain. Energy Rev.* **2016**, *65*, 832–840. [CrossRef]
19. Montoya, F.G.; Montoya, M.G.; Gómez, J.; Manzano-Agugliaro, F.; Alameda-Hernández, E. The research on energy in Spain: A scientometric approach. *Renew. Sustain. Energy Rev.* **2014**, *29*, 173–183. [CrossRef]
20. Konur, O. The scientometric evaluation of the research on the algae and bio-energy. *Appl. Energy* **2011**, *88*, 3532–3540. [CrossRef]
21. Staab, S.; Studer, R.; Schnurr, H.P.; Sure, Y. Knowledge Processes and Ontologies. *IEEE Intell. Syst.* **2001**, *16*, 26–34. [CrossRef]
22. Chen, C. CiteSpace II: Detecting and visualizing emerging trends and transient patterns in scientific literature. *J. Assoc. Inf. Sci. Technol.* **2006**, *57*, 359–377. [CrossRef]
23. Chen, C. Searching for intellectual turning points: Progressive knowledge domain visualization. *Proc. Natl. Acad. Sci. USA* **2004**, *101* (Suppl. 1), 5303–5310. [CrossRef] [PubMed]

24. Yu, D.; Xu, C. Mapping research on carbon emissions trading: A co-citation analysis. *Renew. Sustain. Energy Rev.* **2017**, *74*, 1314–1322. [CrossRef]
25. Chen, K.; Guan, J. A bibliometric investigation of research performance in emerging nanobiopharmaceuticals. *J. Informetr.* **2011**, *5*, 233–247. [CrossRef]
26. Lin, Z.; Wu, C.; Hong, W. Visualization analysis of ecological assets/values research by knowledge mapping. *Acta Ecol. Sin.* **2015**, *35*, 142–154. [CrossRef]
27. D'Alessandro, D.M.; Smit, B.; Long, J.R. Carbon dioxide capture: Prospects for new materials. *Angew. Chem. Int. Ed.* **2010**, *49*, 6058–6082. [CrossRef] [PubMed]
28. Choi, S.; Drese, J.H.; Jones, C.W. Adsorbent materials for carbon dioxide capture from large anthropogenic point sources. *ChemSusChem* **2009**, *2*, 796–854. [CrossRef] [PubMed]
29. Rochelle, G.T. Amine scrubbing for CO_2 capture. *Science* **2009**, *325*, 1652–1654. [CrossRef] [PubMed]
30. Nugent, P.; Belmabkhout, Y.; Burd, S.D.; Cairns, A.J.; Luebke, R.; Forrest, K.; Pham, T.; Ma, S.; Space, B.; Wojtas, L.; et al. Porous materials with optimal adsorption thermodynamics and kinetics for CO_2 separation. *Nature* **2013**, *495*, 80–84. [CrossRef] [PubMed]
31. Metz, B.; Davidson, O.; de Coninck, H.C.; Loos, M.A.; Meyer, L.A. *IPCC Special Report on Carbon Dioxide Capture and Storage*; Cambridge University Press: New York, NY, USA, 2005; ISBN 0-521-68551-6.
32. Xiang, C.; Wang, Y.; Liu, H. A scientometrics review on nonpoint source pollution research. *Ecol. Eng.* **2017**, *99*, 400–408. [CrossRef]
33. Hobbie, S.E.; Schimel, J.P.; Trumbore, S.E.; Randerson, J.R. Controls over carbon storage and turnover in high-latitude soils. *Glob. Chang. Biol.* **2000**, *6*, 196–210. [CrossRef]
34. Schimel, D.; Melillo, J.; Tian, H.; McGuire, A.D.; Kicklighter, D.; Kittel, T.; Rosenbloom, N.; Running, S.; Thornton, P.; Ojima, D. Contribution of increasing CO_2 and climate to carbon storage by ecosystems in the United States. *Science* **2000**, *287*, 2004–2006. [CrossRef] [PubMed]
35. Treseder, K.K.; Allen, M.F. Mycorrhizal fungi have a potential role in soil carbon storage under elevated CO_2 and nitrogen deposition. *New Phytol.* **2000**, *147*, 189–200. [CrossRef]
36. Ravikovitch, P.I.; Vishnyakov, A.; Ron Russo, A.; Neimark, A.V. Unified Approach to Pore Size Characterization of Microporous Carbonaceous Materials from N2, Ar, and CO_2 Adsorption Isotherms. *Langmuir* **2000**, *16*, 2311–2320. [CrossRef]
37. Ding, Y.; Alpay, E. Equilibria and kinetics of CO_2, adsorption on hydrotalcite adsorbent. *Chem. Eng. Sci.* **2000**, *55*, 3461–3474. [CrossRef]
38. Sobkowski, J.; Czerwiński, A. Kinetics of carbon dioxide adsorption on a platinum electrode. *J. Electroanal. Chem. Interface* **1974**, *55*, 391–397. [CrossRef]
39. Serna-Guerrero, R.; Sayari, A. Modeling adsorption of CO_2, on amine-functionalized mesoporous silica. 2: Kinetics and breakthrough curves. *Chem. Eng. J.* **2010**, *161*, 182–190. [CrossRef]
40. Ochao-Fernandez, E.; Roenning, M.; Grande, T.; Chen, D. Nanocrystalline Lithium Zirconate with Improved Kinetics for High-Temperature CO_2, Capture. *Chem. Mater.* **2006**, *37*, 1383–1385. [CrossRef]
41. Johnson, T.L.; Keith, D.W. Electricity from fossil fuels without CO_2 emissions: Assessing the costs of carbon dioxide capture and sequestration in U.S. electricity markets. *J. Air Waste Manag. Assoc.* **2001**, *51*, 1452–1459. [CrossRef] [PubMed]
42. Huang, H.P.; Shi, Y.; Li, W.; Chang, S.G. Dual Alkali Approaches for the Capture and Separation of CO_2. *Energy Fuels* **2001**, *15*, 263–268. [CrossRef]
43. White, C.M.; Strazisar, B.R.; Granite, E.J.; Hoffman, J.S.; Pennline, H.W. Separation and Capture of CO_2 from Large Stationary Sources and Sequestration in Geological Formations-Coalbeds and Deep Saline Aquifers. *J. Air Waste Manag. Assoc.* **2003**, *53*, 645–715. [CrossRef] [PubMed]
44. Nowak, D.J.; Crane, D.E. Carbon storage and sequestration by urban trees in the USA. *Environ. Pollut.* **2002**, *116*, 381–389. [CrossRef]
45. Stewart, C.; Hessami, M.A. A study of methods of carbon dioxide capture and sequestration—The sustainability of a photosynthetic bioreactor approach. *Energy Convers. Manag.* **2005**, *46*, 403–420. [CrossRef]
46. Chu, S. Carbon capture and sequestration. *Science* **2009**, *325*, 1599. [CrossRef] [PubMed]
47. Herzog, H.J. What future for carbon capture and sequestration? *Environ. Sci. Technol.* **2001**, *35*, 148A–153A. [CrossRef] [PubMed]
48. Suekane, T.; Nobuso, T.; Hirai, S.; Kiyota, M. Geological storage of carbon dioxide by residual gas and solubility trapping. *Int. J. Greenh. Gas Control* **2008**, *2*, 58–64. [CrossRef]

49. Keppler, H.; Wiedenbeck, M.; Shcheka, S.S. Carbon solubility in olivine and the mode of carbon storage in the Earth's mantle. *Nature* **2003**, *424*, 414–416. [CrossRef] [PubMed]
50. Mitchell, A.C.; Dideriksen, K.; Spangler, L.H.; Cunningham, A.B.; Gerlach, R. Microbially enhanced carbon capture and storage by mineral-trapping and solubility-trapping. *Environ. Sci. Technol.* **2010**, *44*, 5270–5276. [CrossRef] [PubMed]
51. Rubin, E.S.; Chen, C.; Rao, A.B. Cost and performance of fossil fuel power plants with CO_2, capture and storage. *Energy Policy* **2007**, *35*, 4444–4454. [CrossRef]
52. Davison, J. Performance and costs of power plants with capture and storage of CO_2. *Energy* **2007**, *32*, 1163–1176. [CrossRef]
53. Abu-Zahra, M.R.M.; Niederer, J.P.M.; Feron, P.H.M.; Versteeg, G.F. CO_2, capture from power plants: Part II. A parametric study of the economical performance based on mono-ethanolamine. *Int. J. Greenh. Gas Control* **2007**, *1*, 135–142. [CrossRef]
54. Sumida, K.; Rogow, D.L.; Mason, J.A.; McDonald, T.M.; Bloch, E.D.; Herm, Z.R.; Bae, T.H.; Long, J.R. Carbon Dioxide Capture in Metal–Organic Frameworks. *Chem. Rev.* **2012**, *112*, 724–781. [CrossRef] [PubMed]
55. Millward, A.R.; Yaghi, O.M. Metal-organic frameworks with exceptionally high capacity for storage of carbon dioxide at room temperature. *J. Am. Chem. Soc.* **2005**, *127*, 17998–17999. [CrossRef] [PubMed]
56. Li, J.R.; Ma, Y.; Mccarthy, M.C.; Sculley, J.; Yu, J.; Jeong, H.; Balbuena, P.B.; Zhou, H. Carbon dioxide capture-related gas adsorption and separation in metal-organic frameworks. *Coord. Chem. Rev.* **2011**, *255*, 1791–1823. [CrossRef]
57. Freguia, S.; Gary, T. Rochelle. Modeling of CO_2 capture by aqueous monoethanolamine. *AIChE J.* **2003**, *49*, 1676–1686. [CrossRef]
58. Strazisar, B.R.; Anderson, R.R.; White, C.M. Degradation Pathways for Monoethanolamine in a CO_2 Capture Facility. *Energy Fuels* **2003**, *17*, 1034–1039. [CrossRef]
59. Kleinberg, J. Bursty and Hierarchical Structure in Streams. *Data Min. Knowl. Discov.* **2003**, *7*, 373–397. [CrossRef]
60. Chen, C.; Dubin, R.; Kim, M.C. Emerging trends and new developments in regenerative medicine: A scientometric update (2000–2014). *Expert Opin. Biol. Ther.* **2014**, *14*, 1295–1317. [CrossRef] [PubMed]
61. Chen, C. The CiteSpace Manual (Version 1.01). Available online: https://www.researchgate.net/profile/Arsev_Aydinoglu/publication/274377526_Collaborative_interdisciplinary_astrobiology_research_a_bibliometric_study_of_the_NASA_Astrobiology_Institute/links/5670463b08ae0d8b0cc0e112.pdf (accessed on 18 February 2018).
62. Li, X.; Ma, E.; Qu, H. Knowledge mapping of hospitality research-A visual analysis using CiteSpace. *Int. J. Hosp. Manag.* **2017**, *60*, 77–93. [CrossRef]
63. Kojima, T. *Carbon Dioxide Problem: Integrated Energy and Environmental Policies for the 21st Century*; Gordon and Breach Science Publishers: Tokyo, Japan, 1998; ISBN 90-5699-127-2.
64. Yu, D.; Xu, Z.; Pedrycz, W.; Wanru, W. Information Sciences 1968–2016: A retrospective analysis with text mining and bibliometric. *Inf. Sci.* **2017**, *418*, 619–634. [CrossRef]
65. Boothandford, M.E.; Abanades, J.C.; Anthony, E.J.; Blunt, M.J.; Brandani, S.; Dowell, N.M.; Fernández, J.R.; Ferrari, M.; Gross, R.; Hallett, J.P.; et al. Carbon capture and storage update. *Energy Environ. Sci.* **2014**, *7*, 130–189. [CrossRef]
66. Wang, J.; Huang, L.; Yang, R.; Zhang, Z.; Wu, J.; Gao, Y.; Wang, Q.; O'Hare, D.; Zhong, Z.Y. Recent advances in solid sorbents for CO_2 capture and new development trends. *Energy Environ. Sci.* **2014**, *7*, 3478–3518. [CrossRef]
67. Mcdonald, T.M.; Mason, J.A.; Kong, X.; Bloch, E.D.; Gygi, D.; Dani, A.; Crocellà, V.; Giordanino, F.; Odoh, S.O.; Drisdell, W.S. Cooperative insertion of CO_2 in diamine-appended metal-organic frameworks. *Nature* **2015**, *519*, 303–308. [CrossRef] [PubMed]
68. Furukawa, H.; Cordova, K.E.; O'Keeffe, M.; Yaghi, O.M. The chemistry and applications of metal-organic frameworks. *Science* **2013**, *341*, 974. [CrossRef] [PubMed]
69. Abanades, J.C.; Grasa, G.; Alonso, M.; Rodriguez, N.; Aanthony, E.J.; Romeo, L.M. Cost structure of a postcombustion CO_2 capture system using CaO. *Environ. Sci. Technol.* **2007**, *41*, 5523–5527. [CrossRef] [PubMed]

70. Veltman, K.; Singh, B.; Hertwich, E.G. Human and Environmental Impact Assessment of Postcombustion CO_2 Capture Focusing on Emissions from Amine-Based Scrubbing Solvents to Air. *Environ. Sci. Technol.* **2010**, *44*, 1496–1502. [CrossRef] [PubMed]
71. Plaza, M.G.; Pevida, C.; Arias, B.; Fermoso, A.J.; Casal, M.D.; Martín, C.F.; Rubiera, F.; Pis, J.J. Development of low-cost biomass-based adsorbents for postcombustion CO_2 capture. *Fuel* **2009**, *88*, 2442–2447. [CrossRef]
72. Li, Y.; Su, M.; Xie, X.; Wu, S.; Liu, C. CO_2 capture performance of synthetic sorbent prepared from carbide slag and aluminum nitrate hydrate by combustion synthesis. *Appl. Energy* **2015**, *145*, 60–68. [CrossRef]
73. Li, Y.; Sun, R.; Liu, C.; Liu, H.; Lu, C. CO_2 capture by carbide slag from chlor-alkali plant in calcination/carbonation cycles. *Int. J. Greenh. Gas Control* **2012**, *9*, 117–123. [CrossRef]
74. Sun, J.; Liu, W.; Hu, Y.; Wu, J.; Li, M.; Yang, X.; Wang, W.; Xu, M. Enhanced performance of extruded–spheronized carbide slag pellets for high temperature CO_2 capture. *Chem. Eng. J.* **2016**, *285*, 293–303. [CrossRef]
75. Yu, J.; Le, Y.; Cheng, B. Fabrication and CO_2 adsorption performance of bimodal porous silica hollow spheres with amine-modified surfaces. *RSC Adv.* **2012**, *2*, 6784–6791. [CrossRef]
76. Qin, C.; Liu, W.; An, H.; Yin, J.; Feng, B. Fabrication of CaO-Based Sorbents for CO_2 Capture by a Mixing Method. *Environ. Sci. Technol.* **2012**, *46*, 1932–1939. [CrossRef] [PubMed]
77. Sun, L.B.; Li, A.G.; Liu, X.D.; Liu, X.Q.; Feng, D.; Lu, W.; Yuan, D.; Zhou, H.C. Facile fabrication of cost-effective porous polymer networks for highly selective CO_2 capture. *J. Mater. Chem. A* **2015**, *3*, 3252–3256. [CrossRef]
78. Liu, R.L.; Ji, W.J.; He, T.; Zhang, Z.L.; Zhang, J.; Dang, F.Q. Fabrication of nitrogen-doped hierarchically porous carbons through a hybrid dual-template route for CO_2, capture and haemoperfusion. *Carbon* **2014**, *76*, 84–95. [CrossRef]
79. Chandra, V.; Yu, S.U.; Kim, S.H.; Yoon, Y.S.; Kim, D.Y.; Kwon, A.H.; Meyyappan, M.; Kim, K.S. Highly selective CO_2 capture on N-doped carbon produced by chemical activation of polypyrrole functionalized graphene sheets. *Chem. Commun.* **2012**, *48*, 735–737. [CrossRef] [PubMed]
80. Garciagallastegui, A.; Iruretagoyena, D.; Gouvea, V.; Mokhtar, M.; Asiri, A.M.; Basahel, S.N.; AI-Thbaiti, S.A.; Alyoubi, A.O.; Chadwick, D.; Shaffer, M.S.P. Graphene Oxide as Support for Layered Double Hydroxides: Enhancing the CO_2 Adsorption Capacity. *Chem. Mater.* **2012**, *24*, 4531–4539. [CrossRef]
81. Li, X.; Cheng, Y.; Zhang, H.; Wang, S.; Jiang, Z.; Guo, R.; Wu, H. Efficient CO_2 Capture by Functionalized Graphene Oxide Nanosheets as Fillers to Fabricate Multi-Permselective Mixed Matrix Membranes. *ACS Appl. Mater. Interface* **2015**, *7*, 5528–5537. [CrossRef] [PubMed]
82. Shen, J.; Liu, G.; Huang, K.; Jin, W.; Lee, K.R.; Xu, N. Membranes with fast and selective gas-transport channels of laminar graphene oxide for efficient CO_2 capture. *Angew. Chem.* **2015**, *54*, 588–592. [CrossRef]
83. Li, Q.; Yang, J.; Feng, D.; Wu, Z.; Wu, Q.; Park, S.S.; Ha, C.S.; Zhao, D.Y. Facile synthesis of porous carbon nitride spheres with hierarchical three-dimensional mesostructures for CO_2, capture. *Nano Res.* **2010**, *3*, 632–642. [CrossRef]
84. Lu, J.; Zhang, J. Facile synthesis of azo-linked porous organic frameworks via reductive homocoupling for selective CO_2 capture. *J. Mater. Chem. A* **2014**, *2*, 13831–13834. [CrossRef]
85. Kim, H.; Jang, H.D.; Choi, M. Facile synthesis of macroporous Li_4SiO_4, with remarkably enhanced CO_2, adsorption kinetics. *Chem. Eng. J.* **2015**, *280*, 132–137. [CrossRef]
86. Zheng, B.; Xu, J. Carbon Capture and Storage Development Trends from a Techno-Paradigm Perspective. *Energies* **2014**, *7*, 5221–5250. [CrossRef]
87. Feldpauschparker, A.M.; Burnham, M.; Melnik, M.; Callaghan, M.L.; Selfa, T. News media analysis of carbon capture and storage and biomass: Perceptions and possibilities. *Energies* **2015**, *8*, 3058–3074. [CrossRef]
88. You, H.; Seo, Y.; Huh, C.; Daejun, C. Performance Analysis of Cold Energy Recovery from CO_2 Injection in Ship-Based Carbon Capture and Storage (CCS). *Energies* **2014**, *7*, 7266–7281. [CrossRef]
89. Hardisty, P.E.; Sivapalan, M.; Brooks, P. The Environmental and Economic Sustainability of Carbon Capture and Storage. *Int. J. Environ. Res. Public Health* **2011**, *8*, 1460–1477. [CrossRef] [PubMed]
90. Strazza, C.; Borghi, A.D.; Gallo, M. Development of Specific Rules for the Application of Life Cycle Assessment to Carbon Capture and Storage. *Energies* **2013**, *6*, 1250–1265. [CrossRef]
91. Lin, Q. The feasibilities and principles of climate negotiation guided by climate ethics. *Int. Forum* **2017**, *19*, 7–13. [CrossRef]

92. Qiu, H.-H.; Yang, J. An Assessment of Technological Innovation Capabilities of Carbon Capture and Storage Technology Based on Patent Analysis: A Comparative Study between China and the United States. *Sustainability* **2018**, *10*, 877. [CrossRef]
93. Alphen, K.V.; Noothout, P.M.; Hekkert, M.P.; Turkenburg, W.C. Evaluating the development of carbon capture and storage technologies in the United States. *Renew. Sustain. Energy Rev.* **2010**, *14*, 971–986. [CrossRef]
94. Zhang, X.; Fan, J.L.; Wei, Y.M. Technology roadmap study on carbon capture, utilization and storage in China. *Energy Policy* **2013**, *59*, 536–550. [CrossRef]
95. Sun, L.; Dou, H.; Li, Z.; Hu, Y.; Hao, X. Assessment of CO_2 storage potential and carbon capture, utilization and storage prospect in China. *J. Energy Inst.* **2017**. [CrossRef]
96. Shackley, S.; Waterman, H.; Godfroij, P.; Reiner, D.; Anderson, J.; Draxlbauer, K.; Flach, T. Stakeholder perceptions of CO_2, capture and storage in Europe: Results from a survey. *Energy Policy* **2007**, *35*, 5091–5108. [CrossRef]
97. Rodrigues, C.F.A.; Dinis, M.A.P.; Sousa, M.J.L.D. Review of European energy policies regarding the recent "carbon capture, utilization and storage" technologies scenario and the role of coal seams. *Environ. Earth Sci.* **2015**, *74*, 2553–2561. [CrossRef]
98. Dijkstra, J.W.; Walspurger, S.; Elzinga, G.D.; Pieterse, J.A.Z.; Boon, J.; Haije, W.G. Evaluation of post combustion CO_2 capture by a solid sorbent with process modeling using experimental CO_2 and H_2O adsorption characteristics. *Ind. Eng. Chem. Res.* **2018**, *57*, 1245–1261. [CrossRef]
99. Ge, B.S.; Wang, T.; Sun, H.X.; Gao, W.; Zhao, H.R. Preparation of mixed matrix membranes based on polyimide and aminated graphene oxide for CO_2 separation. *Polym. Adv. Technol.* **2018**, *29*, 1334–1343. [CrossRef]
100. Llerena, P.; Oltra, V. Diversity of innovative strategy as a source of technological performance. *Struct. Chang. Econ. Dyn.* **2002**, *13*, 179–201. [CrossRef]
101. Zhou, L.; Duan, M.; Yu, Y. Exergy and economic analyses of indirect coal-to-liquid technology coupling carbon capture and storage. *J. Clean. Prod.* **2018**, *174*, 87–95. [CrossRef]
102. Braun, C.; Merk, C.; Pönitzsch, G.; Rehdanz, K.; Schmidt, U. Public perception of climate engineering and carbon capture and storage in Germany: Survey evidence. *Clim. Policy* **2018**, *18*, 471–484. [CrossRef]