Research Progress and Hotspot Analysis of Carbon Capture, Utilization, and Storage (CCUS): A Visual Analysis Using CiteSpace

Qin Li, Yijun Liu, Wenlong Li, Yongqiang Yan, and Zhonghao Wu

Abstract

The issue of global climate change has become increasingly prominent. The reduction of fossil energy consumption and the reduction of greenhouse gas emissions have attracted more and more attention from countries. Carbon capture, utilization, and storage (CCUS) technology is considered to have the synergistic effect of achieving large-scale greenhouse gas emission reduction and low-carbon utilization of fossil energy. It is one of the important technological choices for the global response to climate change in the future. It has attracted governments and enterprises from all over the world and the high attention of the academic community. This paper screened out 1890 scientific articles related to global CCUS from the Web of Science Core Collection and used the CiteSpace to analyze the knowledge graph of the papers since 2011. The paper visually displays the most productive institutions, authors, and sources in the CCUS research. In addition, the paper explains how research subjects have changed over time and analyzes research frontiers. The results show that: (1) CCUS research has accelerated globally in the past ten years, with the United States, the United Kingdom, and China ranking the top three. (2) Research hotspots mainly focus on engineering, energy and fuels, engineering chemistry, engineering environment, science and technology, green sustainable technology, environmental science, and ecology. (3) CCUS has become a multidisciplinary research, in which all research subjects related to CCUS have been cited and correlated. In general, this research is helpful for policy guidance and follow-up research.

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Keywords

Carbon capture, utilization and storage (CCUS) • Visualization • CiteSpace • Bibliometric methods

1 Introduction

With the rapid development of the global economy and the human consumption of fossil energy such as coal, oil, and natural gas, a large number of pollutants and greenhouse gases are emitted. Various environmental problems are frequently occurring all over the world, such as the greenhouse effect, haze, deterioration of water quality, and the sharp decline of biodiversity. It has caused a negative impact on the global climate and seriously threatens human health and social development (Fan, 2015). The "Kyoto Protocol" states there are six main greenhouse gases emitted by humans, of which carbon dioxide has the greatest impact on climate change. The warming effect it produces accounts for 63% of the total of all greenhouse gases, and it can last up to 200 years in the atmosphere. With the emergence of global climate issues, scientific research on climate change and how to take actions to mitigate global climate change have become hot topics discussed by the international community, governments, and even the public.

Climate issues are closely related to people's lives, and countries have made many efforts to this end. In order to reduce the greenhouse climate (especially carbon dioxide emissions), the IPCC passed difficult negotiations and finally passed the "United Nations Framework Convention on Climate Change" in 1992. It is the first international convention proposed in human history to comprehensively control carbon dioxide and other greenhouse climate emissions and slow down the adverse effects of global warming on human society. It provides a reliable basis for the international community to deal with global climate issues. On September 27, 2013, in Stockholm, the capital of Sweden, the fifth

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assessment report (AR5) of the First Working Group of the United Nations Intergovernmental Panel on Climate Change (IPCC) conducted a new assessment of the new progress in climate change research since 2007 (Shen et al., 2013; UNFCCC, 1994). It has provided new scientific support for a new round of international climate change, policies and actions, and has played an important role in promoting the adoption and implementation of the "United Nations Framework Convention on Climate Change" by governments.

The measures that we can take to mitigate climate change are very limited, for example, reducing the use of traditional energy, increasing the use of low-carbon energy, capturing carbon dioxide in the production process to achieve geological storage or utilization, biological carbon sequestration, etc. However, due to the huge global energy system and energy demand, human energy production has been deeply dependent on fossil energy, and it is difficult to change the energy consumption structure in the short term.

Therefore, considering the global environmental status, the urgency of achieving carbon emission reduction, and the limitations of emission reduction methods, carbon capture and storage (CCS) will become one of the most effective ways to global emission reduction (GCCSI, 2017).

2 Literature Review

Carbon capture, utilization, and storage (CCUS) is the process of separating CO_2 from industrial processes, energy utilization, or the atmosphere and directly using or injecting it into the formation to achieve permanent carbon dioxide emission reduction. CCUS adds "utilization" to the CCS. This concept is based on the development and deepening understanding of CCS technology, under the vigorous advocacy of China and the United States. CCUS is expected to be a critical method in achieving global warming goals (IEA, 2020; Romasheva et al., 2019; Stuardi et al., 2019). CCUS is divided into capture, transportation, utilization, and storage links according to the technical process (Fig. 1).

CO_2 capture refers to the process of separating CO_2 from industrial production, energy utilization, or the atmosphere (Fig. 2). CO_2 transportation refers to the process of transporting the captured CO_2 to an available or storage site. According to different modes of transportation, it is divided into tanker transportation, ship transportation, and pipeline transportation. CO_2 utilization refers to the process of recycling the captured CO_2 through engineering and technical means. According to different engineering techniques, it can be divided into CO_2 geological utilization, CO_2 chemical utilization, and CO_2 biological utilization. Among them, CO_2 geological utilization is the process of injecting CO_2 into the ground to achieve enhanced energy production and promote resource extraction, such as improving oil and natural gas recovery, mining geothermal, deep salt water, uranium, and other types of resources. Biomass carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) are highly valued as negative carbon technologies. BECCS refers to the process of capturing, utilizing, or storing the CO_2 produced in the process of biomass combustion or conversion. DACCS is a process of directly capturing CO_2 from the atmosphere and using or storing it. Compared with CCS technology, CCUS can recycle carbon dioxide and bring obvious economy benefit (IPCC, 2005). CCUS can contribute nearly one-fifth of the emission reduction required by the entire industrial sector. It is estimated that CCUS technology could account for 32% of the global reduction in carbon dioxide emissions by 2050 (Regufe et al., 2021).

3 Materials and Methods

3.1 Data Sources and Screening

The bibliographic data collected in this study came from the Web of Science Core Collection (WOSCC). WOSCC's bibliographic sources (SCIE and SSCI) are very comprehensive, and its data sources are representative and accessible (Id et al., 2016). The time span of this study is from January 1, 2011 to July 10, 2021. Set the search subjects to the followings: TS = "carbon capture, utilization and storage" OR "carbon capture and storage" OR "carbon capture and utilization." Through the category refinement function of the Web of Science, the document type is refined into "ARTICLE." We went over the titles of all publications and removed those that were not relevant to the study. We ended up with 1890 records and downloaded these bibliographic records (involving titles, authors, keywords, abstracts, periodicals, and other publication information, see Supplementary File S1). Then, we use CiteSpace to perform a scientometric analysis of the data records.

3.2 Analytical Methods

There are many commonly used visual analysis software, including HistCite (Garfield et al., 2002), VOSviewer (Zhu et al., 2021), RefViz (Simboli et al., 2004), SATI (Liu et al., 2012), and CiteSpace (Chen, 2017). By comparing the characteristics of the above programs, we chose to use CiteSpace 5.6R3 as the main tool for literature analysis.

CiteSpace is a software developed by Professor Chen in 2004 (Meerow & Stults, 2016), and it is an important analysis and visualization tool in the field of scientific metrology (Chen, 2010). CiteSpace can professionally analyze the basic knowledge in the literature and achieve

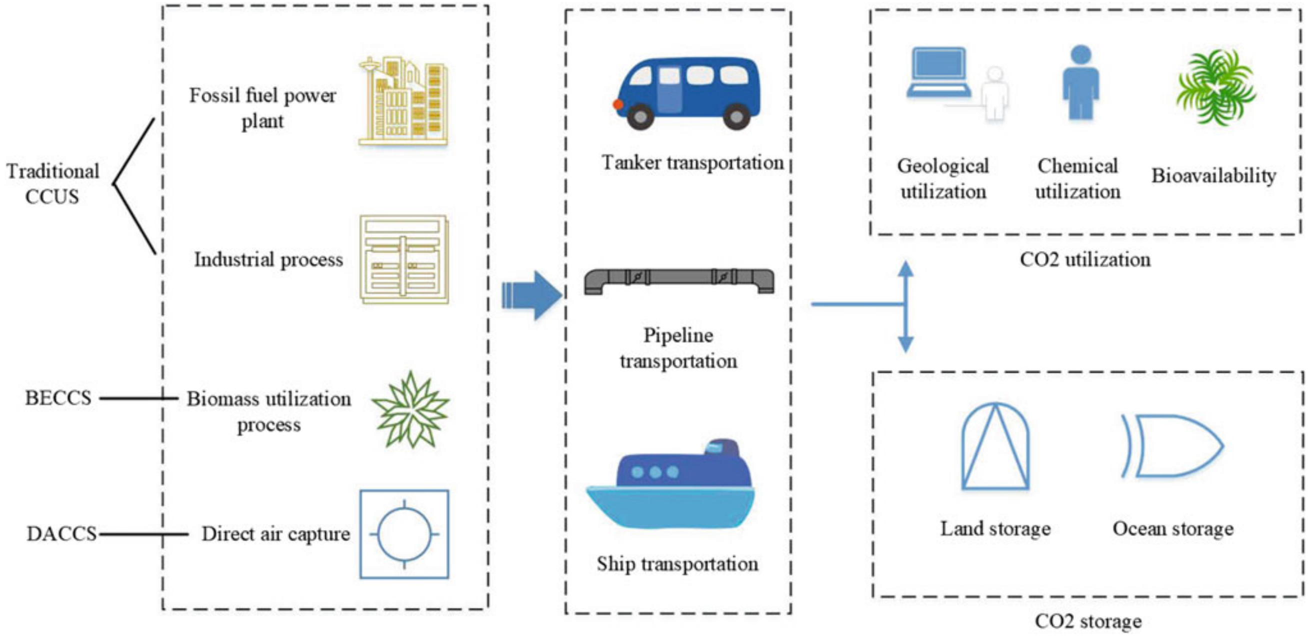


Fig. 1 CCUS technical route diagram (from China agenda 21 management center)

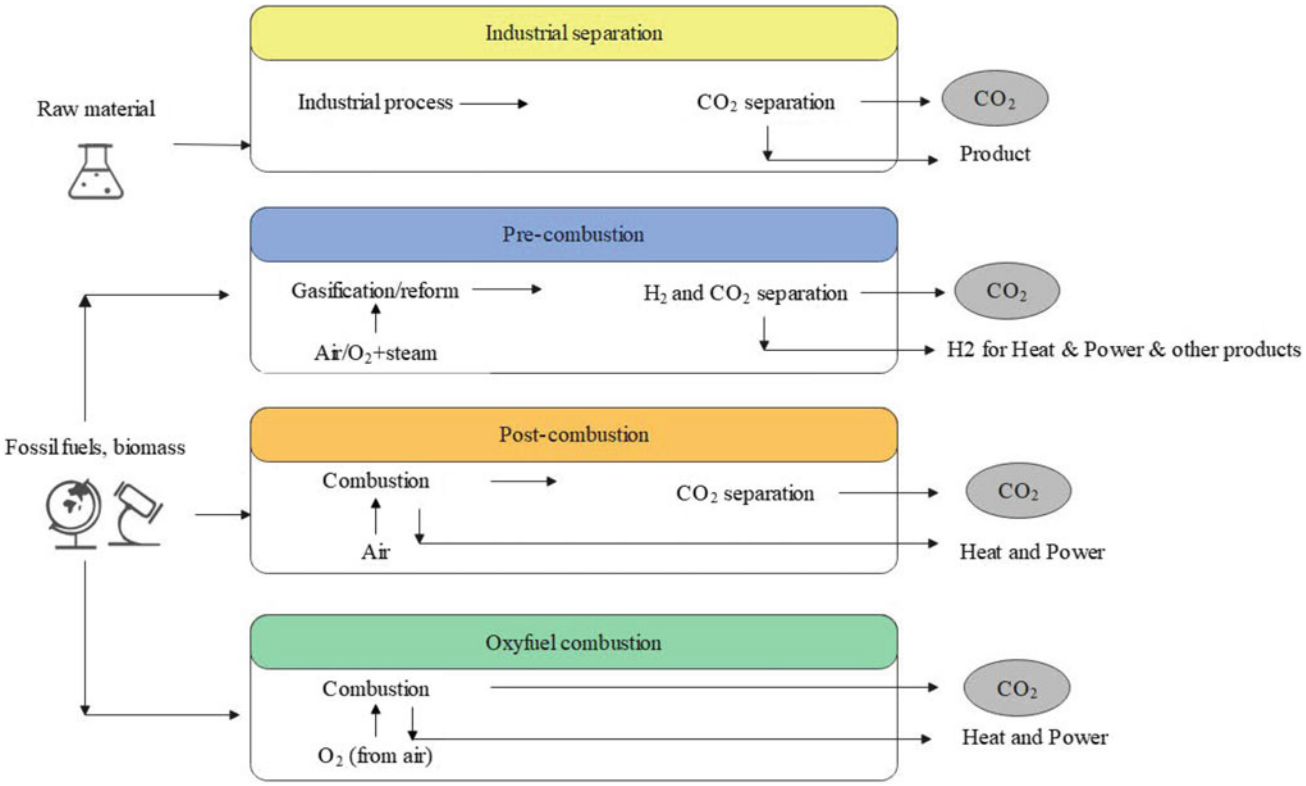


Fig. 2 Carbon capture technology roadmap

multi-dimensional, dynamic, and time-division analysis. In addition, CiteSpace also provides scholars with a bibliographic co-occurrence analysis system such as countries, institutions, and authors, which can conduct cooperative analysis from the perspective of cooperative networks (Muller, 2007).

Compared with other visualization software, the main advantages of CiteSpace are as follows: (1) review and study the theoretical roots of rapid changes and complex regions; (2) improve the clarity and interpretability of visualization; and (3) through the time segmentation visualization in the evolutionary network, detect and explain the tipping point, transformation mode, and emerging research directions for researchers who are not experts in the field (Milman & Short, 2008; Ooi et al., 2013). The overall flow chart of this research is shown in Fig. 3.

4 Results and Discussions

4.1 Characteristics of Publications

Since the amount of annual publications can reflect researchers' attention to a knowledge field, the time trend of data records is shown in Fig. 4. In the past ten years, the number of papers published by CCUS has shown an overall upward trend. In 2011, there were 73 publication records on CCUS. However, the number of publications has suddenly increased since 2012. By 2014, the number of publications on CCUS was twice that of 2011. From 2015 to 2018, although the number of publications fluctuated, it basically showed a steady upward trend, with the number of publications exceeding 150 each year. Since 2019, the number of publications each year has exceeded 200. Especially in 2020, CCUS has attracted the attention of global scholars, which may be related to national policies. More and more governments are incorporating carbon neutrality goals into their national strategies.

For example, the European Union's "Climate Neutral Law" submitted in March 2020 aims to ensure that Europe will become the first "climate neutral" continent by 2050 from a legal perspective. California and China have set targets for "carbon neutrality" in 2045 and 2060, respectively. Due to different stages of development, developed countries have generally experienced "carbon peaks." In order to achieve "carbon neutrality" by 2050, to a greater extent, it is just a continuation of the previous slope of emission reduction. China's total carbon emissions are still increasing, and it needs to experience "carbon peak" before 2030 and then move toward "carbon neutrality" before 2060.

4.2 Cooperation Networks Analysis

4.2.1 Network of Countries and Institutions

Our analysis of cooperation networks focuses on the importance and relevance of countries, institutions, and authors to the field. It reveals the distribution of research power, cooperation intensity, and distribution among different nodes in the global research network. A collaborative relationship network has been formed between the state and the institution. In the collaborative relationship network, nodes refer to different countries and institutions, and links describe their collaborative relationships in CCUS. Figure 5 shows the cooperation relationship between countries and institutions in CCUS.

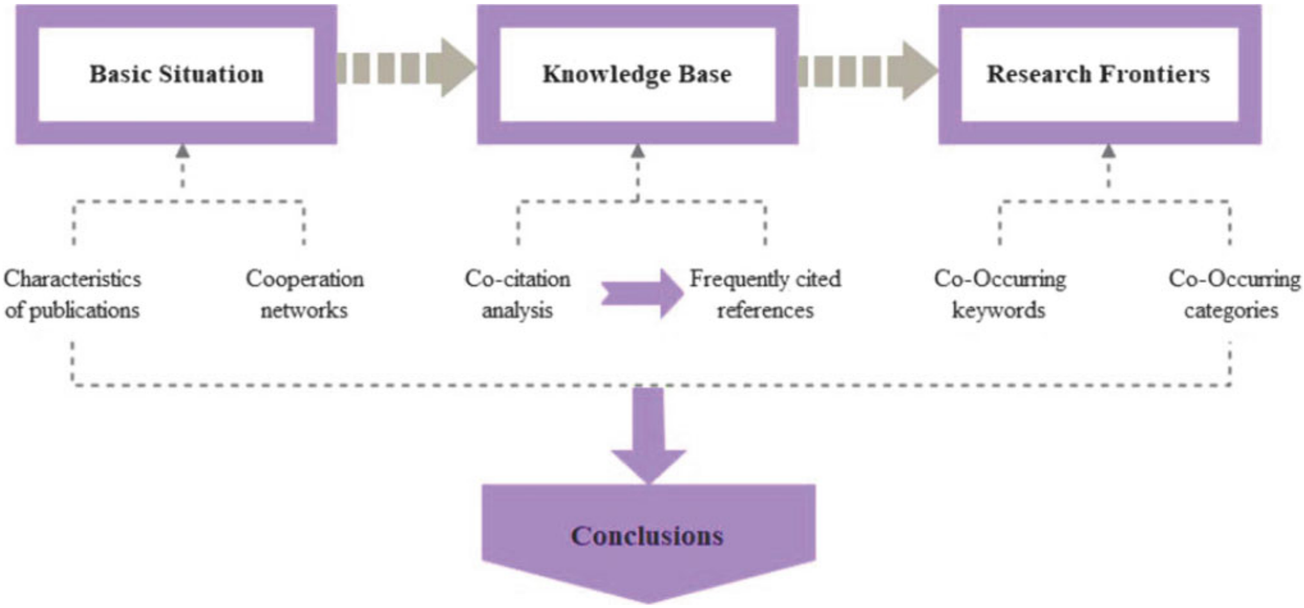


Fig. 3 The overall flow chart of the research

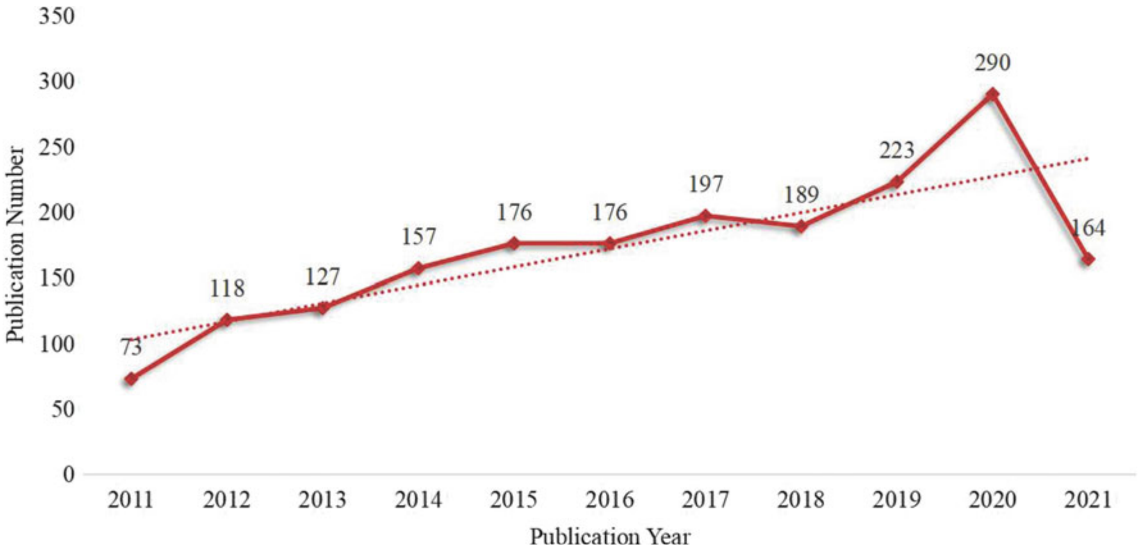
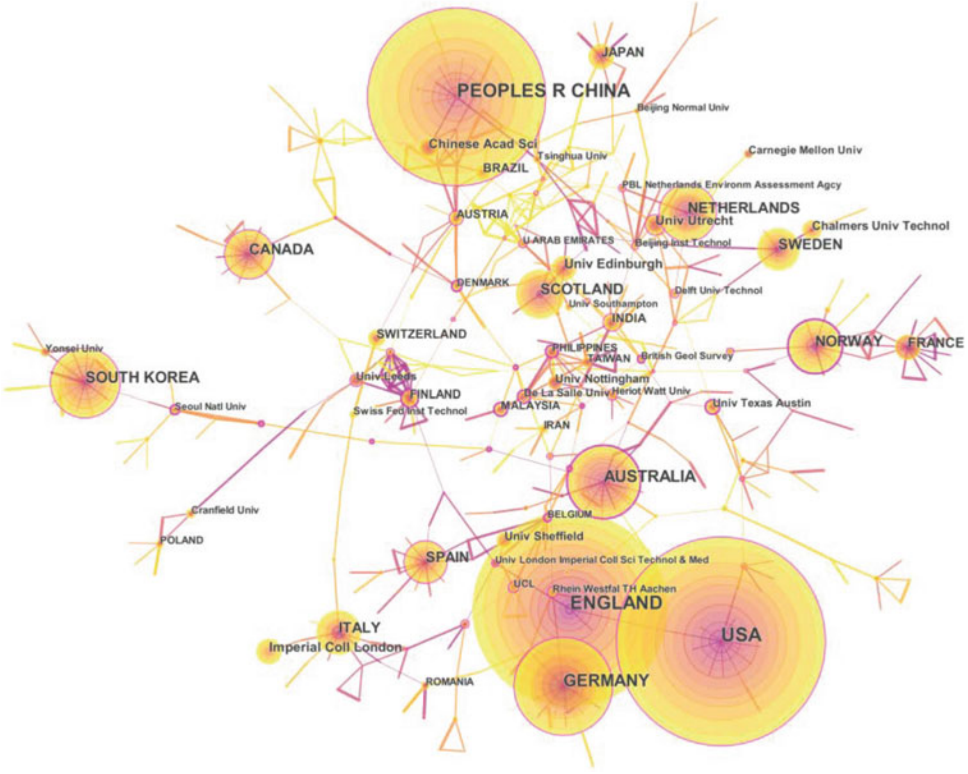


Fig. 4 The time distribution of annual publication records

Fig. 5 Cooperative networks of countries and institutions



We found that 71 countries (regions) and 346 research organizations participated in the CCUS study. Among them, 3 countries and 25 institutions have published the most papers. The United States (Number of publications [Count] = 356) is the main country, followed by the United Kingdom (Count = 339) and China (Count = 307).

As can be seen in Fig. 5, although the United States is the largest contributor to publications of all countries, the influence of the United Kingdom and China in the cooperative relationship network is almost the same as that of the United States. As the main contributors to publications, the three countries of the Netherlands, Australia, and South

Korea also have a great influence in the cooperative network relationship. In addition, China has close cooperative relations with almost countries that have amount of publications, such as the United States, the United Kingdom, the Netherlands, and Australia.

Figure 5 also shows the dedication and collaboration of research organizations in the CCUS study. There are a large number of research institutions in the UK, including the University of Edinburgh (Count = 48), Imperial College London (Count = 48), University of Nottingham (Count = 29), and University of Sheffield (Count = 29).

Research institutions in the United States mainly include the University of Texas at Austin (Count = 24) and Carnegie Mellon University (Count = 21). In contrast, Chinese research achievements come mainly from the Chinese Academy of Sciences (Count = 40) and Tsinghua University (Count = 20). Among them, the Chinese Academy of Sciences stands out, with 40 publications. Among the top five institutions in terms of the number of papers published, in addition to research institutions in the UK and China, there are also Utrecht University in the Netherlands (Count = 40) and Chalmers University in Sweden (Count = 37). The universities ranked at 6% of research organizations are mainly from countries which have a large number of publications, for example, the United States, the United Kingdom, China, and the Netherlands. Table 1 lists the top 6% of research institutions.

4.2.2 Network of Authors

The analysis of academic cooperation network reflects the productivity level of scientific researchers and their contribution to scientific research. The distribution of cooperation networks between countries and institutions is relatively concentrated. However, the authors' contributions to CCUS research are distributed in multiple groups in the network of co-authors (Fig. 6). Currently, 482 authors are studying CCUS, of which 68 authors have published more than 4 articles. As shown in Fig. 3, the authors with the largest number of publications in the CCUS field are Raymod R. Tan and Niall Mac Dowell (Count = 18), followed by Jin-won Park (Count = 15), Calincristian Cormos (Count = 13), and Dominic C Y Foo (Count = 11), as well as Edward S Rubin (Count = 10), Detlef P Van Vuuren (Count = 10), Xian Zhang (Count = 10), and Dongwoo Kang (Count = 9). Table 2 lists the authors who have published the most papers in CCUS research in recent years.

Through the network analysis of co-authors, it is obvious that the two research teams with the largest number of publications are Raymod R. Tan (Tan et al., 2012) from Philippines De La Salle University and Niall Mac Dowell

Table 1 Top 6% of institutions

Institutions	Count	Centrality	Percentage of total (%)
University of Edinburgh	48	0.17	13.9
Imperial Cole, London	48	0.01	13.9
Chinese Academy of Sciences	40	0.14	11.6
University of Utrecht	40	0.10	11.6
Chalmers University of Technology	37	0.01	10.7
University of Nottingham	29	0.00	8.4
University of Sheffield	29	0.01	8.4
The University of Leeds	25	0.11	7.2
University of Texas-Austin	24	0.05	6.9
De La Salle University	21	0.13	6.1
Carnegie Mellon University	21	0.01	6.1
Rhein Westfal TH Aachen	20	0.04	5.8
Cranfield University	20	0.01	5.8
Tsinghua University	20	0.06	5.8
Heriot-Watt University	19	0.14	5.5
University College London	19	0.02	5.5
Yonsei University	18	0.02	5.2
Swiss Federal Institute of Technology	17	0.08	4.9
Beijing Institute of Technology	17	0.13	4.9
Beijing Normal University	16	0.11	4.6
Technische Universiteit Delft	16	0.06	4.6

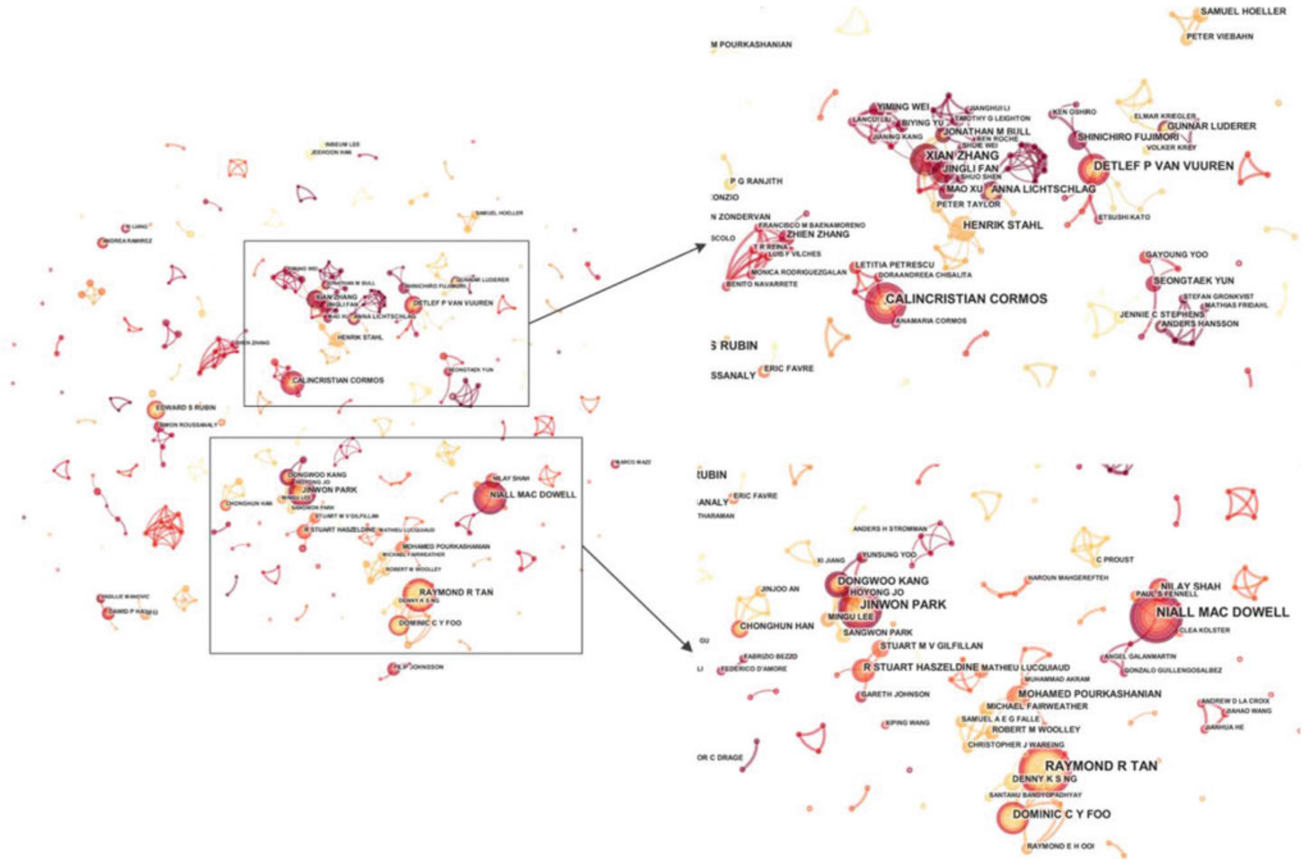


Fig. 6 Cooperative networks of authors

(Bhave et al., 2017; Dowell et al., 2017; Mechleri et al., 2017) from Imperial College London. The research direction of the previous research group is mainly the process integration of resource protection and carbon dioxide emission reduction. The other research group is mainly bioenergy systems and technologies, urban energy systems, and modeling and optimization of low-carbon technologies and systems. The second-ranked research team is composed of scholars from South Korea and is mainly focused on the development of low-carbon industries to reduce carbon emissions, as well as the conversion and application of carbon dioxide. The research team is led by Jinwon Park (Park et al., 2013), who is from Yonsei University. There are also Dongwoo Kang from Chungbuk National University (Kang et al., 2016) and Sangwon Park from Kyung Hee University (Park et al., 2014). Beginning in 2019, a research team has been committed to seeking the least cost-effective way to convert carbon dioxide in the atmosphere and to conduct economic evaluation of CCUS from all aspects (Fan et al., 2019, 2020). Scholars in this group are mainly from the China Agenda 21 Administration Center, China University of Mining and Technology, Beijing Institute of Technology, and Beijing Normal University. Among them, China University of Mining and Technology and Beijing Institute of Technology cooperate closely. Due to the needs of China's national conditions, the Chinese research team has been very active in the field of CCUS, constantly expanding the content and promoting the application of CCUS. China is the country with the largest CO_2 emissions, and its existing CCUS demonstration projects are small. The technical cost of CCUS is an important factor that affects its large-scale application, but with the rapid development of technology, the cost of CCUS technology in China has a large room for decline in the future (Yang et al., 2019). The co-author relationship only reflects the output and contribution of CCUS research results. Highly productive authors do not necessarily have a great influence on CCUS research. The author's level of influence is reflected by the analysis of co-citation in the literature.

4.3 Knowledge Base Analysis

4.3.1 Co-citation Clustering Analysis

Literature co-citation analysis is applied to measure the dependency relationship of formerly CCUS study. We found 64,065 co-cited articles among 1890 publications, of which 302 were cited more than twice (Supplementary File S2).

Table 2 The institutions of authors with more than 10 publications

Frequency	Year	Author	Institution
18	2013	Raymond R. Tan	Philippines De La Salle University
18	2017	Niall Mac Dowell	Imperial College London
15	2013	Jinwon Park	Yonsei University
13	2012	Calin-CristianCormos	Babes-Bolyai University
10	2013	Edward S.Rubin	Carnegie Mellon University
10	2014	Detlef P. van Vuuren	Utrecht University
10	2019	Xian Zhang	The Administrative Centre for China's Agenda 21

We found 6 primary clusters reflecting the CCUS research knowledge base. The clustering of co-cited documents is shown in Fig. 7. The Modularity is 0.8267, indicating that the various research fields of CCUS research can be clearly defined (Chaomei, 2017). The Mean Sihouette is 0.517, indicating that the cluster uniformity is normal.

Although our research time is from 2011 to 2021, there are related papers as early as 2006, and the "co(2) capture" cluster appears the earliest. The cited literature mainly focuses on the technologies and cases of recovery of carbon dioxide after combustion. The keywords used are post-combustion capture, carbon capture and storage, carbon dioxide removal rate, technological innovation, greenhouse gases, climate change, etc. It provides a wealth of case study references for CCUS research. "Environmental impacts" are clusters that appeared in 2007–2011. The former mainly includes low-carbon investment, state policy, CCS investment cost, real options, etc. The latter mainly includes life cycle assessment and bioenergy.

"Bioenergy with carbon capture and storage" has the longest clustering time (2012–2019). It forms the largest cluster and contains the most cited publications, reflecting the field's focus on research topics. The cluster mainly focuses on the technical method level, such as negative emission technologies, prometheus energy system model, energy system and integrated assessment models, and multi-criteria decision analysis. At the same time, the clustering also includes some theoretical methods, such as CO_2 footprint, energy system transformation, biomass resources, energy system decarbonization, and preference elicitation. The "membranes" cluster started in 2012 and lasted until 2020. The cluster mainly focuses on the chemical analysis and physical models involved in CCUS. The keywords used are decompression of real fluid, thermodynamic analysis, geothermal energy, computational fluid dynamics modelling, monte carlo simulation, lignite-fired igcc, and reversible solid oxide cells.

The "beccs" cluster mainly focuses on negative carbon emission technologies, combining bioenergy with carbon capture and storage technologies, and is currently regarded as one of the most feasible negative emission technologies. BECCS absorbs carbon dioxide from the air through the growth of crops or trees. This will not only release energy by burning these trees, but also capture the carbon emitted by the combustion. The captured carbon is sequestered underground to prevent it from returning to the atmosphere, and then, the whole process is repeated. However, the biggest concern about BECCS is that a large amount of land is needed to grow bioenergy first, which may compete with food supply or lead to deforestation. Therefore, more research is needed to verify and support BECCS technology.

"Carbon capture and utilization" started in 2014 and lasted until 2020. It was the last cluster that appeared during our analysis. As the "Double Carbon Action (carbon peak,

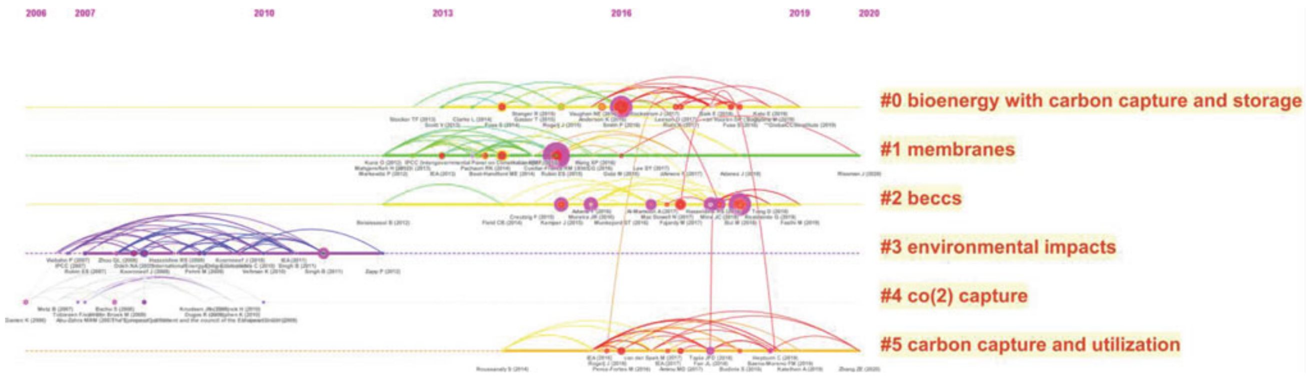


Fig. 7 Clustering of co-cited documents

carbon neutral)" has become the focus of international attention, a lot of research has appeared in related fields. At the same time, clusters #0 and #2 illustrate the necessity of interdisciplinary research and also prove that this field is currently a research hotspot of global concern.

4.3.2 Analysis of the Most Frequently Co-cited Publications

We found 21 papers with more than 20 citations in the co-cited image (Fig. 8). This picture fully demonstrates the general laws, interdisciplinary cooperation, and innovative methods of the development of the discipline to the present and promotes the accumulation of the CCUS research.

We found a book in frequently cited publications (IEA, 2013), which introduced the technical route of CCS and the development direction. It points out that CCS is a key solution to reduce greenhouse gases. Of these 21 papers, 61.9% are journal articles that provide literature reviews or opinions. These publications fully support the development of CCUS research from theoretical basis and other aspects. Energy & Environmental Science has a article by Bui et al. (2018). In this paper, they included the key negative emission technologies (NETs) of bioenergy and CCS (BECCS) and direct air capture in their research scope. Leung et al. (2014) reviewed all aspects of CCS technology, including the latest technologies in CO_2 capture, separation, transportation, storage, leakage, monitoring, and life cycle analysis. Cuellar-Franca (2015) comprehensively compared the environmental impact of CCS and carbon capture and utilization (CCU) technology. Except for GWP, CCS has a higher environmental impacts than CCU. Fuss et al. (2014) published a review article in Nature Climate Change. The review points out that BECCS is unproven. Kemper (2015) reviewed BECCS at the system level and discussed the sustainability issues in BECCS. Both Anderson K and Rogelj J's articles have been cited 26 times. Anderson (2016) raised questions worth thinking about in an opinion paper published in Science. Negative emission technology removes CO_2 from the atmosphere through technical means, but it is not an insurance policy. He believes that if carbon dioxide is not removed from the atmosphere at the level assumed by the Integrated Assessment Models (IAMs), or if it fails, then society will be trapped in the high-temperature channel. Rogelj et al. (2015) analyzed a comprehensive energy economic environment scenarios that keep warming to below 1.5 °C by 2100. In the fifth assessment report of the IPCC (2014) (Climate Change, 2014: Mitigation of Climate Change), Pachauri RK emphasized the importance of technological progress for stabilizing the concentration of greenhouse gases. The key role of CCS as a transitional technology with low or zero emissions in the future has been widely concerned by researchers. Mac Dowell (2017) made it clear that NETs have become the focus of climate science and policy discussions. Aminu (2017) clarified that CCS has been identified as an urgent, strategic, and indispensable method to reduce man-made carbon dioxide emissions and mitigate the serious consequences of climate change.

Cited papers dominated by models and methods accounted for 47.6% of the citation frequency. Among them, Smith et al. (2016) quantified potential global impacts of the different NETs on various factors to determine the biophysical limitations and economic costs. Fajardy et al. (2017) clarified the key leverage to enhance the sustainability of BECCS. Fuss (2018) evaluated the costs, potentials, and side effects of these seven technologies: BECCS, afforestation and reforestation, direct air carbon capture and storage (DACCS), enhanced weathering, ocean fertilization, biochar, and soil carbon sequestration. Perez-Fortes (2016) evaluated methanol (MeOH) produced from hydrogen and captured carbon dioxide through technical, economic, and environmental indicators. Riahi et al. (2016) used a multi-model approach to elaborate on the energy, land use, and emission trajectories based on the shared socioeconomic pathways. Middleton (2009) introduced a scalable CCS infrastructure model. By examining the sensitivity of CCS infrastructure to different carbon dioxide targets, the importance of CCS infrastructure system planning was emphasized, and the key research areas of CCS infrastructure in the future were determined.

The results of case studies accounted for 23.8%, and they provided references for future research. Rubin ES uses different power plants as research objects to evaluate the current cost of CCS for new fossil fuel power plants and compared these results with the costs reported in the IPCC Special Report on Carbon Dioxide Capture and Storage ten years ago. Boot-Handford et al. (2013) introduced the current pilot plants and demonstrations, as well as the importance of optimizing the CCS system as a whole. Koornneef (2008) used the life cycle assessment method to evaluate the environmental impact of three pulverized coal power supply chains with CCS and without CCS. Minx et al. (2018) used scientific measurement tools and conducted an in-depth evaluation of the quantitative and qualitative evidence in NETs.

4.4 Co-word Analysis

4.4.1 Network of Co-occurring Keywords

Co-occurrence keyword analysis provides essential information about core research content and contributes scholars to tracking the development of research topics at different phases. CiteSpace analysis results are as follows: N = 94, Link = 117, and Density = 0.0268.

High-frequency words can be identified from Fig. 9. "Carbon capture and storage" with a frequency of 366 is the

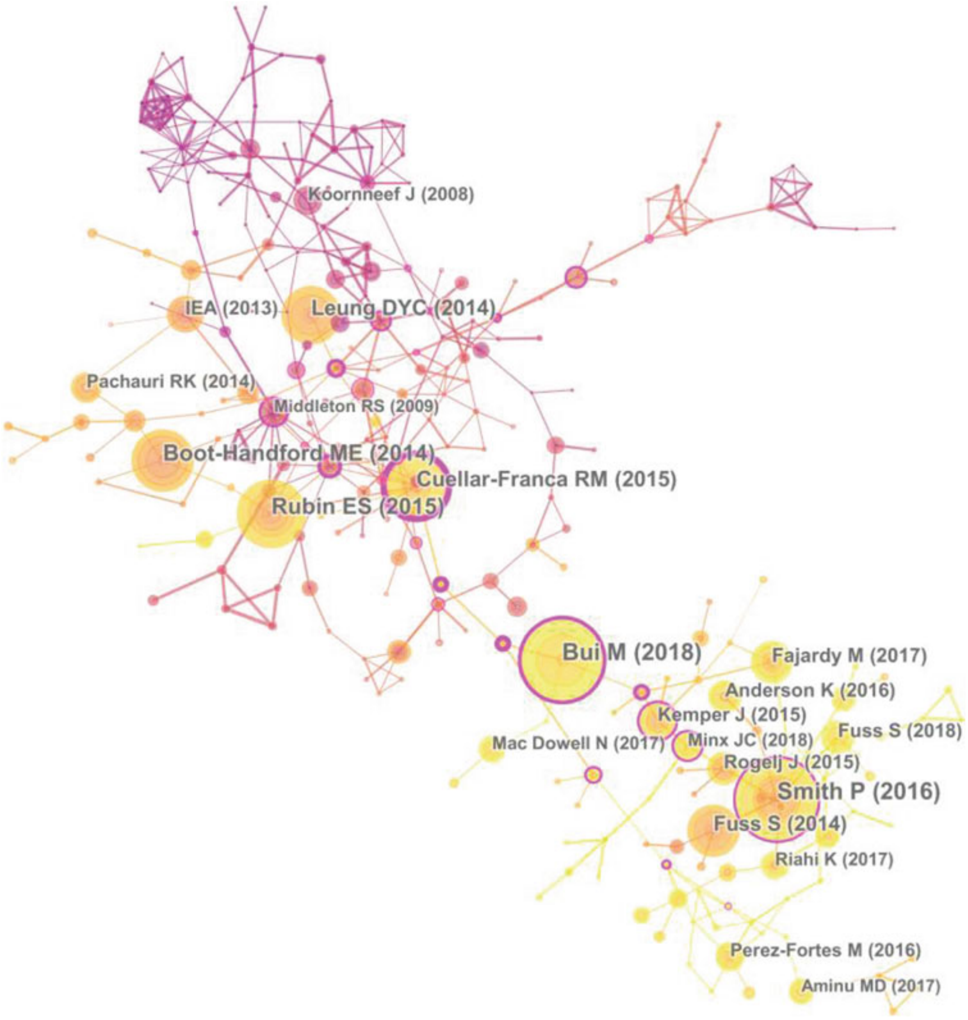


Fig. 8 Most frequently co-cited publications

most important keyword. Related high-frequency keywords are "storage" (Count = 312), "co2 capture" (Count = 296), and "cc" (Count = 277). Other frequently used keywords are "technology" (Count = 216), "carbon capture" (Count = 214), "carbon dioxide" (Count = 204), "capture" (Count = 181), and "co2" (Count = 168).

Keywords with high centrality are "Dioxide" (Centrality [Centr] = 0.80), "power plant" (Centr = 0.78), "life cycle assessment" (Centr = 0.55), "emission" (Centr = 0.43), and "plant" (Centr = 0.43).

In addition, the keywords closely related to research content of CCUS are "energy," "cost," "climate change," "system," "performance," "model," "impact," "bioma," "carbon dioxide capture," "transport," "bioenergy," "chemical looping combustion," "renewable energy," and "coal."

4.4.2 Network of Co-occurring Categories

According to the CiteSpace 5.6.R3, we found 27 topic categories, ten of which have a frequency of more than 100 times. The co-occurrence network analysis of the most common subject categories from 2011 to 2021 is shown in the Figs. 10 and 11.

Engineering is the largest node with a frequency of 1203, followed by Energy & Fuels (Count = 1026) and Engineering, Chemical (Count = 903). Among the top ten disciplines, Environmental Sciences has the highest centrality (Centr = 0.47) and plays a key role in the field of non-point sources 0. In second place is Engineering, followed by Environmental Studies (Centr = 0.26), Engineering & Environmental (Centr = 0.21), Green & Sustainable Science & Technology (Centr = 0.15), Engineering & Civil (Centr = 0.18), and Science & Technology-Other Topics (Centr = 0.17).

The earliest non-point source study involves Engineering & Environmental, Science & Technology-Other Topics, Green & Sustainable Science & Technology, and other fields, followed by Engineering and Environmental Sciences. Non-point source study covers fields ranging from

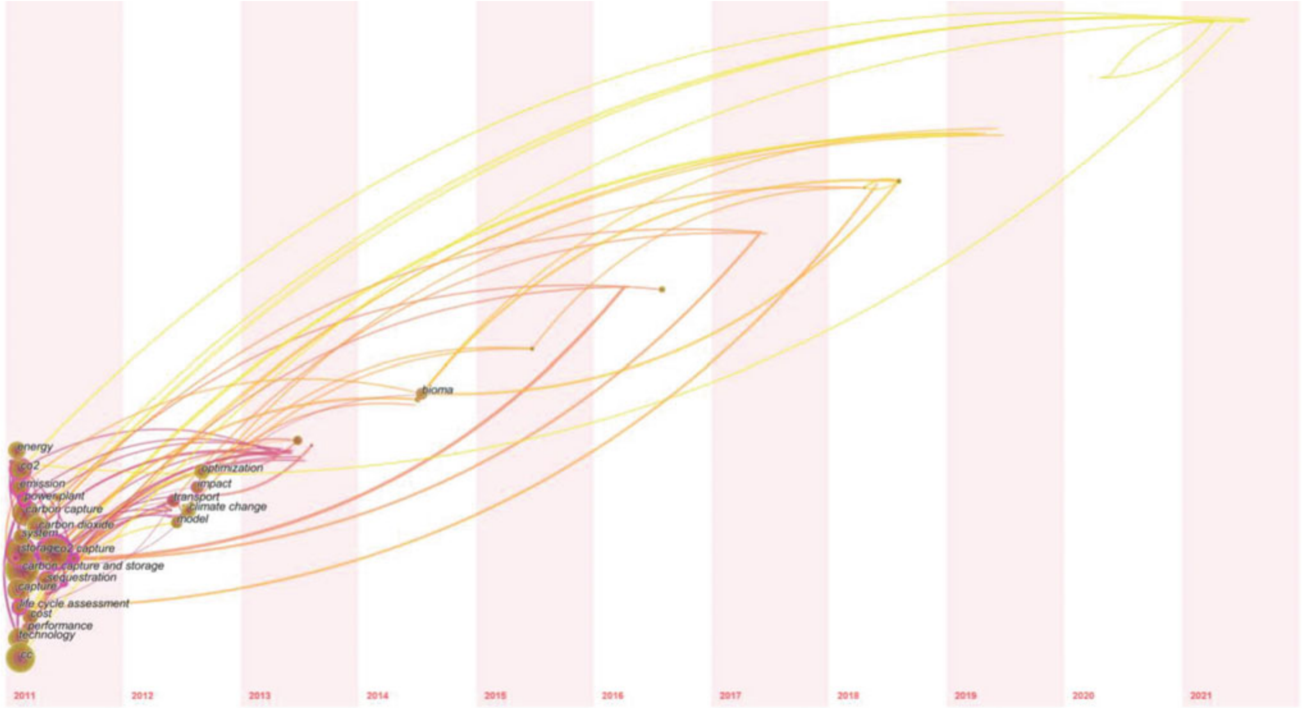


Fig. 9 Keywords co-occurrence time zone network

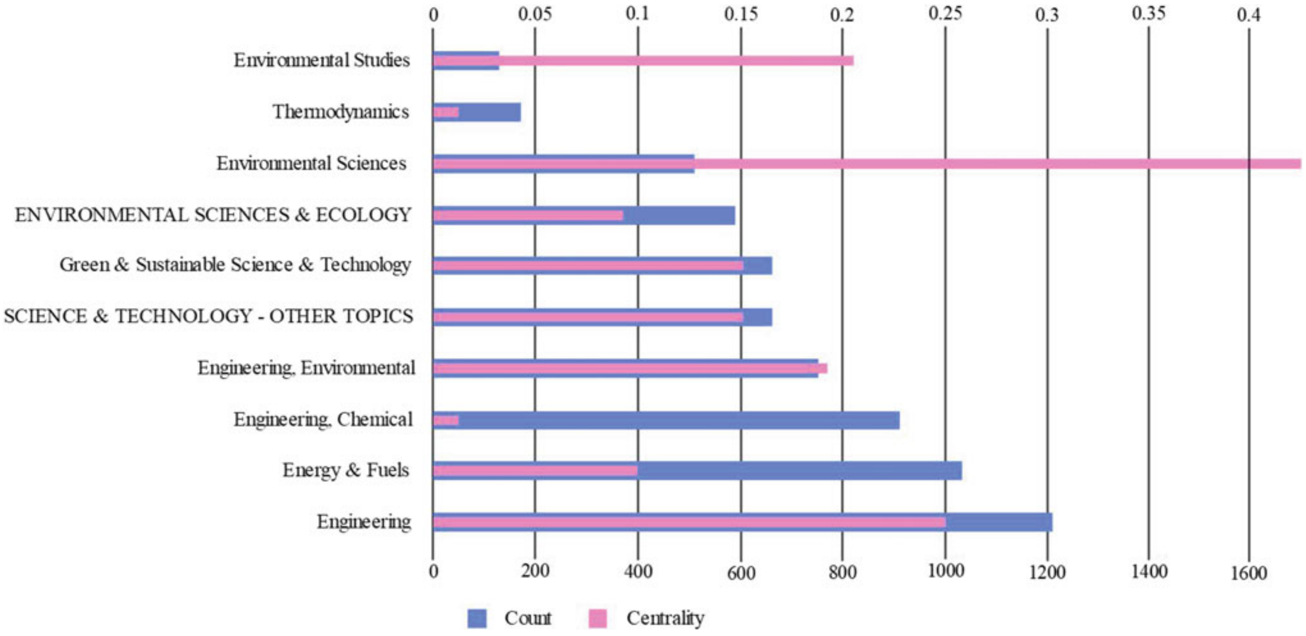


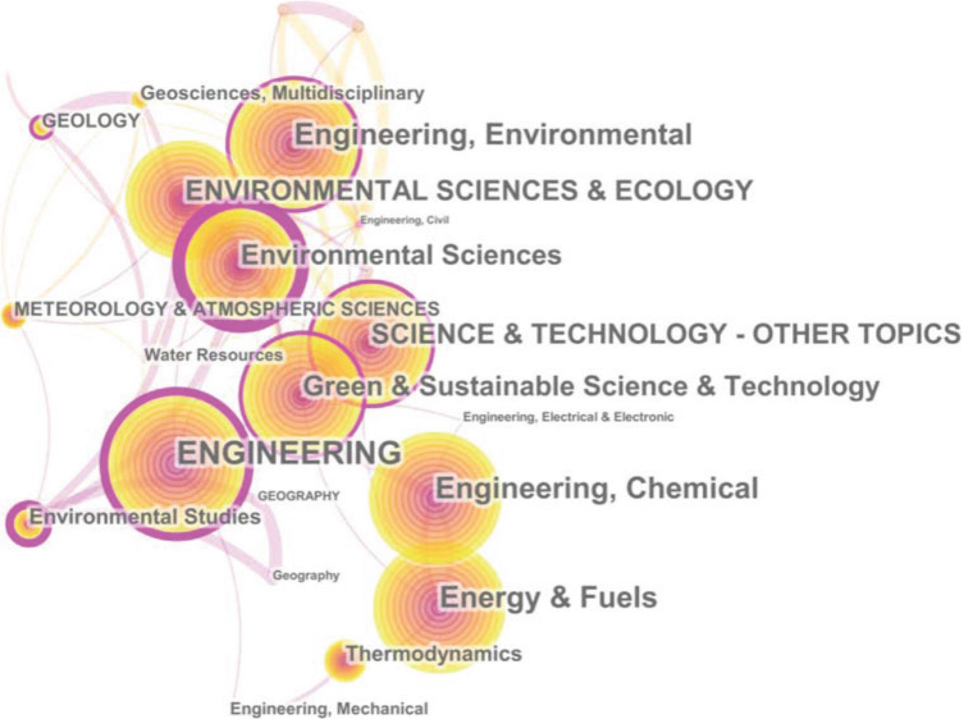
Fig. 10 Topic categories that have been cited more than 100 times

Environmental Sciences & Ecology to Meteorology & Atmospheric Sciences, Thermodynamics, Engineering, Electrical & Electronic, and Construction & Building Technology. The interdisciplinary development of various disciplines has made great contributions to the integration of CCUS research into multidisciplinary science.

5 Conclusions

Industry is the foundation of modern society and the source of economic development. While bringing economic benefits and job opportunities, it also brings many problems.

Fig. 11 The 27 categories of CCUS research



Industry consumes one-third of the world's energy, but produces one-third of the world's greenhouse gases. CCUS technology will play a vital role in the process of coping with global warming, achieving the goal of near-zero emissions, and achieving the roadmap for global temperature control of 1.5 °C in the future.

We use CiteSpace to conduct a quantitative and visual review of CCUS academic achievements and progress. The main findings of basic bibliometric analysis show that from 2011 to 2021, CCUS research on a global scale shows an accelerated growth trend. Among them, the United States is the country with the most publications. The United States has added 12 new CCUS commercial projects in 2020. The number of CCUS projects in operation increased to 38, accounting for about half of the total number of global operating projects, and the CO_2 capture volume exceeded 30 million tons. As the country with the highest carbon emissions, China's total carbon emissions are still increasing. From the point of view of the years to achieve "carbon neutrality," time is more pressing than in developed countries, and the slope of carbon emission decline is greater.

The results of literature co-citation analysis show that BECCS research is an important part of solving carbon emission problems. In addition, the capture and utilization of carbon dioxide and environmental impact have always been research hotspots; energy system transformation is essential to reduce carbon emissions. The subject category co-occurrence network analysis shows that the research subjects related to CCUS are cited and interrelated, which reflects the importance of the cross-development of various disciplines in scientific research.

This study has certain limitations. (1) Because CCUS covers a wide range of fields, we cannot get CCUS-related articles based on the criteria for selecting publications. As CCUS research becomes more abundant and complete, future bibliometric analysis can consider adding more databases and non-English publications in order to better provide development strategies for CCUS research. (2) Due to the data format setting problem of the CietSpace software, some small errors occurred during the research process. However, we try our best to avoid the interference of human factors and carry out research based on the latest data to ensure the reliability of the data. Based on this, in the future, we will conduct a more in-depth content interpretation and policy analysis based on the direction of this research.

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References

Aminu, M. D., Nabavi, S. A., Rochelle, C. A., et al. (2017). A review of developments in carbon dioxide storage. *Applied Energy, 208*, 1389–1419. https://doi.org/10.1016/j.apenergy.2017.09.015

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science, 354*(6309), 182–183. https://doi.org/10.1126/science.aah4567

Bhave, A., Taylor, R., Fennell, P., et al. (2017). Screening and techno-economic assessment of biomass-based power generation with CCS technologies to meet 2050 CO_2 targets. *Applied Energy, 190*, 481–489. https://doi.org/10.1016/j.apenergy.2016.12.120

Boot-Handford, M., Abanades, J., Anthony, E., et al. (2013). Carbon capture and storage update. *Energy & Environmental Science*. https://doi.org/10.1039/c3ee42350f

Bui, M., Adjiman, C. S., Bardow, A., et al. (2018). Carbon capture and storage (CCS): The way forward. *Energy & Environmental Science, 11*, 1062–1176. https://doi.org/10.1039/c7ee02342a

Chaomei, C. (2017). Science mapping: Asystematic review of the literature. *Journal of Data & Information Science, 2017*(2), 1–40.

Chen, C. (2010). CiteSpace: Visualizing patterns and trends in scientific literature. Retrieved January 27.

Chen, C. (2017). Science mapping: A systematic review of the literature. *Journal Data and Information Science, 2*(2), 1e40. https://doi.org/10.1515/jdis-2017-0006

Cuéllar-Franca, R. M., Azapagic, A. (2015). Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. *Journal of CO_2 Utilization, 9* (1), 82–102. https://doi.org/10.1016/j.jcou.2014.12.001

Dowell, N. M., Fennell, P. S., Shah, N., et al. (2017). The role of CO_2 capture and utilization in mitigating climate change. *Nature Climate Change, 7*(4), 243–249. https://doi.org/10.1038/NCLIMATE3231

Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science, 10*, 1389–1426. https://doi.org/10.1039/c7ee00465f

Fan, J. L., Xu, M., Yang, L., et al. (2019). Benefit evaluation of investment in CCS retrofitting of coal-fired power plants and PV power plants in China based on real options. *Renewable and Sustainable Energy Reviews, 115*, 109350. https://doi.org/10.1016/j.rser.2019.109350

Fan, J. L., Shen, S., Xu, M., et al. (2020). Cost-benefit comparison of carbon capture, utilization, and storage retrofitted to different thermal power plants in China based on real options approach. *Advances in Climate Change Research*

Fan, C. (2015). *Analysis of optimal carbon capture and sequestration policy*. Jinan University

Fuss, S., Canadell, J., Peters, G., et al. (2014). Betting on negative emissions. *Nature Climate Change, 4*, 850–853. https://doi.org/10.1038/nclimate2392

Fuss, S., Lamb, F. W., Callaghan, M. W., et al. (2018). Negative emissions—Part 2: costs, potentials and side effects. *Environmental Research Letters, 13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Garfield, E., Pudovkin, A. I., & Istomin, V. S. (2002). Algorithmic citation-linked historiography—Mapping the literature of science. *Proceedings of the American Society for Information Science and Technology. Annual Meeting, 39*, 14–24. https://doi.org/10.1002/meet.1450390102

GCCSI (2017). *The Global Status of CCS: 2017, Docklands, Australia*. Accessed September 2020. https://www.globalccsinstitute.com/wp-content/uploads/2018/12/2017-Global-Status-Report.pdf

Guo, P., Tian, W., Li, H., et al. (2020). Global characteristics and trends of research on construction dust: Based on bibliometric and visualized analysis. *Environmental Science and Pollution Research, 27*(37). https://doi.org/10.1007/s11356-020-09723-y

Id, K. H., Qi, K., Guan, Q., et al. (2016). A scientometric visualization analysis for night-time light remote sensing research from 1991 to 2016. *Remote Sensing, 9*(8), 802. https://doi.org/10.3390/rs9080802

IEA. Technology roadmap, carbon capture and storage, 2013 edn. International Energy Agency, Paris, France. https://doi.org/10.1126/science.1172246

International Energy Agency. (2020). Carbon Capture, Utilisation and Storage. https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage. Accessed August 3, 2020.

Introduction to "Kyoto Protocol". Net of Chinese people. http://www.npc.gov.cn/zgrdw/npc/zxft/zxft8/2009-08/24/content_1515035.htm

IPCC. (2005). IPCC Special Report on carbon dioxide capture and storage; Prepared by Working Group III of the intergovernmental panel on climate change. In B. O. Metz, H. C. Davidson, M. L. de Coninck, L. A. Meyer (Eds.), Cambridge University Press.

IPCC. (2014). Climate Change 2014: *Mitigation of climate change. Contribution of working group III to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Kang, D., Jo, H., Lee, M. G., et al. (2016). Carbon dioxide utilization using a pretreated brine solution at normal temperature and pressure. *Chemical Engineering Journal, 284*, 1270–1278. https://doi.org/10.1016/j.cej.2015.09.043

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control, 40*, 401–430. https://doi.org/10.1016/j.ijggc.2015.06.012

Koornneef, J., Keulen, T. V., Faaij, A., et al. (2008). Life cycle assessment of a pulverized coal power plant with post-combustion capture, transport and storage of CO_2. *International Journal of Greenhouse Gas Control, 2*(4), 448–467. https://doi.org/10.1016/j.ijggc.2008.06.008

Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. (2014). An overview of current status of carbon dioxide capture and storage technologies. *Renewable and Sustainable Energy Reviews, 39*, 426–443. https://doi.org/10.1016/j.rser.2014.07.093

Liu, Q., Ye, Y. (2012). A study on mining bibliographic records by designed software SATI: case study on library and information science. *Journal of Information Resources Management, 2*(1), 50e58. https://doi.org/10.13365/j.jirm.2012.01.012

Mac Dowell, N., Fennell, P., Shah, N., et al. (2017). The role of CO_2 capture and utilization in mitigating climate change. *Nature Climate Change, 7*, 243–249 (2017). https://doi.org/10.1038/nclimate3231

Mechleri, E., Brown, S., Fennell, P. S., et al. (2017). CO2 capture and storage (CCS) cost reduction via infrastructure right-sizing. *Chemical Engineering Research and Design, 119*, 130–139. https://doi.org/10.1016/j.cherd.2017.01.016

Meerow, S., & Stults, M. (2016). Comparing conceptualizations of urban climate resilience in theory and practice. *Sustainability, 8*, 701. https://www.mdpi.com/2071-1050/8/7/701

Middleton, R. S., & Bielicki, J. M. (2009). A scalable infrastructure model for carbon capture and storage: SimCCS. *Energy Policy, 37* (3), 1052–1060. https://doi.org/10.1016/j.enpol.2008.09.049

Milman, A., & Short, A. (2008). Incorporating resilience into sustainability indicators: an example for the urban water sector. *Global Environmental Change, 18*, 758–767.

Minx, J. C., et al. (2018). Negative emissions: Part 1—Research landscape, ethics and synthesis. *Environmental Research Letters, 13* (6), 063–071. https://doi.org/10.1088/1748-9326/aabf9b

Muller, M. (2007). Adapting to climate change: Water management for urban resilience. *Environment and Urbanization, 19*, 99–113. https://doi.org/10.1177/0956247807076726

Ooi, R. E. H., Foo, D. C. Y., Ng, D. K. S., & Tan, R. R. (2013). Planning of carbon capture and storage with pinch analysis techniques. *Chemical Engineering Research & Design, 91*(12), 2721–2731. https://doi.org/10.1016/j.cherd.2013.04.007

Park, S., Min, J., Lee, M. G., et al. (2013). Characteristics of CO2 fixation by chemical conversion to carbonate salts. *Chemical Engineering Journal, 231*, 287–293. https://doi.org/10.1016/j.cej.2013.07.032

Park, S., Jo, H., Kang, D., & Park, J. (2014). A study of CO2 precipitation method considering an ionic CO_2 and $Ca(OH)_2$ slurry. *Energy, 75*, 624–629. https://doi.org/10.1016/j.energy.2014.08.036

Pérez-Fortes, M., Schöneberger, J. C., Boulamanti, A., et al. (2016). Methanol synthesis using captured CO_2 as raw material: Techno-economic and environmental assessment. *Applied Energy-Barking Then Oxford, 161*(15), 718–732. https://doi.org/10.1016/j.apenergy.2015.07.067

Regufe, M. J., Pereira, A., Ferreira, A., et al. (2021). Current developments of carbon capture storage and/or utilization—looking for net-zero emissions defined in the Paris agreement. *Energies, 14*. https://doi.org/10.3390/en14092406

Riahi, K., van Vuuren, D. P., Kriegler, E., et al. (2016). The Shared Socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change, 42*, 153–158. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Rogelj, J., Luderer, G., Pietzcker, R., et al. (2015). Energy system transformations for limiting end-of-century warming to below 1.5° C. *Nature Climate Change, 5*, 519–527. https://doi.org/10.1038/nclimate2572

Romasheva, N., & Ilinova, A. (2019). CCS projects: How regulatory framework influences their deployment. *Resources, 8*, 181. https://doi.org/10.3390/resources8040181

Shen, Y., & Wang, G. (2013). Key findings and assessment results of IPCC WGI fifth assessment report. *Journal of Glaciology and Geocryology, 2013*(05), 10–18. https://doi.org/10.7522/j.issn.1000-0240.2013.0120

Simboli, B., & Zhang, M., (2004). Software: Science literature clustering concepts. *Science, 303*(5659), 768. https://doi.org/10.1126/science.1094282

Smith, P., Davis, S., Creutzig, F., et al. (2016). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change, 6*, 42–50. https://doi.org/10.1038/nclimate2870

Stuardi, F. M., MacPherson, F., & Leclaire, J. (2019). Integrated CO2 capture and utilization: a priority research direction. *Current Opinion in Green and Sustainable Chemistry, 16*, 71–76. https://doi.org/10.1016/j.cogsc.2019.02.003

Tan, R. R., et al. (2012). Optimal source-sink matching in carbon capture and storage systems with time, injection rate, and capacity constraints. *Environmental Progress & Sustainable Energy, 32*(2), 411–416.

United Nations Framework Convention on Climate Change (UNFCCC). (1994). *United Nations Climate Change*. https://unfccc.int/

Yang, L., Xu, M., Yang, Y., et al. (2019). Comparison of subsidy schemes for carbon capture utilization and storage (CCUS) investment based on real option approach: evidence from China. *Applied Energy, 255*. https://doi.org/10.1016/j.apenergy.2019.113828

Zhu, E., Qi, Q., & Sha, M. (2021). Identify the effects of urbanization on carbon emissions (EUCE): A global scientometric visualization analysis from 1992 to 2018. *Environmental Science and Pollution Research, 2021*(8), 1–12.