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Three Decades of Progress and Hot Topic Prediction in CCUS Studies: Visual Analysis of the Citation Network by CitNetExplorer Based on the WOS Database

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ABSTRACT

As a major strategic technology for reducing greenhouse gas emissions and ensuring energy security, carbon capture, utilization, and storage (CCUS) is of great significance to large-scale emission reduction. Most previous CCUS studies have focused on technological implementation, application prospect, and economic analysis. From the perspective of knowledge discovery, it is important to explore the study progress based on existing study achievements, evolution characteristics of study topics over time, and stage-specific findings. This will help researchers gain an overall understanding of CCUS studies and serve to develop an academic study community of CCUS, as well as promote the industry-college-research cooperation in respect to CCUS. Based on the Web of Science (WOS) database platform, the present study conducts a literature review of international CCUS studies from 1989 to 2018 using the bibliometric method. Through the software CitNet-Explorer, this study identifies the core study topics in the CCUS field and explores the evolutionary trends and characteristics of the topics, using visual and cluster analysis methods. According to the H-index-based citation network, this study could track six hot modules within the CCUS field. Consequently, the cutting-edge trends of CCUS studies were predicted.

Keywords: CCUS, bibliometric, citation network, development trend

NONMENCLATURE

Abbreviations	
APEN	Applied Energy
Symbols	
n	Year

1. INTRODUCTION

While global warming causes increasingly severe damage to ecosystems, it has become an issue of global concern of how to control greenhouse gas emissions effectively, reduce carbon emission intensity, and conduct environmental harnessing scientifically. Among strategic technologies for reducing greenhouse gas emissions, carbon capture, utilization, and storage (CCUS) is the single technology which contributes most significantly to carbon emission reduction [1]. CCUS serves to achieve the dual goals of low-carbon cycled development and environmental harnessing [2], and is of great significance to large-scale emission reduction [3]. Today, CCUS is a hot topic of research globally and has gained an increasing amount of attention since it was initiated in 1989. Specifically, the number of published CCUS articles continues to increase, and academic achievements related to CCUS are emerging constantly. In addition, the topics of CCUS studies extend from risk assessment and management, application prospect analysis and economic feasibility analysis to public acceptance, capital input, and cost-benefit analysis,

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investment strategy, technical implementation, and related laws and regulations. Most existing CCUS studies in academia mainly discuss specific issues around specific topics, and few of them have conducted a general review of CCUS. In particular, there have been no studies conducted to explore the development trends or evolution law of related topics, nor the structural relationship between knowledge groups. In brief, existing CCUS studies fail to effectively reveal the interrelationships and progressive hierarchy between different topics in the CCUS field, nor do they provide methods for acquiring a systematic understanding of the CCUS knowledge domain.

This study comprises an academic literature review based on previous achievements of CCUS studies. The objective was to identify the development course of international CCUS studies and evolution law of related study topics since the advent of CCUS, as well as explore the developmental course of knowledge groups and structural relationship between them within the CCUS field. Using CitNetExplorer (a cutting-edge and advantageous citation network analysis tool), this study has revealed the knowledge structure, citation network structure, and disciplinary development trends in the CCUS field by utilizing a large amount research literature. The ultimate objective was to integrate technological achievements with academic research achievements, presenting an all-encompassing view of academic development of CCUS from the perspective of scientific discovery.

In this study, the following scientific discovery model was adopted: 1) cognize World 3 (the knowledge world) through World 2 (the spiritual world); 2) ascertain the essence and law of World 1 (the physical world) [4]. Under guidance of the knowledge graph theory, this study retrieved and processed the global CCUS articles included in the Web of Science (WOS) database in the last three decades, and summarizes the progress of CCUS studies from the perspective of bibliometrics. Using CitNetExplorer as a technological tool, this study uses the citation network visual analysis and clustering analysis methods to explore the relationship between different topics of CCUS studies, reveal their process and law of revolution, track the hot topics, and predict the trends of CCUS study topics. The objective was to provide a complete knowledge graph for the development of CCUS, thus better promoting CCUS studies and encouraging achievement of carbon emission targets in the future.

2. DATA SOURCES AND STUDY METHODOLOGY

2.1 Data sources

The CCUS system consists of four steps (i.e., carbon dioxide capture, transportation, utilization, and storage). Specifically, carbon dioxide is first separated from industrial or other emission sources (e.g., power plants), and then either captured, compressed, and transported to new production sites for storage and reutilization, or transported to storage places for injection into the ground. The ultimate objective is to achieve a long-term separation between carbon dioxide and atmosphere, recycle carbon dioxide as a resource, and reduce carbon emissions thoroughly [5]. CCUS studies were first initiated by the Massachusetts Institute of Technology (MIT), and the term CCUS was originally derived from carbon capture and storage (CCS). Inspired by the engineering practice of oil displacement by carbon dioxide, MIT proposed the idea that carbon dioxide generated by fossil fuels should be isolated from the atmosphere and permanently stored, in order to reduce greenhouse gas emissions substantially. Accordingly, MIT launched a CCS project, marking the formal advent of CCS technology. In 2011, the CCUS concept was proposed in the fourth ministerial conference of the Carbon Sequestration Leadership Forum (CSLF) held in Beijing. Based on CCS, CCUS incorporates the utilization of carbon dioxide as a type of resource. In the international community, there is no essential difference between CCUS and CCS [6] [7].

CCUS is a multi-step complex system, which covers a variety of disciplines (e.g., physics, chemistry, energy dynamics, hydrogeology, oil-gasified surface engineering, and economics). To gain a comprehensive understanding of the status quo and developmental course of international CCUS studies, the indexes SCI-EXPANDED and SSCI in the WOS Core Collection are used as retrieval sources, the advanced search method is used, and "TS = (CCUS OR CCS OR carbon capture AND utilization AND storage OR carbon capture AND storage)" is used as the search theme. According to the relatively large scope of disciplines covered by CCUS, some disciplines (e.g., medicine, botany, and material science) were excluded from this study, and the disciplines covered by CCUS were refined as disciplines under the WOS (e.g., Energy Fuels, Engineering Petroleum, Engineering Chemical, Engineering Environmental, Environmental Sciences, Green Sustainable Science Technology, Ecology, Environmental Studies, Economics,

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and Business). In addition, the time span was set to "1989–2018", the language was set to "English", the type of literature was set to "Article", and the date of update was set to December 12, 2019. Within the above time span, we retrieved a total of 4,879 articles with any of the themes including "CCUS", "CCS", "carbon capture, utilization, and storage", and "carbon capture and storage".

2.2 Study methodology

Three analysis methods were utilized in this study: bibilometrics, citation network visual analysis, and clustering analysis. For bibliometrics, based on the statistical data in the WOS database, the characteristics of research literature were analyzed in terms of annual number of publications, source journals, and source countries. The objective was to identify the overall trend of topics of CCUS studies, as well as international progress in CCUS studies. For the citation network visual analysis, under the guidance of the knowledge graph theory, a knowledge graph was generated using CitNetExplorer in order to conduct a visual analysis of the time-sequenced citation network in the CCUS field. For the clustering analysis, clustering of literature was conducted in order to identify the topics (including hot topics) of CCUS studies, evolution path of study topics, and cutting-edge trends of CCUS studies.

3. RESULTS AND DISCUSSION

3.1 Analysis of literature characteristics

3.1.1 Distribution of annual number of publications

Fig 1 shows the distribution of annual number of published CCUS articles in international academia during recent three decades retrieved from the WOS database. Overall, the annual number of published CCUS articles tends to increase. Roughly, the CCUS studies can be divided into four stages.

(1) At the first stage (1989–2003), the number of publications was not large. No CCUS articles were published within two years after the CCS technology was proposed in 1989. During the three years of 1991 to 1993, only one article was published every year. In the years subsequent to 1993, the number of publications increased slowly (specifically, fluctuating to the extent of 10). Evidently, after the CCS technology was proposed by MIT in 1989, academia began to conduct CCS studies, but such studies were only in initial stages.

(2) At the second stage (2004–2008), the annual number of publications tended to increase; specifically, from 21 (in 2004) to 95 (in 2008). Evidently, the significant emission reduction effect of CCUS had gradually received attention from international academia. In particular, the annual number of published CCUS articles increased significantly after the Intergovernmental Panel on Climate Change (IPCC) specially recommended CCUS as one of the most effective solutions to greenhouse gas emission reduction.

(3) At the third stage (2009–2011), CCUS studies tended to increase rapidly. By this time, the greater pressure of carbon emission reduction was an increasing global issue since the goal of "controlling the temperature rise to the extent of 2 °C" was written into the Copenhagen Accord in the Fifth Conference of the Parties to the Kyoto Protocol in 2009. In this context, CCUS studies were conducted more actively and fruitfully in academia. Up to 270 articles on CCUS were published in 2011.

(4) At the fourth stage (2012–2018), the number of publications showed a rapid growth trend, or specifically, increasing from 401 (in 2012) to 665 (in 2018). Evidently, CCUS had become an issue of universal concern in international academia because of its outstanding contribution in addressing global warming; in addition, great achievements had been attained in theoretical and practical studies of CCUS.

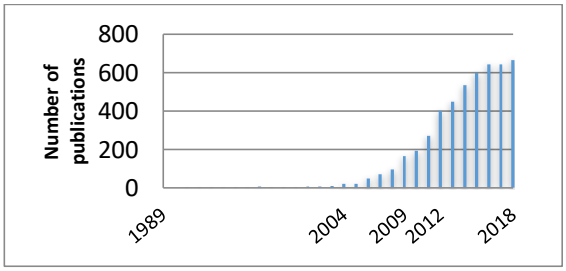

Fig 1 Temporal distribution of number of international research articles on CCUS

3.1.2 Analysis of source journals

Table 1 gives a statistical analysis of the source journals of CCUS articles retrieved from the WOS database. The top 10 source journals, listed in order of the total percentage of publications devoted to CCUS from greatest to least, are: International Journal of Greenhouse Gas Control, Applied Energy, Energy, Energy Policy, Journal of Materials Chemistry A, Environmental Science & Technology, Journal of Cleaner Production, Industrial Engineering Chemistry Research, International

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Journal of Hydrogen Energy, and Greenhouse Gases Science and Technology. These are all important journals in international academia. Among these journals, International Journal of Greenhouse Gas Control and Applied Energy have published the largest number of CCUS articles, accounting for 15.823% and 6.087% of total published CCUS articles respectively. In terms of total number of published CCUS articles, CCUS articles are mainly published in environmental science journals, followed by chemical and chemical engineering journals. In terms of the distribution of CCUS articles published in journals, CCUS studies mainly concentrate on the topic of greenhouse gas emission control, followed by the topic of energy utilization and energy policy-making, then the topics of petroleum and chemical technology and clean production. Evidently, CCUS is a multi-disciplinary complex system, which is intended to reduce carbon emissions, and integrate different functions (e.g., environment harnessing, petroleum engineering, and chemical technology and management).

Table 1 Top 10 source journals of published CCUS articles in international academia

No.	Source Journal	Number of Publications	Percentage
1	International Journal of Greenhouse Gas Control	772	15.823%
2	Applied Energy	297	6.087%
3	Energy	197	4.083%
4	Energy Policy	186	3.812%
5	Journal of Materials Chemistry A	153	3.316%
6	Environmental Science Technology	133	2.726%
7	Journal of Cleaner Production	113	2.316%
8	Industrial Engineering Chemistry Research	110	2.255%
9	International Journal of Hydrogen Energy	101	2.070%
10	Greenhouse Gases Science and Technology	96	1.968%

3.1.3 Analysis of literature source countries

To date, CCUS has been rated as an important strategic technology for addressing climate change by major energy organizations (e.g., IEA, IEF, and OPEC) and most countries worldwide. To promote the development of CCUS and achieve large-scale emission reduction, many countries have established CCUS research institutions to guide the R&D of CCUS projects and formulate development plans. Table 2 lists the top 10 countries in terms of the number of published CCUS articles retrieved from the WOS database. The top 10 countries collectively published 4,414 CCUS articles, accounting for 90.469% of total published CCUS articles.

Table 2 Top 10 countries by the number of published CCUS articles

No.	Country	Number of publications	Percentage
1	USA	1,156	23.693%
2	China	863	17.688%
3	England	598	12.257%
4	Germany	348	7.133%
5	Australia	276	5.657%
6	Netherlands	268	5.493%
7	South Korea	248	5.083%
8	Spain	237	4.858%
9	Canada	215	4.407%
10	Italy	205	4.202%

In terms of the number of published CCUS articles from 1989 to 2018, the USA ranks first, accounting for 23.693% of all published CCUS articles. Due to its reliance on thermal power generation, the USA considers CCUS as the most effective technology for reducing the greenhouse gas emissions from thermal power plants [8]. Hence, the USA attaches great importance to CCUS and conducts extensive CCUS studies. In addition, this also demonstrates the USA's substantial research strength in CCUS. In this regard, China ranks second. As a party to the United Nations Framework Convention on Climate Change and Kyoto Protocol, China is a not country specified in Annex I; therefore, China is not obligated to meet binding emission reduction targets[8].. However, China takes active part in the strategic action for addressing climate change in a responsible manner, and has established emission reduction targets. In particular, China has conducted multiple theoretical explorations in CCUS, and attained increasingly numerous research achievements since the 19th CPC National Congress. In this regard, the UK ranks third. The UK passed the Energy Act 2008 to stipulate a framework for CCUS licensing, implementation, and storage site registration, thus affirming the legitimacy of CCUS[8].. By means of direct government funding, the UK encourages scientific research institutions to carry out research and development (R & D) and popularization of CCUS, thus promoting the output of CCUS research achievements to some extent. In terms of the number of published CCUS articles, the UK is followed by Germany, Australia, Holland, South Korea, Spain, Canada, and Italy. All these countries attach importance to the development of

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CCUS, have carried out multiple R & D activities, and are world-leaders of CCUS technology. Moreover, their governments have rendered great institutional and financial support to CCUS, thus facilitating the output of R & D achievements. It should be noted that South Korea, which ranks seventh, is of one of the two Asian countries in the top 10 countries. From a temporal perspective, South Korea initiated CCUS technology later than Western countries; however, the South Korean Government attached significant importance to CCUS from the beginning. Clear planning and institutional guarantees were formulated for related policies or laws and regulations. In addition, the South Korean Government plays a dominant role in subsidizing and investing in the scientific research of CCUS. These all lay a firm foundation for attaining great research achievements. In brief, South Korea can be viewed as another example that CCUS is valued in Asian countries.

3.2 Topic detection and evolution of CCUS studies

Using CitNetExplorer, this study analyzes the topic identification and evolution in the CCUS field. Jointly developed by Doctor Van Eck and Waltman from Erasmus University (Holland) [9], CitNetExplorer is a piece of visual and interactive software that supports a great network scale. Based on clustering analysis, CitNetExplorer can reveal the domain knowledge structure from large amounts of literature, as well as present the interrelationships between and evolution tracks of different research topics over time [10] [11][12].

3.2.1 Visual graph of time-sequenced citation network

The use of CitNetExplorer is based on the analytical data exported from the WOS database. Fig 2 shows that there are 17,800 citation relationships between the 4,879 CCUS articles published from 1991 to 2018. It should be noted that because no CCUS articles were published from 1989 to 1990, the time span presented by the CitNetExplorer is 1991 to 2018. Fig 3 shows the time-based citation relationships between the marked articles. For example, it can see marked by the red square that the citation relationship of the article titled “An engineering-economic model of pipeline transport of CO_2 with application to carbon capture and storage” published by the first author McCoy in the International Journal of Greenhouse Gas Control (the citation score is 68).

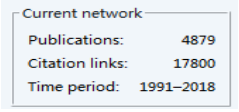

Fig 2 Current network of the CitNetExplorer

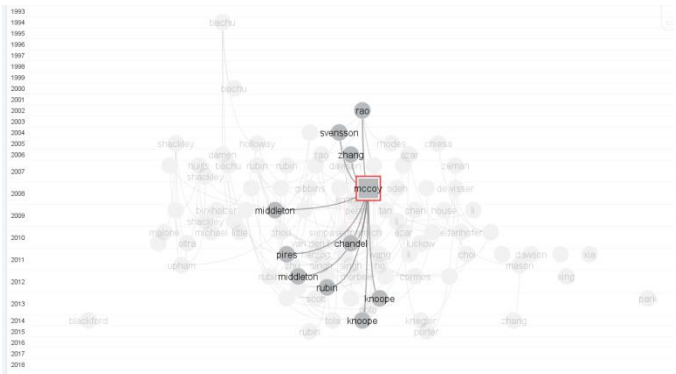

Fig 3 Bibliographic citation relationship

3.2.2 Topic detection in the CCUS field

3.2.2.1 Topic identification in the CCUS field

In this study, study topics were identified through clustering analysis. Clustering is the process of grouping the studied objects into clusters, that is, each article in a citation network is assigned to a cluster, and the clustering group is referred to as a cluster, meaning the set of clustered articles. Elements in the same cluster are highly similar, whereas articles in different clusters are weakly correlated. Usually, a cluster represents a topic of research articles错误!未找到引用源。.

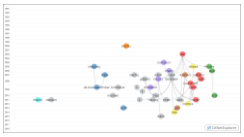

Fig 4 Topic identification graph of CCUS studies

Through cluster analysis, CitNetExplorer detected 17 valid clusters. As shown in Fig 4, clusters to which network nodes belong were marked with different colors, galaxy clusters with different colors were generated, and clusters composed of galaxy clusters with different colors were mapped to different topics in the

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CCUS field. The 17 clusters represent 17 topics or research orientations: The cluster to which blue nodes belong deals with social acceptability and public attitude, involving 220 articles; dark-green nodes deal with economic feasibility and development prospect, involving 182 articles; purple nodes deal with transportation pipeline scale and engineering models, involving 172 articles; red nodes deal with technical, economic, and environmental assessment of CCUS projects, involving 120 articles; and grey nodes in the 13th group constitute a cluster of 110 articles, which analyze the citation relationships about the citing article with the first author of Edenhofer.

3.2.2.2 Core literature mining of CCUS studies

From the article information represented by the above different-colored nodes, the general orientations of CCUS studies were extracted. However, their accuracy needed to be verified through core literature mining. Fig 5 shows the citation network for core articles that share Topic 1 represented by the blue star cluster. Fig 6 shows that there are seven total articles with the citation score of 30 (or above) among the core literature with Topic 1. Article titles can roughly reflect public cognition, public opinions, and social acceptability with respect to CCS.

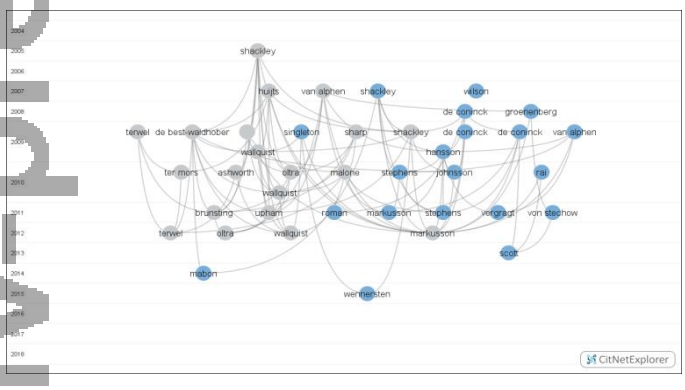

Fig 5 Analysis results of core articles relating to Topic 1

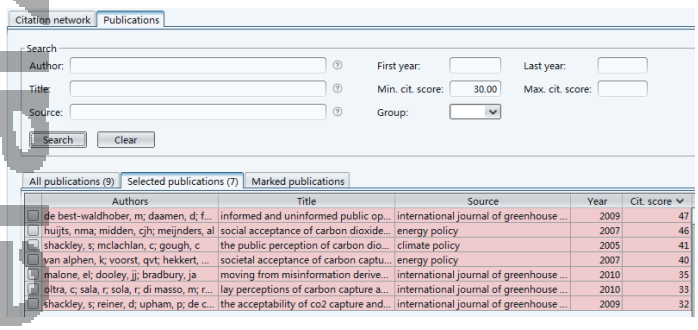

Fig 6 Core article list for Topic 1

To verify the accuracy of topic orientations, characteristic words of core literature were extracted based on the information shown in Fig 6, and their coincidence rate was analyzed (as described in Table 3). The frequently-encountered characteristic words with high coincidence rate included public opinion, carbon dioxide capture and storage, social identity, and social acceptability. Therefore, it is concluded that the orientation of Topic 1 of CCUS studies is social acceptability.

Table 3 List of characteristic words of core literature with Topic 1

Author of Core Literature	*Article Title*	*Characteristic Word*
De Best-waldhober (2009) [13]	*Informed and uninformed public opinions on CO_2 capture and storage technologies in the Netherlands*	*Information-Choice Questionnaire; Public opinion; CCS; Acceptance; Choice*
Huijts (2007) [14]	*Social acceptability of carbon dioxide storage*	*Carbon dioxide storage; Trust; Risk*
Shackley (2005) [15]	*The public perception of carbon dioxide capture and storage in the UK: The results from focus groups and a survey*	*Carbon dioxide capture and storage; CCS; Public perceptions*
Van alphen (2007) [16]	*Societal acceptance of carbon capture and storage technologies*	*Public opinion; Stakeholders' attitudes; Media content analysis*
Malone (2010) [17]	*Moving from misinformation derived from public attitude surveys on carbon dioxide capture and storage towards realistic stakeholder involvement*	*Stakeholder involvement; Public involvement; Carbon dioxide capture and storage; CCS; Surveys*
Oltra (2010) [18]	*Lay perceptions of carbon capture and storage technology*	*Public perception; Social acceptability; Carbon capture and storage; Focus groups; Public engagement*
Shackley (2009) [19]	*The acceptability of CO_2 capture and storage (CCS) in Europe: An assessment of the key determining factors: Part 2. The social acceptability of CCS and the wider impacts and repercussions of its implementation*	*Social acceptability; Stakeholder perceptions; CDM*

Using the above methods and principles for extensive investigation and obtaining the characteristics words of core literature, topic detection was performed on the 17 clusters in the CCUS field in terms of the academic influence of citation analysis. Excluding co-citation literature clustering of Edenhofer, 16 topics of international CCUS studies were identified, including 1) social acceptability, 2) economic feasibility and application prospect, 3) engineering construction models (especially the engineering construction model for the transportation system), 4) hydrate-based carbon dioxide capture and storage, 5) techno-economic analysis and assessment of integrated gasification combined cycle (IGCC), 6) performance-cost-benefit analysis of coal power generation devices at the stage of carbon capture,

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7) carbon dioxide adsorption performance, 8) technical, economic, and environmental assessment & lifecycle assessment, 9) underground storage risk of carbon dioxide , 10) investment strategy assessment, 11) carbon dioxide capture method, 12) Carbon dioxide separation and capture technology, 13)synthesis of carbon dioxide agent, 14) Aquifer treatment for carbon dioxide storage,15) Biomass and property of carbon dioxide,and 16) Purity of carbon dioxide.

The nationality information of the first authors of core articles[13][14][15][17][18][19][20-44] can reveal the contributions that different countries have made to the topics of CCUS studies. For example, the study achievements of the USA and Sweden have mainly concentrated on the cost accounting analysis of CCUS projects and construction models for transportation engineering. China has conducted high-quality studies in two aspects, including carbon dioxide adsorption capacity and investment strategy assessment. The UK and Holland have concentrated on social acceptability and underground storage risk of carbon dioxide. In particular, the UK has attained remarkable achievements in the studies of performance-cost-benefit analysis of coal power generation devices. Italy and Romania have advantages in the studies of integrated gasification combined cycle (IGCC). South Korea and Singapore have made remarkable achievements in the studies of hydrate-based carbon dioxide capture and storage. Japan has made certain contributions to the benefit analysis of power plant devices. Moreover, the two topics of 1) technical, economic, and environmental assessment, and 2) lifecycle assessment are of universal concern in international academia, and the citation rate of articles with these topics is relatively high. The USA, Holland, and Italy have made great contributions to the studies of these topics.

3.2.3 Evolution of the topics of CCUS studies

Table 4 describes the earliest time of publication, number of all publications, number of citation relationships, and maximum citation score with respect to each topic. Based on the results of topic identification and analysis in CCUS studies attained by CitNetExplorer combined with the information in Table 5, the time-based evolution of different topics of CCUS studies could be determined. From a lateral perspective, the topics of CCUS studies continued to extend; from a longitudinal perspective, the studies of different topics were increasingly in-depth, thus forming a criss-crossed citation network.

(1) Beginning with initial concentration on the topic of the underground storage risk of carbon dioxide in 1992, the topics of CCUS studies moved on to the impact of carbon dioxide leakage, and impact of underground storage of carbon dioxide on hydrogeology. Then, the topics were extended to aquifer treatment for carbon dioxide storage, and hydrate-based carbon dioxide capture and storage technology.

Table 4 Evolution of topics of CCUS studies (through the end of 2018)

Topic	Earliest Time of Publication	Number of all publications	Number of Citation Relationships	Maximum Citation Score
Underground storage risk of carbon dioxide	1992	106	463	36
Aquifer treatment for carbon dioxide storage	1994	115	313	49
Hydrate-based carbon dioxide capture and storage	1995	148	562	46
Economic feasibility and application prospect	2001	182	589	72
Carbon dioxide adsorption performance	2001	134	435	36
Technical, economic, environmental and lifecycle assessment	2002	120	477	123
Performance-cost-benefit analysis of coal power generation devices at the stage of carbon capture	2002	141	489	108
Social acceptability	2004	220	1151	47
Investment strategy assessment	2004	105	305	41
Carbon dioxide capture method	2004	125	327	25
Synthesis of carbon dioxide agent	2004	112	269	19
Engineering construction model	2004	172	1007	86
Techno-economic analysis and assessment of IGCC	2005	144	482	63
Biomass and property of carbon dioxide	2008	109	454	90
Carbon dioxide separation and capture technology	2009	126	252	45
Carbon dioxide purity	2011	107	365	59

(2) Considering that CCUS projects are characterized by large industry span, large spatial scale, long time span, high technical cost, and high investment risk, the development of CCUS has always been faced with a contradiction between excessive funding demand and limited actual funding input. While investigating the risk and treatment of carbon dioxide storage, researchers

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began to explore the economic feasibility of CCUS in 2001. Specifically, they examined the overall cost effectiveness of CCUS projects, cost effectiveness of carbon capture devices in coal power plants, scientificity of carbon capture methods used in coal power plants, and cost accounting and comparison for CCUS projects. In addition, the value contribution of CCUS in alleviating global warming also has received attention in academia; therefore, researchers have conducted quite a few studies of the application prospect of CCUS.

(3) Public perception then had a direct impact on the progress of CCUS projects. Therefore, academia has conducted surveys on the public perception and social acceptability of CCUS projects since 2004, concentrating on the investment strategy and assessment methods of CCUS projects.

(4) In 2004, certain researchers began to study the construction framework of the CCUS project system (especially engineering design of the transportation system) from the perspective of engineering analysis, and extended the scope of CCUS studies to the overall CCUS technology (especially in terms of economic analysis and assessment).

(5) Multiple researchers then turned their attention to the chemical extraction, separation, and utilization modes of carbon dioxide, and studied a series of problems of carbon dioxide from a chemical perspective. Such studies were initially conducted in 2001, concentrating on the carbon dioxide adsorption performance, and their scope was gradually extended. Specifically, these studies began to discuss the synthesis of carbon dioxide agents in 2004, as well as introduce other topics (e.g., biomass, properties, purity improvement, utilization, separation, and capture) in 2008.

In summary, the evolution of topics of CCUS studies can roughly be divided into three stages: feasibility analysis, popularization studies, and scientific development. At the first stage, the CCUS studies mainly demonstrated whether CCUS was practicable and worth implementing from the perspectives of environmental risk, contribution value towards emission reduction, and economic feasibility. Since CCS was proposed and originated in MIT in 1989, academia immediately gave attention to the following questions: 1) whether the underground, land, or seafloor storage of carbon dioxide causes an environmental risk; 2) how high the environmental risk is (if any); 3) whether the risk can be avoided; and 4) what can be done to avoid the risk. When the storage risk of carbon dioxide was delved to a certain degree (e.g., feasibility analysis and basic measures for environmental safety), the CCUS studies mainly concentrated on the following topics: 1) contributions of CCUS to large-scale emission reduction; 2) economic feasibility analysis-based cost accounting. At the second stage, the CCUS studies mainly discussed how to popularize CCUS technology, concentrating on economic benefits, lifecycle assessment, investment strategy, and social acceptability. The objectives were to achieve the emission reduction targets and promote the development of CCUS in diverse investment ways, thus alleviating the funding pressure of CCUS projects. To attain further development, any technology had to be safe, cost-effective, and feasible, and more importantly, had to be capable of improvement and constant reformation. In other words, it was necessary to ensure the technology's scientificity, cost-effectiveness, and safety. Hence, it can be seen that at the third stage, the CCUS studies gave more attention to the advancement, development, and vitality of the CCUS technology, concentrating on engineering construction, carbon capture methods, carbon separation technology, IGCC technology, metal-organic framework capture and separation technology, and carbon dioxide purity optimization. The objective was to scientize the CCUS technology itself, thus better developing the technology.

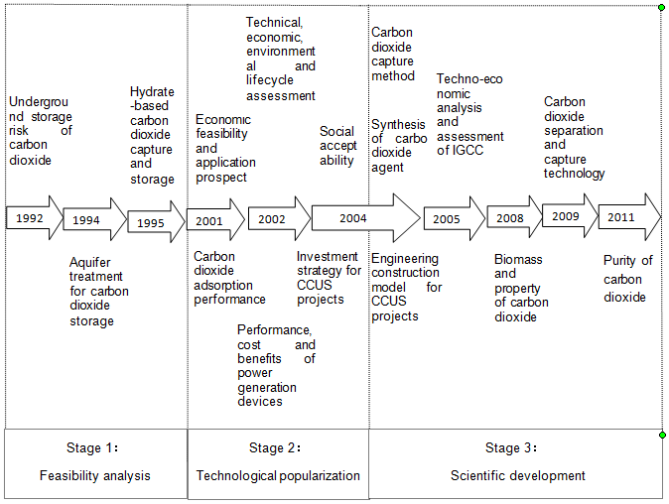

Fig 7 Evolution of topics of CCUS studies

3.3 Analysis of hot topics of CCUS studies

In terms of the number of all publications and citation relationships (as described in Table 4,14 papers 错误!未定义书签。错误!未定义书签。错误!未定义书签。[45]错误!未定义书签。错误!未定义书签。[46]错误!未定义书签。错误!未定义书签。错误!未定义书签。[47]错误!未定义书签。错误!未定义书签。错误!未定义书签。are

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included), the CCUS studies gave substantial attention and detail to topics such as social acceptability, economic feasibility and application prospects, engineering models, techno-economic analysis and assessment of CCUS engineering, performance-cost-benefit analysis of power plants, and storage risk of carbon dioxide. Articles with the maximum citation score concentrated on two topics: performance-cost-benefit analysis of power plants and technical, economic, environmental and lifecycle assessment of CCUS projects; followed by three topics: the biomass and property of carbon dioxide, engineering construction models, and cost accounting analysis. Evidently, overall, the researchers gave significant attention to two primary topics: economic analysis and project assessment. Based on the results of clustering analysis, further analysis of three indices (i.e., the number of all publications, citation relationship, and maximum citation score), and the H-index-based citation network with Publications-Min.Cit.Score = 60 in CitNetExplorer, we can see that the international hot topics of CCUS studies mainly concentrate on the following aspects:

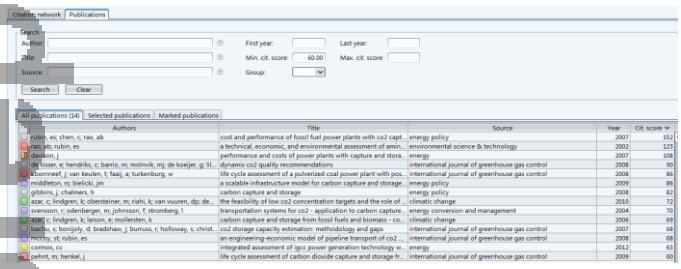

Fig 8 Publications with the top 60 H-index

(1) System assessment of CCUS. This topic mainly refers to the technical, economic, and environmental assessment of CCUS technology, and lifecycle assessment of CCUS projects. Within this module, the most influential article was “A technical, economic, and environmental assessment of amine-based CO_2 capture technology for power plant greenhouse gas control” (Rao,Rubin.2002) 错误!未定义书签。错误!未找到引用源。, published in Environmental Science & Technology, with a citation score of 123. That article discusses how to capture the post-combustion carbon dioxide using the amino absorption technology, and develops a general model framework accordingly. From the perspectives of system impact of performance of power plant, environmental emission and cost, the article assesses various options for capture of carbon dioxide from the source of combustion power generation and its safe storage (isolation). The article concludes that the technology for capture of carbon dioxide has relatively low requirements for funds and electric power cost, and has remarkable advantages in terms of key performance and potential tradeoffs between diverse pollutants. Other studies concentrate on the lifecycle assessment of CCUS projects. Representatively, Koornneef et al.(2008) 错误!未定义书签。 used the lifecycle assessment method to assess the environmental impact of three electric power supply chains by pulverized coal (PC) combustion in the absence and presence of CCS technology. Their results showed that CCS technology reduced greenhouse gas emissions dramatically to 243 g per kilowatt-hour. Compared with the subcritical and state-of-the-art supercritical technology of PC combustion power generation, CCS technology reduced greenhouse gas emissions per kilowatt-hour by 78% and 71% respectively. Michela et al. (2013)[48] investigated the specific rules to be obeyed when the lifecycle assessment method is applied to CCS and discussing a series of key issues, e.g., the definition of service category, functional unit and system boundary, as well as the selection of allocation rules, specified lifecycle inventory results, and parameters of environmental factors.

(2) Engineering construction model of transportation system. In the process of CCS, carbon dioxide sources may be spatially scattered away from carbon dioxide geological repositories; therefore, the sources need to be connected through a special carbon dioxide pipeline network. In academia, it is an issue of common concern how to determine where and how much carbon dioxide needs to be captured and stored, and where pipelines of varying sizes should be built and connected to minimize transportation costs. As early as 2004, Svensson et al.错误!未定义书签。 performed a scenario analysis of different transportation schemes of CCS in different aspects (e.g., cost, capacity, distance, transportation mode, and storage type), arguing that pipelines (including ashore and offshore pipelines), water transport vehicles (offshore), and the combination of them are feasible transportation schemes. In addition to the design of transportation engineering, the economic analysis of pipeline transportation of carbon dioxide has also received attention in academia. McCoy et al. (2008) 错误!未定义书签。 constructed an engineering economics model for pipeline transportation of carbon dioxide, based on an estimation of the total cost and per-ton cost of transporting different amounts of carbon dioxide at different distances in different regions of the continental US. With the ability of probability analysis,

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the model can be used to quantify the sensitivity of transportation cost to the variability and uncertainty of model input parameters. An analysis using this model shows that there is a 90% probability that the per-ton cost of transportation of carbon dioxide in the Midwestern USA ranges from $1.03–2.63; in this case, the transportation cost is most sensitive to the pipeline capacity factor and capital recovery factor. Considering the advantages of scale economy and related factors (e.g., topography and social impact), Middleton et al. (2009)错误!未定义书签。 constructed a simple model for carbon capture system infrastructure, in which the carbon dioxide flows between sources and repositories are gathered into a trunk pipeline. As exemplified by 37 carbon dioxide sources and 14 Californian reservoirs, they demonstrated the scientificity of this simple carbon capture system, highlighting the importance of systematic planning of CCS infrastructure. After the article was published, it has received attention from many researchers, and its citation score is as high as 86.

(3) Cost accounting analysis of CCUS. CCUS is always faced with the bottleneck issue of high cost. As CCS has received wide attention as an alternative solution to greenhouse gas emission mitigation, the assessment of its cost and performance has become a key factor in energy and policy analysis (Rubin et al., 2007) 错误!未定义书签。. According to a report released by the IPCC in 2005, CCS technology will be applied on a large scale only when its operating cost falls to US $25–30 per unit of carbon dioxide. To study the relationship between emission reduction efficiency, resource demand and cost, Rubin et al. (2007) 错误！未定义书签。 comparatively analyzed the carbon capture cost and emission reduction efficiency of three types of power plants (i.e., power plants with PC, with the natural gas combined cycle (NGCC), and with IGCC). Their analysis results showed that power plants with NGCC incurred higher carbon capture cost than power plants with IGCC or PC because of diverse factors (e.g., capital cost, rising natural gas price, equipment utilization rate, financing and operation hypotheses of IGCC, variation in equipment scale, and differences in fuel quality). Azar 错误!未定义书签。 错误!未定义书签。22] published articles respectively in 2006[1] and 2010[2], to discuss the techno-economic feasibility of achieving the targets for the concentration of greenhouse gas within a stable atmosphere. In 2006, he argued in his article that the bioenergy with carbon capture and storage (BECCS) technology could significantly increase the possibility of achieving the targets of low concentration. In 2010, Azar further estimated the cost and conversion efficiency of different power generation technologies (e.g., hydrogen, fossil fuel, and biomass thermal power generation) when the concentration of carbon dioxide in the atmosphere stably remains at 350 and 450 ppm. Accordingly, Azar argued that the CCS technology applied to fossil fuels and BECCS could respectively reduce cost by 50% and 80% under the stable carbon dioxide concentration of 350 ppm, and respectively by 40% and 42% under the stable carbon dioxide concentration of 450 ppm.

(4) Techno-economic analysis and assessment of IGCC engineering. IGCC is a clean and efficient power generation technology, through which solid raw materials are partially oxidized by oxygen and steam to produce synthesis gas. The IGCC technology has great potential and bright prospects. Combined with CCUS technology, it has advantages such as low carbon dioxide capture cost, high power generation efficiency, and low pollutant emissions, and plays an important role in reducing greenhouse gas emissions (Cormos, 2012) 错误！未定义书签。. The studies of IGCC mainly concentrated on the following topics: 1) evaluation of the hydrogen and power co-production scheme in the process of carbon capture, storage, and gasification; 2) performance and carbon emission of hydrogen and power co-generation; 3) evaluation of energy integration in hydrogen and power co-generation; 4) techno-economic comparison between coal-fired and gasification technologies; 5) effect of carbon dioxide control technology on the performance and cost of IGCC devices; and 6) energy and economic comparison between IGCC-CCS and IGFC-CCS power plants. The article “Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS)” (Cormos, 2012) 错误!未定义书签。 had a substantial impact, and had the highest citation score (specifically, 63) within its module. The article created the most important technical, economic, and environmental indicators for IGCC-CCS (e.g., power generation capacity, auxiliary electricity consumption, energy efficiency, continuous electricity consumption, standardized mass and energy balance, cost of plant building materials, capital, operation and maintenance, specific carbon dioxide emissions, and power cost), and constructed models for the cost of capital, operation, management, and carbon dioxide capture, as well as cash flow estimation. Accordingly, the article evaluated the alternative carbon capture solutions for the IGCC-based power generation technology.

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(5) Risk management for carbon dioxide storage. CCUS technology is faced with substantial risk. In particular, carbon storage may be faced with potential safety and environmental risks (e.g., leakage and earthquake). Hence, researchers have explored the problem to varying degrees in the aspects of risk management and assessment, and have proposed to establish a perfect risk management system or risk supervision policy. Within this module, an article published by Holloway in 2005 错误!未定义书签。had the highest citation score. Considering the fact that carbon dioxide was stored in porous and permeable reservoir rocks in the Sleipner West gas field in the past five years, Holloway reflected on the underground storage of carbon dioxide. Specifically, he argued that carbon storage must address primary issues such as the cost effectiveness of carbon capture, safety of carbon storage, safety demonstration, and social acceptability. Similarly, Damen et al. (2006) 错误!未定义书签。argued that to ensure that underground storage of carbon dioxide is used as a safe and effective solution to greenhouse gas emission reduction, it would be necessary to have an in-depth understanding of the related risks. Hence, because such risks (e.g., leakage, seismicity, surface movement, and saltwater displacement) were yet to be known, it was first necessary to identify and control the process of well leakage, fault leakage, and fracture leakage, to assess leakage rates and their impact on the (marine) ecosystem. Considering the uncertainty of the CCS system, Gerstenberger et al. (2009) [49] proposed the logical tree risk assessment method. Based on modularization and probability analysis, the entire risk assessment process was construed as a controllable part, playing an important role in identifying the main risk factors.

(6) Social acceptability of CCUS projects. The acceptability of CCUS by the public is the key factor that affects the sustainability of CCUS. In this regard, some researchers have investigated the public perception and social acceptability of CCUS in their countries or regions. Representatively, Shackley et al. (2005)错误!未定义书签。 discussed the public opinion of the UK on offshore carbon dioxide capture and storage, finding the following phenomena: 1) in the absence of CCS information, the public had negative emotions toward CCUS; 2) if informed that CCS plays a role in reducing carbon emissions in the atmosphere, the public did render minimal support instead of negative emotions. Evidently, information disclosure and transparency are of great importance to public perception. Shackley et al. (2006) [50] continued to investigate the public perception of the UK toward "the role of CCS in the future production system", finding that most people have viewed CCS as a part of the low-carbon energy system. Shackley et al. (2007) [51] extended the scope of investigation to the whole of Europe. Their results showed that most of the respondents had a positive attitude toward the necessity of CCS to carbon dioxide emission reduction, and more than half of the respondents were of the opinion that the risk coefficient of CCS was low. In contrast, the investigation results in Holland were not optimistic. Through information selection questionnaires (ISQ), De Best-Waldhober (2009)错误!未定义书签。 investigated the public perception of CCS in Holland. The results showed that most Hollanders did not know of CCS technology, nor did they know that the current energy utilization would lead to global warming. The differences in public attitudes between the two countries also demonstrates the relationship between social acceptability and the degree of governments' attention to CCS, as well as the degree of technological development in different countries. The higher the degree of public perception towards CCS is in a country, the more developed the CCS technology is in the country. In addition, the degree of public perception is also affected by the social acceptability of CCUS by the related policy-makers, masses, and media, as well as the propagation mode of CCUS (Oltra, 2010)错误!未定义书签。. Huijts错误!未定义书签。 surveyed the social acceptability of CCS in 2007, finding that people living near potential storage sites had a negative attitude toward CCS, and the general public seemed to know little about carbon dioxide storage nor did they have any desire to learn more of the subject. That study argued that public reaction is related to the reaction of professional participants. Among the three groups including governments, industry, and environmental non-governmental organizations (NGOs), NGOs were considered to be the most trusted by the public, whereas industry was considered to be the least trusted. Based on a series of previous studies, Shackley et al. 错误!未定义书签。 conducted a study titled "Acceptability of CCS in Europe: Assessment of key determinants" in 2009. Part I of the study (i.e., the European Union's ACCSEPT project from 2006 to 2007) discussed the key factors such as scientific, technical, legal, economic, and social acceptability. Based on the findings of Part I, Part II analyzed the social acceptability of CCS by the public and stakeholders under the Clean Development Mechanism

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specified in the Kyoto Protocol. Accordingly, the study team pointed out that the efforts made in Europe to understand and reach out to the non-professional public and extensive stakeholders (i.e., as opposed to only enterprises) were still insufficient.

3.4 Trend prediction of CCUS studies

Using CitNetExplorer, the 38 articles [51-89] with high citation scores from 2016 to 2018 were analyzed. Evidently, nearly all publications with a top H-index concentrated on topics such as process technology and infrastructure construction, technological cost analysis and techno-economic assessment, and role analysis and technological deployment, whereas only two publications concentrated on the analysis of public attitudes towards technological implementation in Germany. Table 5 lists the statistics on the distribution of publications with different topics.

Table 5 Distribution of publications and topics with a top H-index in the CCUS field (2016 to 2018)

Topic of CCUS Studies	Number of Publications with a Top H-index			Number of All Publications
	2016	2017	2018	
Process technology and infrastructure construction	5	7	6	18
Application prospect and project deployment	4	4	1	9
Cost analysis and techno-economic assessment	5	5	0	10
Public attitude	0	0	2	2
	15	16	9	40

Among the four topics in Table 5, the topic of process technology and infrastructure construction covered the largest number of publications (18 total publications in three years). In 2018, publications with this topic accounted for 66.7%. These publications investigated specific technologies such as supercritical PC power plants, BECCS, technology for effective capture of carbon dioxide, enhanced carbon dioxide adsorption capacity, and efficient temperature swing adsorption (TSA) and efficient vacuum pressure swing adsorption (VPSA) for separating carbon dioxide. This demonstrates that process technologies played an important role in the evolution of topics of CCUS studies, and technological progress of CCUS was the ultimate goal in the CCUS field. Three additional topics (i.e., cost analysis and techno-economic assessment, role analysis and technological deployment, and public attitude) were respectively covered by ten, nine, and two publications, accounting for 25%, 22.5%, and 5% of total publications with a top H-index in three years. Evidently, the economic analysis of CCUS, with considerations of cost, environmental impact and risk preference, and application prospect and demonstration project deployment, are still hot topics of CCUS studies.

The above analysis shows that continuous technological improvement and infrastructure construction, centered on technological development, can be expected to continue as a hot topic and main trend in the CCUS field. In particular, techno-economic analysis of emerging new process technologies (e.g., analysis of cost effectiveness and efficiency) and studies of their development prospect will be expected to attract the interest of researchers, representing a cutting-edge trend in future studies.

4. CONCLUSIONS AND PROSPECT

Since the advent of CCS in 1989, CCUS as a large-scale emission reduction mode has been a hot issue because of its remarkable contributions in addressing global warming. Based on the WOS database platform combined with CitNetExplorer, this study analyzed the achievements of CCUS studies from 1989–2018 using diverse methods (i.e., bibliometrics, visual analysis of citation network, and clustering analysis). The objective was to explore the study progress, evolution of topics, and hot topics in the CCUS field in the last three decades. The findings of this study can be summarized as follows:

(1) In the last three decades, both theoretical and practical studies of CCUS have been fruitful. Roughly, the CCUS studies have undergone four stages: 1) embryo stage (1989−2003); 2) gradual development (2004−2008); 3) rapid growth (2009−2011); 4) rapid development (2012−2018). Among the source journals, International Journal of Greenhouse Gas Control and Applied Energy have published the largest number of CCUS articles. Among the source countries, the USA, China, and UK have published a large number of CCUS articles, and are hotspots of CCUS studies.

(2) Using CitNetExplorer, clustering analysis was conducted to identify topics of CCUS studies and mine characteristic words of core literature. In total, 16 topics (including ten core topics) were identified in the CCUS field. Overall, the topics of CCUS studies present an evolution path from feasibility analysis to technological popularization, and then technological development.

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(3) Among the topics detected by CitNetExplorer, six had high clustering density, diverse citation relationships, and the highest citation scores, here listed in order from highest to lowest density: 1) system assessment of CCUS; 2) engineering construction model for the transportation system; 3) cost accounting

(4) At present, CCUS studies are still at the stage of rapid development. According to the statistical data on refined disciplines in the WOS database acquired using the advanced search method, a total of 863 additional CCUS articles were included into the WOS database in 2019. With the change in global climate, we can predict that the scope of CCUS studies will continue to expand. In this study, the achievements of CCUS studies in recent years were analyzed using the CitNetExplorer. The analysis results show that three topics (i.e., process technology and infrastructure construction, cost-effectiveness assessment, and development prospect and project deployment) cover a large number of articles and have high citation scores in different years. Namely, these three topics are expected to continue as preferred focuses of CCUS studies in the future. In particular, specific technological methods with high cost-effectiveness and efficiency are cutting-edge trends of CCUS studies. With the development and application of CCUS technology, it is imperative to formulate and perfect related laws, regulations and policies, and develop a legal framework and complete regulatory system in favor of the technological and industrial development of CCUS. This will surely become another hot topic and receive much attention from researchers.

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analysis; 4) techno-economic analysis and assessment of IGCC engineering; 5) risk management for carbon dioxide storage; and 6) social acceptability of CCUS projects. The six topics take a dominant status in CCUS studies and are hot topics in this field.

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