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A Review of Carbon Capture and Storage Project Investment and Operational Decision-Making Based on Bibliometrics

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Abstract: The research on carbon capture and storage (CCS) project planning and investment and operational decision-making can provide a reference for enterprises to invest in CCS and for policy-makers to formulate policies to promote CCS development. So what are the current research hotspots in this field and the gaps that still need to be further studied in the future? This paper reviews the research in the field by a bibliometric analysis. The results show that the research in this field first focus on cost analysis, followed by project investment evaluation, project planning (cost curve and pipeline network), and project operation. In particular, fossil fuel power plants, pipeline transportation, and oil fields are the most crucial objects in the three technical links of CCS projects, respectively. Policies, carbon pricing, and uncertainty in cost and benefits are factors that are mainly discussed in this field. The methods used for CCS project planning are cost curve model and optimization model. The real option approach is suitable for the evaluation of investment decision-making. The evaluation of operational decision is mostly based on optimization model. The future research directions can be summarized as five points: (1) continuously and systematically update the calculated costs in the current research to the unified price of the latest year; (2) calculate the cost curve from the perspective of emission sources; (3) expand the planning region of pipeline network to the country, continent, and even the entire world; (4) pay more attention to the investment assessment of the CCS project that may be implemented with low cost and high return; and (5) analyze the optimal operation mode of CCS in the low-load power system.

Keywords: CCS; project planning; investment and operational decision-making; review; bibliometrics

1. Introduction

The global climate is undergoing significant changes characterized by warming, which has become a major challenge facing the human race regarding human survival and development in the 21st century. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) indicates that the global average temperature has increased by 0.85 °C from 1880 to 2012 [1]. The rising temperature seems to be insignificant, but it has a serious impact on the global environment, ecology and economic systems, such as melting glaciers [2], crop yield reduction [3], extinction of marine life [4], reduction of grassland carbon stock [5], increasing extreme climate disasters [6], etc.

CO_2 is the most important greenhouse gas causing the greenhouse effect. The Third Assessment Report of the IPCC indicates that the contribution ratio of greenhouse gases to global warming is 60% for CO_2, 20% for CH_4, 6% for N_2O, 14% for CF_{11}, CFC_{12}, etc. [7]. In addition, approximately 69%

of global CO_2 emissions come from processes such as the combustion and processing of energy [8]. Therefore, reducing energy-related CO_2 emissions is a key measure to mitigate climate change.

The need to address climate change has reached a global consensus [9]. Many countries have introduced regulatory policy schemes for carbon reduction [10]. Mitigating climate change can start from three aspects: (1) efficiency improvement, (2) replacing fossil fuels with low-carbon energy, and (3) capture and storage of CO_2. Although improving energy efficiency is the fundamental way to reduce greenhouse gas emissions by controlling growth in total energy demand, its potential for reducing emissions is gradually decreasing. The goal of developing low-carbon energy is to reduce emissions by reducing fossil fuel demand. However, the low-carbon energy development in some regions, especially in the low-carbon energy resource-poor regions, is not economically viable in the short term. In the foreseeable future, our world will still rely heavily on fossil energy [11].

Carbon dioxide capture and storage (CCS) technology is a potential approach for mitigating climate change. Overall schematic of carbon capture and storage concept is shown in Figure 1. CCS technology is the key means to achieve emission reduction of large-scale emission point sources, even the only means to reduce emissions in power generation and industrial processes [12]. The captured CO_2 from fossil fuel power plants, iron, steel plants, etc. is transported to storage sites such as oil and gas fields, unmineable coal seams, and deep saline aquifers for storage, so as to achieve permanent isolation from the atmosphere. If there is no CCS contribution towards achieving global atmospheric concentrations within a range from 430 to 480 ppm CO_2 equivalent, the global emission reduction cost will increase by 138% from 2015 to 2100 [1]. However, the early capital investment of hundreds of millions or even billions of dollars [13,14], as well as the high operating and maintenance costs [15], coupled with future uncertain emission reduction policies [16], have put enterprises with CCS investment willingness in a dilemma.

For CCS technology, we can mitigate these adverse impacts from three aspects: project planning, investment, and operation. The research on project planning can provide a reference for finding more economically feasible projects to be carried out on a priority basis to promote the development of CCS technology. The research on CCS projects investment and operational decision-making can not only enable investors to understand the investment value, investment opportunity, optimal operation strategy, etc., but can also provide a reference for policy-makers (governments) to formulate policies to promote CCS development [17]. The purpose of this study is to sort out the current status and future trends of the research on CCS project planning and investment and operational decision-making in the form of review.

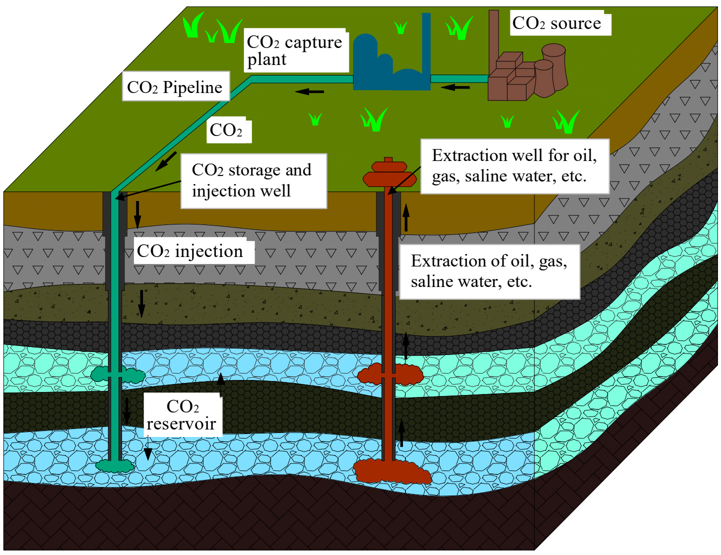

Figure 1. Overall schematic of carbon capture and storage concept.

Bibliometrics first appeared in 1969 [18]. With the aid of the bibliometrics, the review can present the future research trend, research hotspots, scientific collaborations, etc. At present, bibliometrics is widely used in the review of low-carbon electricity transition [18], low-carbon technology investment [19], and CCS technology evaluation [20,21]. Wang, et al. [18] examined the characteristics of the literature on decarbonization in the power system from 1990 to 2016, and pointed out that low-carbon electricity transition has been highly concerned. Based on the frequency analysis of keywords related to low-carbon technology investment, Yu, et al. [19] found that renewable energy has received much attention, and CCS technology is an emerging low-carbon technology field receiving increasing attention. Karimi and Khalilpour [20] pointed out that research on CCS seems to be closely following the trend of international negotiations on mitigating climate change. Viebahn and Chappin [21] explored the reasons for the huge gap between the scale of the expected CCS assembly and the scale of the actual assembly. This paper reviews the studies on CCS project planning and investment and operational decision-making by a bibliometric analysis.

2. Research Scope, Methods, and Framework

2.1. Research Scope

At present, CCS technology has developed into three technical fields. The most traditional CCS technology refers to the process of CO_2 capture, transportation, and geological storage [22]. Subsequently, based on the consideration of improving economic returns, much research has highlighted the importance of "CO_2 utilization" in promoting carbon capture, utilization, and storage (CCUS) technology development [23,24]. At the fourth Ministerial Meeting of Carbon Sequestration Leaders Forum (CSLF), "CO_2 utilization" was included in the CSLF Charter [25]. Compared with CCS, CCUS technology highlights the utilization of CO_2 before permanent storage [22]. In recent years, some scholars proposed the concept of carbon capture and utilization (CCU) [26,27], which generally only achieves short-term isolation between CO_2 and the atmosphere. In view of the original intention of proposing CCS technology, that is, to mitigate climate change by achieving long-term isolation of CO_2 from the atmosphere, we only focus on the research on CCS and CCUS project planning and investment and operational decision-making.

2.2. Research Methods and Framework

The Web of Science platform is the largest comprehensive academic information resource database covering almost all subjects in the world, all in all totaling over 33,000 journals [28]. The data were collected from the database of the Science Citation Index Expanded (SCI- Expanded) and Social Sciences Citation Index (SSCI), which was accessed on October 23, 2018. In addition, we set the document type and language as "article" and "English", respectively. After several trial searches, the search query is finally determined as TS = ((CCS and CO_2) or (CCUS and CO_2) or (CCS and carbon) or (CCUS and carbon) or (CCS and "carbon dioxide") or (CCUS and "carbon dioxide") or "CO_2 capture" or "CO_2 transport *" or "CO_2 storage" or "CO_2 sequestration" or "CO_2 capture, utilization and storage" or "CO_2 capture and storage" or "carbon capture" or "carbon transport *" or "carbon storage" or "carbon sequestration" or "carbon capture, utilization and storage" or "carbon capture and storage" or "carbon dioxide capture" or "carbon dioxide transport *" or "carbon dioxide storage" or "carbon dioxide sequestration" or "carbon dioxide capture, utilization and storage" or "carbon dioxide capture and storage") And TI = (cost or econom * or incentive or tax or price or curve or investment or "business model *" or "deployment model *"). TS is equivalent to the topic. TI is equivalent to the title. The asterisk (*) denotes any character group, including null characters. What needs to be explained here is that the research on CCS project planning and investment and operational decision-making is inseparable from the analysis of costs and benefits; thus, the research on CCS technical cost and benefit is also included in the review. One-thousand-four-hundred-and-ninety-five papers were initially searched, but some did not match the topic of this study. We conducted a manual search and finally obtained 678 publications, 92% of which are journal articles and 8% were conference articles.

For the searched publications, we will start with the review from six aspects as shown in the research framework (Figure 2). The subject and journal distribution helps researchers and readers understand the characteristics and attributes of this research field. The geographical distribution and timeline of publications shows the attention of global and countries and its changes in this field. To a certain extent, the high-yield institutions and high-yield authors reflect their influence in this field. In addition, the researchers' influence can be further evaluated based on the h-index developed by Jorge Hirsch in 2005 [18]. The national and auctorial collaboration is shown in both static and dynamic aspects. The static collaboration is demonstrated by the collaboration network, and the dynamic collaboration analysis requires the help of Equation (1) [18,19]. Highly cited papers refer to the top 1% cited papers in the past ten years, reflecting the influence of the study, which helps identify future research trends to a certain extent. The analysis of research hotspots are an important approach to sort out research objects, research methods, etc. in this field, and identify future research trends and frontiers.

$$C_{i=1\ or\ 2} = \frac{\sum_{j=1}^{N} \varphi_{i,j}}{N} \quad (1)$$

where $C_{i\ =\ 1\ or\ 2}$ is national or auctorial collaboration degree, respectively; $\varphi_{i,j}$ is the number of countries or authors for each paper; and N is the total number of publications in this field.

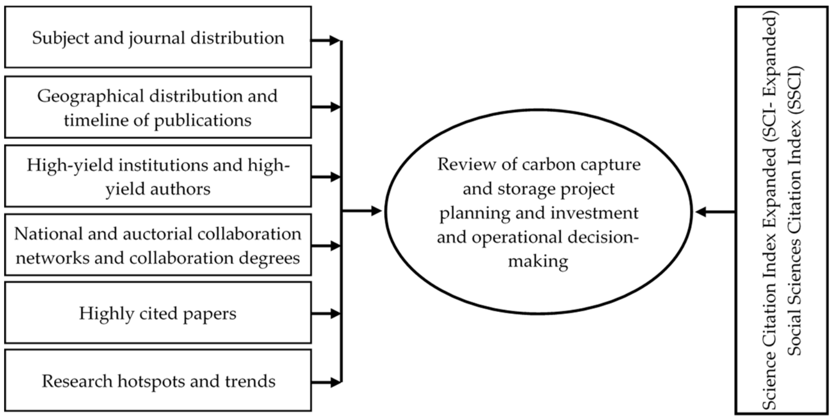

Figure 2. Research framework.

3. Results and Discussion

3.1. Subject and Journal Distribution

CCS is an interdisciplinary technology, which aims to realize the emission reduction of large-scale emission sources that burn and process fossil fuels [15,29]. Therefore, research on CCS project planning and investment and operational decision-making will be positioned in the subjects of Energy Fuels (396) and Green Sustainable Science Technology (153). As shown in Table 1, among the top 10 subjects, Engineering Environmental (191), Environmental Sciences (151), Green Sustainable Science Technology (153), and Environmental Studies (68) are environmental subjects. This is because climate change is an environmental problem [30]. Although the emission reduction potential of CCS technology has been widely recognized, its high cost and high energy consumption hinder its development [31]. Chemical absorption is currently the most mature and widely used capture process, and will be the mainstream capture technology in the short term. The heat consumption for chemical absorbent regeneration in the world's major demonstration projects is as high as 2.6–3.2 GJ/t CO_2 [32]. 110–150 KWh/t CO_2 of electricity should be used for running compressors hydraulic pumps, flue gas blowers, etc. [33]. Research and development of more energy-saving and lower-cost capture technologies is a research hotspot in the research field of CCS technology, which is also well reflected in the subject distribution (Engineering Chemical (189), Thermodynamics (78), and Chemistry Physical (34)).

The distribution of journals will correspond to the discipline attributes of CCS technology. The International Journal of Greenhouse Gas Control, a professional journal on CCS, has the most articles, accounting for 17.70% of the total (Table 2). In addition, the publications mainly are published in comprehensive journals related to the subject of Energy Fuels, including Applied Energy, Energy, Energy Policy, Energy Conversion and Management, Fuel and International Journal of Hydrogen Energy. The publications of the six journals account for 27.58% of the total publications.

Table 1. The 10 most productive subjects.

Rank	Subjects	TP	*R*
1	Energy Fuels	396	58.41%
2	Engineering Environmental	191	28.17%
3	Engineering Chemical	189	27.88%
4	Green Sustainable Science Technology	153	22.57%
5	Environmental Sciences	151	22.27%
6	Thermodynamics	78	11.50%
7	Environmental Studies	68	10.03%
8	Economics	58	8.56%
9	Chemistry physical	34	5.02%
10	Mechanics	32	4.72%

Note: TP is the number of total publications and *R* (%) is the ratio of the number of one subject's publications to the total number of publications.

Table 2. Top 10 productive journals.

Rank	Journals	TP	*R*	IF (2017)
1	International Journal of Greenhouse Gas Control	120	17.70%	4.078
2	Applied Energy	59	8.70%	7.900
3	Energy	41	6.05%	4.968
4	Energy Policy	35	5.16%	4.039
5	Energy Conversion and Management	24	3.54%	6.377
6	Industrial & Engineering Chemistry Research	23	3.39%	3.141
7	Environmental Science & Technology	21	3.10%	6.653
8	Fuel	15	2.21%	4.908
9	Journal of Cleaner Production	14	2.07%	5.651
10	International Journal of Hydrogen Energy	13	1.92%	4.229

Note: TP is the number of total publications; *R* (%) is the ratio of the number of one journal's publications to the total number of publications; and IF is the Impact Factor of the journal in 2017.

3.2. Geographical Distribution and Timeline of Publications

The timeline of publications in the world is shown in Figure 3. The earliest article in the field was published in 1991 with the title "Technology and cost of recovering and storing carbon dioxide from an integrated-gasifier, combined-cycle plant". Overall, 2004 is a turning point in the number of publications. Before 2004, the number of annual publications was in single digits, without obvious growth. After 2004, the number of annual publications gradually entered an outbreak period, and by 2016, reached 87. 2004 is the time for the inaugural CSLF Ministerial meeting [29], and the time for international organizations such as International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) and IPCC to issue CCS technology-related reports [15,34–42]. The CSLF is a Ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for CCS. The CSLF and international organizations, IEA GHG, IPCC, IEA, etc. play a crucial role in promoting the development of global CCS technology.

From the perspective of timeline of publications, scholars in Europe and the United States paid close attention to this field and carried out active research. The number of USA publications ranked first, with 181 articles (Figure 4). The world's first large-scale CCS project was the Val Verde project, launched by the United States in 1972 [13,43]. So far, nine of the 21 large-scale CCS projects in operation or about to be put into operation are in the United States [44]. The number of the United Kingdom (91) and the Netherlands (54) ranked third and fourth, respectively. Before 2006, Chinese scholars began to enter the field. Before 2009, CCS technology received the attention of the Chinese government. A series of state-supported demonstration projects and scientific research projects were launched one after another [24]; thus, the number of publications rapidly increased and ranked second in the world. So far, seven of the 16 large-scale CCS projects in advanced development or early development are in China [44].

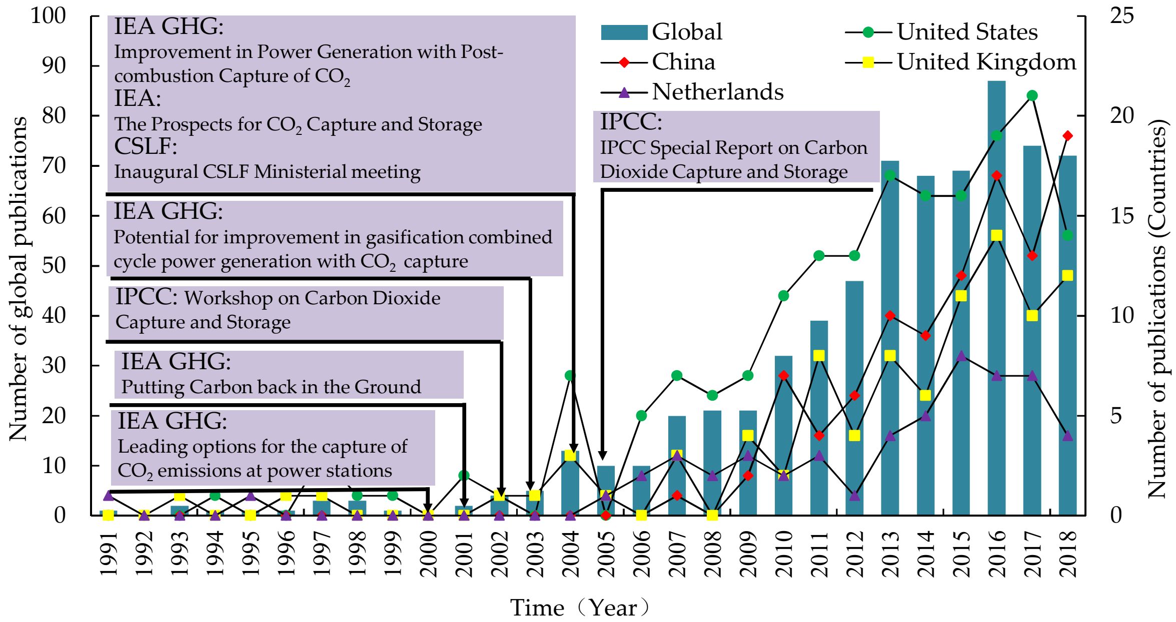

Figure 3. Timeline of publications in the world and top four countries.

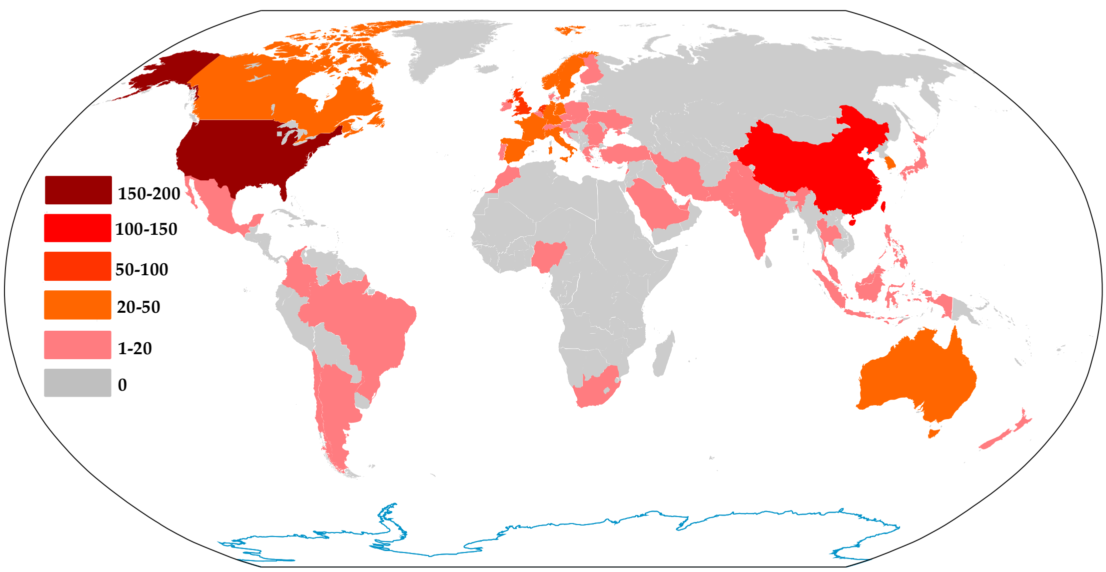

Figure 4. Geographical distributions of publications.

3.3. High-Yield Institutions and High-Yield Authors

The 678 publications were drawn from contributions from 706 institutions, 34 of which contribute to more than 1% ($\geq$7 publications) of the world's publications. High-yield institutions with more than 12 publications are mainly concentrated in the United States, China, and some developed countries in Europe (Table 3), which corresponds well to the publications distribution of the countries. The U.S. Department of Energy and Carnegie Mellon University ranked first and second among all the institutions. The U.S. Department of Energy participates in many CCS projects, and often conducts economic assessments of investment in the CCS projects to determine whether to fund them or not [13,45]. Publications from Carnegie Mellon University are mainly contributed by Rubin E and Zhai H, who rank first and eighth among high-yielding authors, respectively. In addition, similar situations exist in high-yield institutions, such as Utrecht University, the University of New South Wales, and Imperial College London, that high-yield authors contribute to almost all publications (Table 4). The Chinese Academy of Sciences and Tsinghua University, respectively, rank fourth and tenth in the top 10 high-yield institutions. These two academic institutions entered the research field early, and then participated in some research and development projects of CCS technology [24].

Table 3. High-yield institutions.

Rank	Institution	TP	*R*	Country
1	United States Department of Energy	39	5.75%	USA
2	Carnegie Mellon University	29	4.28%	USA
3	Utrecht University	28	4.13%	Netherlands
4	Chinese Academy of Sciences	22	3.25%	China
5	Chalmers University of Technology	16	2.36%	Swedish
6	Norwegian University of Science and Technology	16	2.36%	Norwegian
7	University of New South Wales	16	2.36%	Australia
8	Imperial College London	15	2.21%	UK
9	Consejo Superior de Investigaciones Científicas	13	1.92%	Spain
10	Tsinghua University	13	1.92%	China

Note: TP is the number of total publications and *R* (%) is the ratio of the number of one institution's publications to the total number of publications.

Table 4. High-yield authors.

Rank	Authors	TP	TC	CPP	H-index	Institution
1	Rubin E	18	2562	142.33	16	Carnegie Mellon University
2	Faaij A	18	755	41.94	13	Utrecht University
3	Ramirez A	15	304	20.27	9	Utrecht University
4	Wiley D	13	646	49.69	9	University of New South Wales
5	Ho M	12	628	52.33	9	University of New South Wales
6	Mac dowell N	10	151	15.1	6	Imperial College London
7	Cormos C	9	97	10.78	5	Babeș-Bolyai University
8	Zhai H	8	204	25.05	6	Carnegie Mellon University
9	Shah N	7	136	19.63	5	Imperial College London
10	Van den broek M	7	229	32.71	6	Utrecht University

Note: Institution refers to the first institution that appears in the author's publications; TP is the number of total publications; TC is the number of total citations; and CPP is citations per publication.

3.4. National and Auctorial Collaboration Networks and Collaboration Degrees

A collaboration network of 15 countries is shown in Figure 5a. The United States has the largest number of CCS projects in the world, and has rich experience in project planning and investment and operation. Meanwhile, American researchers also pay great attention to CCS technology. Therefore, the United States has closely cooperated with other countries in various aspects, such as research methods and engineering projects [46,47]. Moreover, China and the United States work most closely together. Since 2014, "U.S.-China Seminar on CO_2 Capture, Utilization and Storage" has been held five times in a row [48]. The EU (European Union) has a holistic planning for the construction of CCS projects or the management of funds related to CCS projects [49,50]. A study may involve the participation or contribution of scholars and governments from different countries [37,51]. Therefore, the cooperation among EU countries is particularly close. In addition, from Figure 6, we can find that the global collaboration of research on CCS project planning and investment and operational decision-making is getting closer and closer, and the average national collaboration degree in recent three years has reached 1.51.

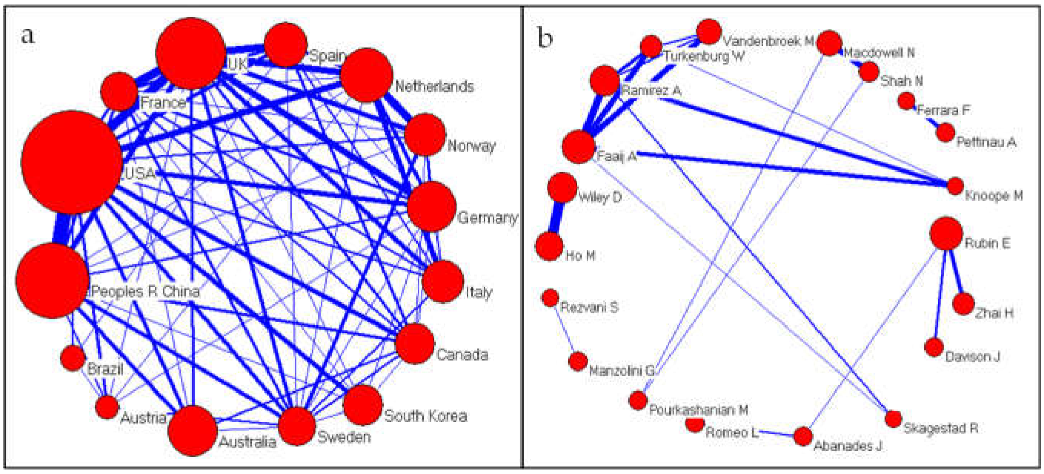

Figure 5. National (**a**) and auctorial (**b**) collaboration networks.

The growth rate of auctorial collaboration degree (from 2001 to 2018, increased by 158%) is shown in Figure 6, is obviously faster than that of national collaboration degree (from 2001 to 2018, increased by 147%). This finding suggests that collaboration among researchers around the world is becoming closer and closer, but mainly within countries or institutions. This fact can also be found by reading the coauthored papers is shown in Figure 5b. Strengthening the collaboration of global researchers can realize the global sharing of project planning, investment and operational experience, and research and development achievements, so as to accelerate the development of CCS technology worldwide. Therefore, it is important to strengthen the communication of global researchers in various ways.

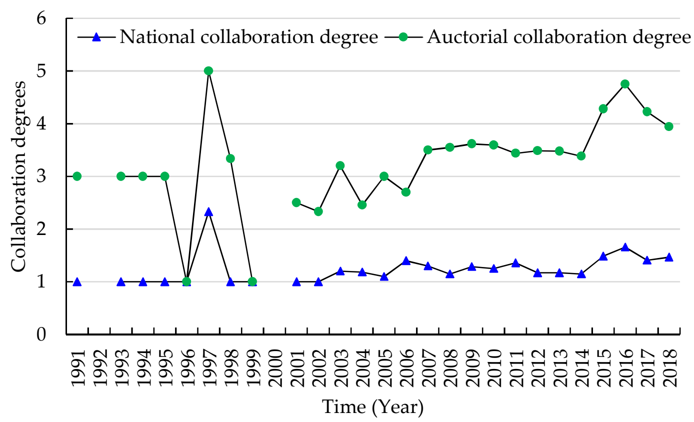

Figure 6. National and auctorial collaboration degrees.

3.5. Highly Cited Papers

Table 5 lists the top 10 highly cited papers in this field, with the cited frequency above 54. A close reading of the 10 articles reveals that they can be divided into six topics: (1) to reduce the CO_2 capture cost (the 1st, 3rd, 4th, and 10th publications); (2) the impact of CCS technology on energy production costs (the 2nd publication); (3) review of CCS technology cost (the 5th publication); (4) comparison of production cost of different power generation technologies with CCS (the 6th publication); (5) the CO_2 utilization costs (the 7th publication); and (6) the economics of flexible operating power plants or power systems with CCS (the 8th and 9th publications). The topics of the highly cited papers show that exploring the low-cost CO_2 capture technologies remains the main task in the research field, followed by the low-cost operational approach.

Table 5. Top 10 highly cited papers.

Rank	Publications and Author	Publication Year	Title	TC
1	Ho, et al. [52]	2008	Reducing the cost of CO_2 capture from flue gases using pressure swing adsorption	270
2	van Vliet, et al. [53]	2009	Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow, and cost analysis	166
3	Romeo, et al. [54]	2008	Integration of power plant and amine scrubbing to reduce CO_2 capture costs	157
4	Raynal, et al. [55]	2011	From MEA to demixing solvents and future steps, a roadmap for lowering the cost of postcombustion carbon capture	119
5	Rubin, et al. [56]	2015	The cost of CO_2 capture and storage	110
6	Tola and Pettinau [57]	2014	Power generation plants with carbon capture and storage: A techno-economic comparison between coal combustion and gasification technologies	84
7	Pérez-Fortes, et al. [58]	2016	Methanol synthesis using captured CO_2 as raw material: Techno-economic and environmental assessment	76
8	Brouwer, et al. [59]	2015	Operational flexibility and economics of power plants in future low-carbon power systems	72
9	Brouwer, et al. [60]	2016	Least-cost options for integrating intermittent renewables in low-carbon power systems	58
10	Li, et al. [61]	2016	Systematic study of aqueous monoethanolamine (MEA)-based CO_2 capture process: Techno-economic assessment of the MEA process and its improvements	54

Note: TC is the number of total citations.

3.6. Research Hotspots, Gaps, and Trends

Keywords reflect the core content of the study; we can find research hotspots and trends with an in-depth analysis of them [62,63]. According to the types of keywords, we analyze the research hotspots from four levels: research topics, research objects, internal and external factors introduced, and research methods. After that, we summarized the research gaps and trends in this research field based on a detailed reading of the retrieved publications.

3.6.1. Research Topics

CCS technology contains three technical links of CO_2 capture, transportation, and storage, which is an emerging technology. The cost of the three technical links varies with CO_2 capture objects, transport modes and storage sites, respectively. Therefore, the cost accounting of CCS technology is a must-do and complicated work. In addition, the current CCS technology is accompanied by high capital costs [13,14], high energy consumption [64,65], and other deficiencies. Many researchers are committed to reducing the cost of CCS technology. As a result, there are many publications focusing on the research topic of cost (Table 6). Three cost metrics widely used in existing CCS studies: (1) the levelized cost of electricity (LCOE); (2) the cost of CO_2 avoided; and (3) the cost of CO_2 captured [66,67]. The LCOE focus on the cost of CCS that installed in power plans [68]. The cost of CO_2 captured is generally only used to quantify the cost of capturing CO_2 [69]. The cost of CO_2 avoided must include the whole process cost of CCS, since emissions to the atmosphere are not avoided unless/until the captured CO_2 is permanently sequestered [69]. On the basis of the basic perfection of CCS technology cost accounting, many researchers focus on the research on CCS project planning and investment and operational decision-making. The research on CCS project planning can be divided into two aspects: (1) to obtain a cost curve with the comprehensive consideration of the capture sources, storage sites and transport distance in the planning area [37,46] and (2) to achieve the large-scale transportation of CO_2 at low cost with the optimization of pipeline network [70,71]. Research on operational decision-making focuses on how to achieve economical optimal CCS projects through flexible operations [72,73]. In addition, from the temporal distribution of the four research topics shown in Table 7, the research in this field first focused on cost analysis, followed by project investment evaluation, and the latest is project planning and operation. This does not take into account the time when IPCC, IEA, and other international organizations issue CCS reports on similar topics.

Table 6. Research topics and representative keywords.

Research Topics	TK	Representative Keywords (Number)
Cost	78	Cost (7); Levelized cost of electricity (5); Cost of CO_2 avoided (4); CO_2 capture cost (4)
Investment	11	Investment (3); CCS investment (3)
Planning	5	Cost curve (3); CO_2 pipeline network (2)
Operation	4	Flexible operation (3); Operating conditions (1)

Note: TK is the total number of occurrences of keywords directly related to a research hotspot. In addition, many keywords, such as economics, techno-economic analysis, etc., have ambiguous topical attributes; thus, they are not listed here.

Table 7. The temporal distribution of research topics.

Time Range	Cost	Planning	Investment	Operation
1991–2000	1	0	0	0
2001–2010	23	0	1	0
2011–2018	54	5	10	0

Note: Many keywords, such as economics, techno-economic analysis, etc., have ambiguous topical attributes; thus, they are not used as reference keywords.

3.6.2. Research Objects

(1) CCS projects

1) CO_2 capture

The cost of CO_2 capture is the highest, usually accounting for 50–80% of the total cost of CCS [74,75]. Current studies have pointed out that the cost of CO_2 capture has great potential to decrease. Taking the cost of postcombustion capture in coal-fired power plants as an example, the cost of CO_2 capture in 2050 will decrease by 20–60% compared with that in 2001 [76]. Therefore, much research focuses on CO_2 capture.

In 2000, there were more than 8100 large-scale emission sources (>0.1 Mt/year) in the world, and their total emissions (about 15 Gt CO_2) accounted for more than 60% of the global anthropogenic CO_2 emissions. The emissions from fossil fuels (coal, oil, and gas) power plants accounted for 71% of the total emissions [77], which has the greatest potential to reduce emissions and is the largest application market of CCS [78,79]. As a result, as many as 127 studies have clearly focused on fossil fuel power plants (Table 8). Negative emissions technologies include biomass energy CCS (BECCS), direct air capture, afforestation, reforestation, etc. [80]. To achieve an average global warming target of 2 °C, BECCS needs to contribute 14 Gt of emission reduction during 2013 to 2050 [29]. Therefore, the emission reduction potential and economy of negative emission technologies have become the research hotspots in recent years [81,82]. Although the proportion of CO_2 emissions from cement plants (6%), refineries (5%), and iron and steel plants (5%) is small, the contribution to emission reduction is still considerable [77]. Eleven per cent of total emissions are from some industries of high purity CO_2, such as ammonia production, ethanol production, ethylene oxide production, natural gas processing units, hydrogen production facilities, etc. [77]. High-purity means that the cost of CO_2 capture in these industries is small, which is generally less than USD 15/ton [77,83]. The high-purity sources are potential candidates for early implementation of CCS in the world, especially in China [15,84]. This conclusion is obtained by simply considering the CO_2 capture cost. If the transportation cost and storage cost are taken into consideration, it will make it more reference value [46,70].

2) CO_2 transportation

The captured gaseous CO_2 is concentrated to a supercritical state or liquid, and then transported to a storage site. CO_2 can be transported by pipeline, ship, road tanker, or rail tanker, and the corresponding transportation technology is relatively mature [33]. Road tankers have low transport capacity and high cost, which are mainly applicable to current small-scale CCS demonstration projects. Railway tankers are still not in use. Pipelines and ships are currently in operation [85], with pipeline transportation technology being the most mature. The global onshore CO_2 pipeline has a length of more than 7600 kilometers and a transportation capacity of more than 68 million tons per year [86,87]. Pipeline and ship transport methods have the advantage of large transportation capacity and low transportation cost [15], which is key for large-scale CO_2 transportation in the future; thus, more attention has been paid to them (Table 8).

3) CO_2 utilization and storage

This paper focuses on the research on CO_2 geological utilization and storage, the earliest of which is the CO_2-EOR (CO_2-enhanced oil recovery) project, and it has been documented as early as the 1920s [88]. CO_2-EOR is currently the most mature, most widely used, and most economical CO_2 geological utilization and storage technology [89], and will be the main option for CCS projects in the coming period. Currently, 16 of the 21 large-scale CCS projects in operation, or about to be put into operation, in the world are CO_2-EOR projects [90]. Therefore, the keywords related to CO_2-EOR is the most frequent (14 times). Compared with oil and gas fields and unmineable coal seams, deep saline aquifers are considered to be the best potential reservoirs for CO_2 storage because of their large storage capacities and widespread distribution [91]. At present, deep saline aquifers storage projects have been carried out one after another [13]. Other storage sites, such as natural gas field, unmineable coal seams and shale gas fields, have small storage potential or few demonstration projects [92,93], therefore receive less attention (Table 8). Other CO_2 utilization technologies belong to CCUS or CCU, including biological CO_2 utilization, mineralization of CO_2 as inorganic carbonates, etc., have not been reviewed in this study. Many quality review articles of these technologies exist. Both Pan, et al. [94] and Aresta, et al. [95] give a detailed introduction to these technologies.

(2) Other low-carbon power generation technologies

A large amount of energy needs to be used for the operation of CCS technology. The large-scale CCS retrofit in the power system is bound to affect its stability [15]. Besides, the fact that the supply and demand of power systems in many countries or regions, especially those with a large number of photovoltaic power plants, wind power plants, etc. are unstable will lead to frequent adjustment between high and low loads in fossil fuel power plants [96]. In addition, if the energy consumed by CCS is supplied by fossil energy, the depletion of nonrenewable fossil energy will be accelerated [65,97]. The stability of a power system is the foundation of social and economic development [98]. Therefore, to realize the direct coupling of CCS technology with photovoltaic power, wind power and other clean power generation technologies, or to adapt CCS to the unstable power system with a large number of photovoltaic power plants, wind power plants, etc. through flexible control of capture rate, is the current research hotspots (Table 8). Of course, the research in this field cannot be separated from the discussion of economy. Taking the national or regional power system as the research object, Cohen, et al. [99] analyze the dispatching mechanism of minimizing the cost through flexible operation of CCS. In addition, there are studies comparing the emission reduction costs of fossil fuel power plants with CCS and other low-carbon power generation technologies [100].

Table 8. Research projects and representative keywords.

Research Hotspots			TK	Representative Keywords (Number)
CCS technology	Capture	Fossil fuel power plant	127	IGCC (18); Coal-fired power plant (10)
		Negative emission technology	42	Biomass (13); Negative emissions (4)
		High purity CO_2 emission source	27	Hydrogen (7); Gasification (7)
		Petroleum refinery	6	Refinery (2); Oil refinery(2)
		Iron and steel plant	5	Iron and steel (2); Iron and steel industry (2)
		Cement plant	4	Cement (2); Cement plant (2)
	Transportation	Pipeline	14	Pipeline transport (7); Pipeline transportation (4)
		Ship	4	Ship transport (2); Vessel transport (2)
		Rail tanker	1	Train-based transport (1)
	Storage	Oil field	14	Enhanced oil recovery (5); CO_2-EOR (3)
		Deep saline aquifer	8	Reverse osmosis (4); Brine concentrate disposal (2)
		Natural gas field	5	Natural gas (5)
		Unmineable coal seams	3	Underground coal gasification (3)
		Shale gas field	2	Shale gas (2)
		Mature and depleted gas fields	1	Mature and depleted gas fields (1)
Other low-carbon power generation technologies		Wind power	3	Offshore wind (1); Wind energy (1)
		Photovoltaic power	3	Solar thermal energy (3)
		Nuclear power	2	Nuclear (2)

Note: TK is the total number of occurrences of keywords directly related to a research hotspot.

3.6.3. Internal and External Factors of Evaluation Objects Introduced

High energy consumption is an important factor of the high cost of CCS projects [15,101]. The source, type, and current and uncertain future price of energy consumed by a CCS project will affect its cost, and then affect its investment and operational decision-making [102,103]. Uncertainty exists not only in costs, but also in benefits from preferential policies and product sales (Table 9). Capital cost accounts for a large proportion of CCS project cost, generally up to 40–60% [104,105]. For this reason, many studies put forward the suggestion that the government should give a certain capital subsidy to CCS projects [17,33]. Some countries have already taken positive action [106]. At the same time, the inclusion of CCS projects into other carbon trading systems and the clean development mechanism (CDM), or exemption from carbon tax are seen as the key to incentivizing investment in CCS technology [106]. After several rounds of global climate change negotiations, global climate policy remains uncertain [16]. The uncertainty of global climate policy will be reflected in subsidy policies, CO_2 price, etc. Faced with huge uncertainties, investors should avoid the emergence of stranded assets and make the project run effectively based on flexible investment and operational decision-making [107]. In addition, due to the existence of additional energy consumption, possible leakage, etc., the actual emission reduction of CCS is inevitably lower than the amount of captured CO_2 [108,109], which in turn affects the investment economy of CCS. The research on CCS project planning mainly considers the cost of CCS project [37,46].

Table 9. Internal and external factors introduced and representative keywords.

Research Hotspots		TK	Representative Keywords (Number)
Internal factors	Cost	78	Cost (7); Levelized cost of electricity (5); Cost of CO_2 avoided (4); CO_2 capture cost (4)
	Uncertainty	15	Uncertainty (9); Uncertainty analysis (2)
	Energy consumption	5	Efficiency penalty (2); Energy consumption (2)
	Flexible operation	3	Flexible operation (3)
	Learning curve	3	Learning curve (3)
	Accounting	2	Accounting (2)
	Stranded assets	2	Stranded assets (2)
External factors	Carbon pricing	42	Carbon price (8); Carbon tax (8); Clean development mechanism (3); Offset schemes(1)
	Policy	17	Climate policy (7); Policy (4)
	Uncertainty	15	Uncertainty (9); Uncertainty analysis (2)
	Subsidies	2	Subsidies (2)

Note: TK is the total number of occurrences of keywords directly related to a research hotspot.

3.6.4. Research Methods

The method of keyword display can be used to study 4 topics: cost accounting, project planning, investment decision-making and optimization of low-carbon power generation technology portfolio and CCS operational decision-making (Table 10). CCS project planning mainly adopts the cost curve method and optimization method [46,70]. The CCS cost curve is the cost of the point-to-point full value chain in all feasible source-sink sets. The constraint condition in the cost curve model is the storage capacity of each storage site. The optimization method used for CO_2 pipeline network planning is to realize low-cost transportation of CO_2 by replacing the point-to-point pipeline between multiple sources and sinks with a main transport pipeline. CCS technology cost accounting methods mainly include process simulation [110], life cycle assessment [111], levelized cost [100], avoidance cost [56,69], capture cost [15], and thermo-economic analysis [112]. Process simulation is generally used to simulate a process, which is the basis of optimizing the process and reducing the cost of the process [110]. Life cycle assessment generally covers a broader range of assessment, including energy acquisition, transportation, and even the use of electricity [111]. Three cost metrics widely used in existing research on the cost of CO_2 capture are (1) the levelized cost, (2) the avoidance cost, and (3) capture cost [67–69]. The levelized cost is often used to characterize the cost of CCS that installed in power plans [68]. The cost of CO_2 captured is generally only used to quantify the cost of capturing CO_2 [69]. The cost of CO_2 avoided must include the whole process cost of CCS, since emissions to the atmosphere are not avoided unless/until the captured CO_2 is permanently sequestered [69]. The concept of avoidance cost takes full account of the energy consumption of CCS [113]. Real options and net present value (NPV) methods are currently used to evaluate investment decisions of CCS projects [114,115]. However, in comparison, due to the consideration of uncertainty and investment flexibility, the real option method has better applicability in evaluating CCS investment [116,117]. MARKet ALlocation (MARKAL) and optimization methods are used to study the optimization of low-carbon power generation technology portfolio and CCS operation [118,119]. Scenario analysis and uncertainty analysis have wide applicability.

Table 10. Research methods and representative keywords.

Research Hotspots	TK	Representative Keywords (Number)
Optimization model	22	Optimization (12); Optimal design (2)
Real options	20	Real options (8); Real options analysis (3)
Process simulation	17	Process simulation (9); Process modelling (4)
Life cycle assessment	15	Life cycle assessment (8); Life cycle analysis (3)
Levelized cost	10	Levelized cost of electricity (5); Levelized cost (5)
Avoidance cost	9	Cost of CO_2 avoided (4); CO_2 avoidance cost (3)
Capture cost	5	CO_2 capture cost (4); Total capture cost (1)
MARKAL	3	MARKAL (2); MARKet ALlocation (MARKAL) energy system model (1)
Thermo-economic theory	3	Thermo-economic analysis (1); Thermo-economic theory (1)
Sensitivity analysis	3	Sensitivity analysis (3)
Scenario analysis	2	Scenario analysis (2)
NPV	2	NPV (2)

Note: TK is the total number of occurrences of keywords directly related to a research hotspot.

3.6.5. Research Gaps and Trends

(1) Costs of CCS technologies

The accounting of CCS technology costs is the basis for conducting research in this field. In addition, the costs of CCS technology can be used as a reference for policy-makers and investment decision makers to understand CCS technology and related planning and investment issues. However, the time and currency unit of each research are not uniform, which causes inconvenience for many readers to understand the development of CCS technology cost. For this reason, some studies have collated the costs of existing research and unified them into constant 2004 US dollars (USD) [120], or the constant 2013 USD [56,113], etc. With the passage of time and the publication of new research, we should further update the existing research. In addition, the current research in the review is not comprehensive. [113] only reviewed the CO_2 capture cost of various industries. [56] unified CO_2 capture cost of power plant, transportation cost, and storage cost. [120] made a comparative analysis of the current cost accounting methods of CO_2 pipeline transportation and storage.

(2) CCS project planning

1) Cost curve

The drawing of the cost curve is conducive to the development of CCS projects. The CCS cost curve is the cost of the point-to-point full value chain in all feasible source-sink sets. The calculation of the cost curve is mostly based on the method developed by Dahowski in 2001 [121]. At present, the cost curves of CCS technologies in the world [122], North America [42], Europe [37], and China [46] have been systematically analyzed. Specifically, the current research object contains as many of the large-scale emission sources as possible in the study area, as well as all feasible storage sites. However, from the results presented, the above research only presents the cost curve from the perspective of the storage site, but lacks the cost curve from the perspective of the source. This has certain deficiencies in providing reference for CCS project planning at the national or regional level. After all, the CCS project sponsor should be the source of emissions rather than the storage site.

2) CO_2 pipeline network

CO_2 pipeline network planning is to realize low-cost transportation of CO_2 by replacing the point-to-point pipeline between multiple sources and sinks with a main transport pipeline. The research in this field is in its infancy and the planning area of the most existing research is only a subregion of the overall planning level (i.e., country) [70,71]. It would make more sense if the planning area could be expanded to a country, continent or even the world. Of course, this is a huge and complex project, and may even require the joint efforts of scholars or governments in various fields or countries.

(3) CCS project investment

Current studies mostly focus on the evaluation of investment in full-process CCS projects [17,123,124], but some of them focus on the detailed analysis of parameters, cost and benefit of the capture link, ignoring the details of transportation distance and costs, storage sites and costs [123,124]. The cost uncertainty of the storage link is large, which may have a significant impact on investment decision-making. In addition, in terms of the costs and benefits of capture and storage, capturing CO_2 from high-concentration emission sources and using it for enhanced oil recovery is currently the most economical option. Most of the current large-scale CCS projects in operation or about to be operated are such projects [13]. However, research on investment economic evaluation of such projects is relatively lacking.

(4) CCS project operation

The research on CCS technology operation optimization mainly focuses on the power industry [72,125]. Of course, some optimization schemes are also applicable to CO_2 capture in industrial processes. Large-scale assembly of CCS technology with high energy consumption power systems will inevitably affect the stability of power system operation. The coupling of CCS technology with other low-carbon power generation technologies or the control of flexible capture rate can weaken the impact of CCS on the operational stability of power systems. However, the impact of the energy consumption of CCS technology on the power system generally only occurs when the power system has high load or large load fluctuations. The operation optimization of CCS technology in the long-term low-load operation power system is currently less concerned. At present, average capacity factors of various power generation technologies in many countries around the world are at a low level, even under 60% [126,127].

4. Conclusions

According to the review of CCS project planning and investment and operational decision-making based on bibliometrics, the following conclusions are drawn.

(1) The subjects related to CCS technology mainly include Energy Fuels, Engineering Environmental, Green Sustainable Science Technology, etc. Therefore, the research on CCS project planning and investment and operational decision-making cannot be separated from these disciplines. In addition, the journal distribution echoes this conclusion. The journals, such as International Journal of Greenhouse Gas Control, Applied Energy, Environmental Science & Technology, Journal of Cleaner Production, etc. focus on the collection of academic papers on energy, environment, clean energy technology, etc.

(2) International organizations such as the IEA GHG, IPCC, IEA, and CSLF have played an important role in the development of CCS technology. Taking the time for the inaugural CSLF Ministerial meeting, and for IEA GHG, IEA, and IPCC to issue CCS technology-related reports as the node of 2003–2005; with a deepening understanding of the feasibility and emission reduction potential of CCS technology, the number of publications in this research field has undergone rapid growth. In addition, the number of publications in each country is generally closely related to the strength of policy support and the level of project development. After all, whether CCS technology can be supported and valued by the state and enterprises under the background of difficult-to-make profits is related to the needs and values of research. The publications of the United States topped the list, with China ranking second with a rapid increase since 2009.

(3) The publications of the U.S. Department of Energy ranks first among all institutions in terms of its involvement in many CCS projects. In addition, high-yield authors usually come from high-yield institutions, and contribute to almost all the publications of the high-yielding institutions they work for. Besides, collaboration among researchers around the world is becoming closer and closer, but mainly within countries or institutions. We should strengthen the collaboration of global researchers in various ways, because it can promote the development of CCS.

(4) The fossil fuel power generation sector is the industry with the most potential to reduce emissions, pipeline transportation is the most suitable for large-scale transportation, and oil fields are the most mature and economic storage option. Therefore, they are the most concerned objects in the research field, respectively. CCS project planning focuses on the cost of all CCS projects in the planning area. Policies, carbon pricing, and uncertain costs and benefits are key factors influencing investment

and operational decision-making. The methods used for CCS project planning are cost curve model and optimization model. Real option method is suitable for investment decision-making evaluation. The evaluation of operational decision is mostly based on optimization model.

(5) The cost of existing CCS technology should be continuously and comprehensively updated to a uniform price, which will enable policy-makers and investment decision-makers to better understand CCS technology and related development issues such as planning and investment. The research on CCS project planning can be divided into two aspects: (1) to obtain a cost curve with the comprehensive consideration of the capture sources, storage sites and transport distance and (2) to achieve the large-scale transportation of CO_2 at low cost with the optimization of pipeline network. In the field of cost curve research, further research is needed by scholars to shift the assessment perspective from the storage site to the emission sources. In the field of CO_2 pipeline network research, it would make more sense if the planning area could be expanded to a country, continent, or even the world. We believe that it is more realistic to focus on the investment assessment of CCS projects that are likely to be implemented early due to lower costs rather than those with the greatest potential for emission reduction. In the research field discussing the optimal operation of CCS projects, the optimization operation research of CCS projects in low-load power systems will be a future research branch.

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