Advancing CCUS

Insights From Academic Research

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Publication date:
2024

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ADVANCING CCUS

INSIGHTS FROM ACADEMIC RESEARCH

Alexandra E. Carst, Louise B. Kringelum & Yariv Taran

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EXECUTIVE SUMMARY

In the quest to achieve carbon neutrality, carbon capture, utilization, and storage (CCUS) plays a pivotal role in climate change mitigation. Considering the significance of CCUS in this context, this report is designed to present the current state-of-the-art of CCUS research by exploring the contribution of academic studies to the development and enhancement of CCUS technologies and practices. It is also the objective of this report to identify the current research directions and uncover critical gaps that necessitate further scholarly exploration.

For these purposes, a dataset of 1,663 documents with CCUS-related keywords in their topics was extracted from the Web of Science (WoS) database. The included articles originate only from sources within the fields of business, economics, and operations research management science. Based on a bibliometric analysis of the dataset, the report provides an overview of the CCUS research, identifies current trends and themes, as well as the potential and challenges addressed in contemporary research.

The findings show not only an exponential global increase in publication output indicating a growing interest, but also relevant recognition of the CCUS-related studies within the scientific community. The analysis also reveals that the United States of America (USA) is leading the charge in CCUS research, with five US universities ranking in the global top ten based on number of publications. Until 2020, the United Kingdom had held second place, but it was surpassed by China, which experienced a noticeable surge in this research field. This remarkable progress has been spearheaded by Tsinghua University's prominence in the global publication ranking.

Regarding research topics, the academic community continues to prioritize *climate change,* with a strong emphasis on *climate policy* and *carbon sequestration*, while the topic of *CC(U)S* seems less explored. It is also noteworthy that *carbon utilization* rarely appears as an independent author's keyword—this does not necessarily imply a disinterest in the topic, but rather a sign of a research field that is currently underexplored. In conclusion, the review indicates that contemporary research has predominantly focused on technological aspects, while those related to marketization and holistic perspectives on business potentials remain relatively underdeveloped.

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INTRODUCTION TO CCUS

WHAT IS CCUS?

Carbon capture, utilization, and storage (CCUS) is a concept that covers a broad range of technologies that are aimed at mitigating carbon dioxide (CO_2) emissions (Gibbins & Chalmers, 2008). CCUS is considered a fundamental concept to achieve carbon neutrality in the battle against climate change (Tapia et al., 2018). Generally speaking, it can be divided into processes of carbon capture and storage (CCS) and carbon capture and utilization (CCU), as illustrated in Figure 1. In CCS, the CO_2 that is emitted as part of industrial processes and energy production is captured by various methods. Once captured, CO_2 is transported by truck, vessel, or pipeline to a suitable storage facility, which often involves underground injection. In contrast, CCU focuses on the utilization of captured CO_2, either chemically or biologically. This means that technologies are applied post-capture to convert CO_2 into other valuable products—rather than passively storing it (INNO-CCUS, 2023).

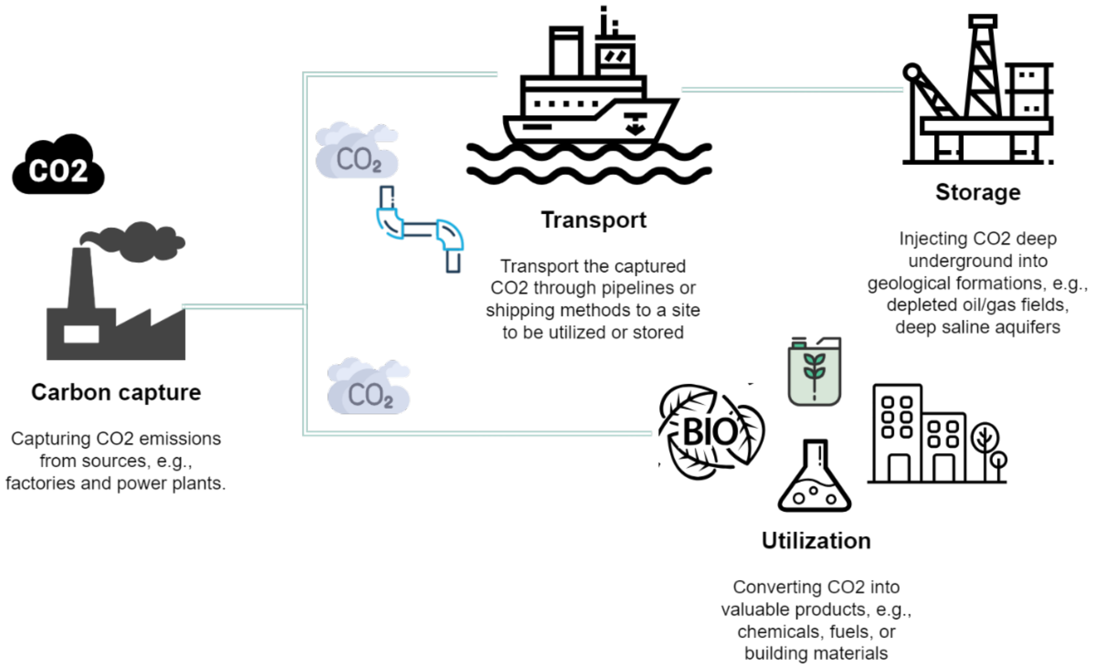

Figure 1. Schematic representation of CCUS components.

The technological maturity in the field of CCS is considerable, and the feasibility of conducting CCS on a commercial scale has existed for many years (Gibbins & Chalmers, 2008). In 2008, Gibbins & Chalmers anticipated a surge in flagship carbon capture demonstration projects aimed at elucidating and clarifying the commercial potential during the 2010s. In fact, this prediction has materialized, as evidenced by the growing number of CCUS projects in Denmark. Since 2003, more than one hundred projects have been established with a focus on CCUS in Denmark (Teknologisk Institut, 2024) and the number of public and private stakeholders involved in these projects continues to increase. Although most flagship projects have been launched to develop and assess technological advances with the scope of societal change as the primary driver, CCUS is still widely perceived as a pre-commercial technology in most industries. Consequently, the full extent of its commercial potential remains unclear (Muslemani et al., 2020).

RELEVANCY OF CCUS

At a societal level, the mitigation of CO_2 emissions to create a low carbon society requires substantial transformation through low carbon technology innovation (LCTI) (Neij & Nemet, 2022). This is a radical innovation process of high complexity at industrial/sectorial levels, which will involve many stakeholders ranging from businesses and government to communities. However, the demand for CCUS is not established through conventional market forces. In contrast, the demand is created through a societal concern for reduction of carbon emission to mitigate climate change. Moreover, the idea of relying solely on CO_2 abatement policies and carbon tax will not ensure a shift towards CCUS technologies (Acemoglu et al., 2016; Goulder & Schneider, 1999). In essence, the shift assumes the establishment of a new industry—an industry based on technological innovation with an unclear idea of the potential value from both an economic and societal perspective. Creating such a new industry presupposes transition activities of the sociotechnical system, alongside policy adjustments to support the process towards abatement of CO_2 emissions.

Establishing this industry gives rise to various challenges that present "chicken-and-egg" problems. The nature of these challenges is especially connected to financial/investment ownership and the role and responsibility of organizations in forming the pipeline infrastructure, etc. As these challenges reflect, there is a need for more focus on the business and organizational dimensions of CCUS, which are often overlooked (Muslemani et al., 2020).

On an organizational level, the decision to embark on CCUS is affected by, amongst other things, current emissions, CO_2 capture efficiency, resource requirements, and the reduction of process and current costs, as well as verification of environmental sustainability (Pires et al., 2011; Rubin et al., 2007). Therefore, it is essential to explore the business activities related to CCUS and the inherent potential and challenges. However, the demand for CCUS is relatively small, which leads to challenges in organizing a (stable) supply chain and managing interorganizational initiatives. For this reason, the shift towards CCUS requires significant investment in research to ensure identification of efficient approaches to reduce carbon emission.

RESEARCH AIM AND DESIGN

In general, there is limited research on the potential of value creation and capture in CCUS (Yao et al., 2018). While some insights have been presented regarding potential business models that could facilitate commercialization (CCU Advisory Group et al., 2019), further exploration is necessary to understand the key drivers that characterize successful large-scale deployment of CCUS technology.

The aim of this report is to showcase the current state-of-the-art of CCUS research in order to achieve an understanding of the role of academic research in investigating and advancing CCUS technologies and practices. Furthermore, we are interested to learn about the current research progress trajectories and possible gaps which require further investigation.

This report presents findings from a bibliometric analysis conducted between November 2023 and February 2024. Based on the Web of Science (WoS) database, a dataset of 1,663 documents that contain CCUS-related keywords within the fields of business, economics and operations research management science was extracted and analyzed to identify current trends and themes, as well as the potential and challenges addressed in contemporary research.

in the following section, the bibliometric methodology, search strategy, and analytical approach utilized are elaborated. The remainder of the report is structured into four main sections. Section 4, *Overview of CCUS Research,* provides an overview of CCUS research, laying the groundwork for understanding the current state at the metadata level. Section 5, *Conceptual structure of CCUS,* research presents the conceptual structure of CCUS research, offering insights into the keywords and themes that attract(ed) scholarly attention. Lastly, the final sections, *Summary of key findings* and *Conclusion,* highlight the key findings and deliver the overall conclusion, respectively, emphasizing the significant discoveries and providing avenues for further research.

METHODOLOGY

This study employs a systematic review approach because of its suitability for exploratory purposes (Rousseau, 2006). Although developed and extensively used in medical science, systematic reviews have also become prevalent in social sciences due to their structured approach to transparently synthesize findings, a process that can be reproduced (Davis et al., 2014; Tranfield et al., 2003). Following the systematic review guidelines and its structured approach, relevant documents were first identified in the extant body of knowledge. To identify all relevant documents, inclusion criteria are followed with a pre-established strategy and precise data collection. Then, the articles were critically assessed, analyzed, and synthesized to provide reliable, evidence-informed findings with a minimal level of bias (Tranfield et al., 2003). Using this approach, the findings of systematic reviews can be transposed into practical decisions (Moher et al., 2009).

To conduct this review, we followed three main steps: (1) search strategy and selection of studies; (2) descriptive bibliometric analysis to grasp an overview of the extant knowledge; and, (3) synthesis of findings and themes rendered by the conceptual structure of the dataset.

SEARCH STRATEGY

We extracted a collection of bibliographic data from Web of Science (WoS), a multidisciplinary database that includes a wide variety of high-quality journals and other subscription-based sources, covering a wide timeframe (Gavel & Iselid, 2008; Prins et al., 2016). To ensure the inclusion of all keywords and their plurals, truncation of keywords was implemented. As CCS and CCU can refer to, or closely resemble, other acronyms such as *"culturalist branch of cognitive sociology, co-created service recovery (CCS-R), consumer co-operatives (CCs), critical care unit (CCU),"* the acronyms were used in conjunction with the keyword *"carbon."* In this way, irrelevant articles from health, sociology, marketing, and medical economics were avoided. Despite this measure, two irrelevant articles were included, which were later removed under the last exclusion step of relevance. Additionally, the search string includes various synonyms and similar terminologies, identified through several initial rounds of searches. Although broader in its sense, we also decided to include the truncated keywords of CO_2 or carbon technologies. The results were further filtered by language, document type, research area, and relevance. The search strategy and inclusion criteria are shown in Table 1.

((“CCUS” OR “CCS” OR “CCU”) AND "carbon") OR “carbon captur*” OR "CO2 captur*" OR “carbon sequestrat*” OR "CO2 sequestrat*" OR "carbon abat*" OR "CO2 abat*" OR "carbon stor*" OR "CO2 stor*" OR "carbon utili*" OR "CO2 utili*" OR "carbon tech*" OR "CO2 tech*"		**91,290**	
Language	English	90,460	-830
Document type	Article, review article, early access, book chapters	80,729	-9,731
Research areas	Business economics, operations research management science	1,665	-79,064
Relevance check	Adequate use of CC(U)S-related keywords (all articles that use CCS/CCUS abbreviations as referring to other concepts were excluded)	**1,663**	-2

Table 1. Search string and strategy as per February 5, 2023.

The final dataset includes 1,663 articles, which shows a significant gap in the business studies compared to the majority of results which approach CCUS from different perspectives, e.g., engineering (24,427), environmental sciences ecology (22,433), energy fuels (17,254), or chemistry (13,114).

Considering the multiple keywords used for the same CCUS concepts, we decided to harmonize the dataset by merging the synonyms before analysis, as illustrated in Table 2. This step ensured that a more accurate overview of the CCUS field was gained without the distraction of using multiple terminologies or formats for the same keywords.

Keywords replaced	Keywords used
CCUS Carbon capture, utilization, and storage Carbon capture, utilization, and storage (CCUS)	Carbon capture, utilization, and storage (CCUS)
CCS Carbon capture and storage Carbon capture and storage (CCS) Carbon dioxide capture and storage (CCS) CO2 capture and storage CO2 capture and storage (CCS)	Carbon capture and storage (CCS)
CO2 capture	Carbon capture
CO2 sequestration	Carbon sequestration
CO2 storage	Carbon storage

Table 2. Harmonization of author’s keywords.

Although carbon capture and carbon sequestration are two overlapping concepts that are sometimes used interchangeably (Lebling et al., 2023), their implications and the process of reducing CO_2 are different. Carbon sequestration refers to the process of storing carbon dioxide that has been captured and removed from the atmosphere. This can also be done through the biological processes assumed by forests, oceans, and soil. Thus, carbon capture encompasses carbon sequestration, while carbon capture may be a technology-oriented approach to capture CO_2 from industrial and energy-related sources. For this reason, we decided to keep both concepts in the dataset without merging them.

METHOD AND ANALYSIS

To analyze and map relevant knowledge regarding CCUS, we employed quantitative methods of bibliometric analysis (Zupic & Čater, 2015). We relied on RStudio and its packages, i.e., bibliometrix and biblioshiny (Aria & Cuccurullo, 2017), as well as VOSViewer (Van Eck & Waltman, 2009) and Microsoft Excel for generating the figures and tables. An initial descriptive analysis of the articles' bibliographic metadata was performed. Such analysis generates useful findings that can be leveraged in the next steps of science mapping (de Oliveira et al., 2019).

The second analysis step consisted of co-word analysis for science mapping of the conceptual structure. Co-word analysis reveals relationships between studies and dominant themes (Su & Lee, 2010; Zupic & Čater, 2015). Using words as the unit of analysis, which are then grouped, networks or clusters are created to map the conceptual structure through a network (co-word) or factorial analysis. Relationships are then established among the included studies through word counting and co-occurrences extracted from the keywords found in the bibliographic dataset (Aria & Cuccurullo, 2017; Liu et al., 2012). Thus, using author's keywords as method parameters, the topics within the CCUS field are reproduced in semantic maps (Aria & Cuccurullo, 2017).

LIMITATIONS

Despite the systematic approach of this analysis, the report is not exempt from limitations. First, the study relies only on a single database, i.e., Web of Science (WoS). Although WoS has strict indexing criteria for journals, other databases may include more relevant articles published in journals that are not indexed in WoS. Nevertheless, our database choice is justified by WoS's focus on indexing high-impact journals, which ensures the quality of this study's findings.

Furthermore, due to the quantitative nature of the bibliometric analysis and its limitations, only the metadata of the documents included in the dataset, e.g., authors' names, affiliations, article titles, abstract, and keywords are used to analyze the field of CCUS. Thus, the analysis does not examine the content of the publications in more depth, relying only on the titles, authors' keywords, and abstracts to understand their content. Therefore, further qualitative analysis of the studies' content may provide a more detailed overview of the themes and topics studied.

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OVERVIEW OF CCUS RESEARCH

The dataset spans 33 years from 1991 to 2024, with articles published in 210 sources. Most of the included articles are multi-authored, with an average of three authors per article.

Timespan	1991–2024
Sources	210
Documents	1,663
Annual growth rate	9.66%
Authors	3,517
Authors of single-authored documents	205
International co-authorship	29.77%
Co-authors per document	3.03
Authors' keywords	4,124
Document average age	9.76
Average citations per document	38.74

Table 3. Descriptive statistics of the bibliographic metadata.

The dataset mainly contains articles including early access, proceedings, reviews, and book chapters.

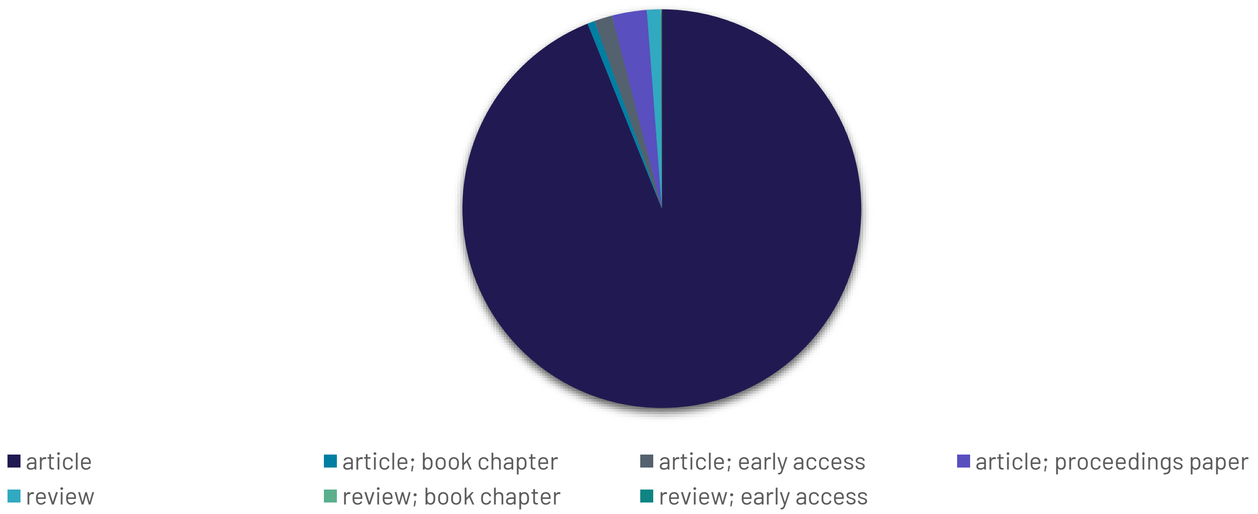

Figure 2. Types of documents included in the dataset.

ANNUAL SCIENTIFIC PRODUCTION

With an annual percentage growth rate of 9.66%, CCUS has been receiving increasing research attention. The first peak was noticed in 2012 and this momentum has since been maintained, as illustrated in Figure 3. The past couple of years have shown a slight upward trend. Although the dataset only contains articles up to and including January 2024, 21 articles have already been published in the first month of the year.

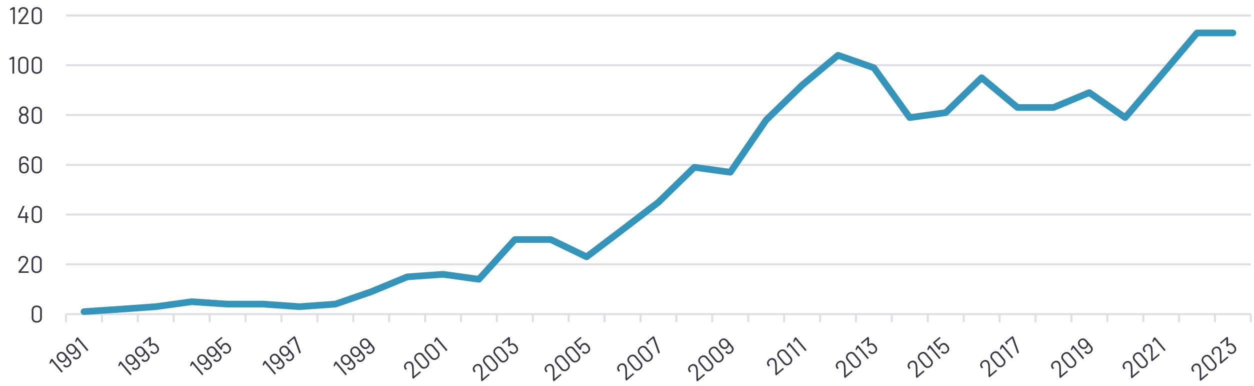

Figure 3. Annual scientific production.

TOP SOURCES OF CCUS PUBLICATIONS

The top sources represent mainly energy- and environmental economics-related journals. The only journal that differentiates itself is Technological Forecasting and Social Change, due to its technological and societal perspective, while the remaining journals focus on energy and environmental economics, with Energy Policy uppermost within CCUS-related research.

Sources	Articles
Energy Policy	448
Ecological Economics	159
Energy Economics	149
Forest Policy and Economics	148
Environmental and Resource Economics	48
Journal of Forest Economics	47
Technological Forecasting and Social Change	45
Resource and Energy Economics	43
Journal of Environmental Economics	33
Energy Journal	30

Table 4. Leading sources within CCUS-related research.

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Examining the growth profiles of the sources, Energy Policy has been distancing itself from the rest of the journals at an increasing pace since 2008. Ecological Economics, Energy Economics, and Forest Policy and Economics, while showing upward trends, are some distance behind as illustrated in Figure 4.

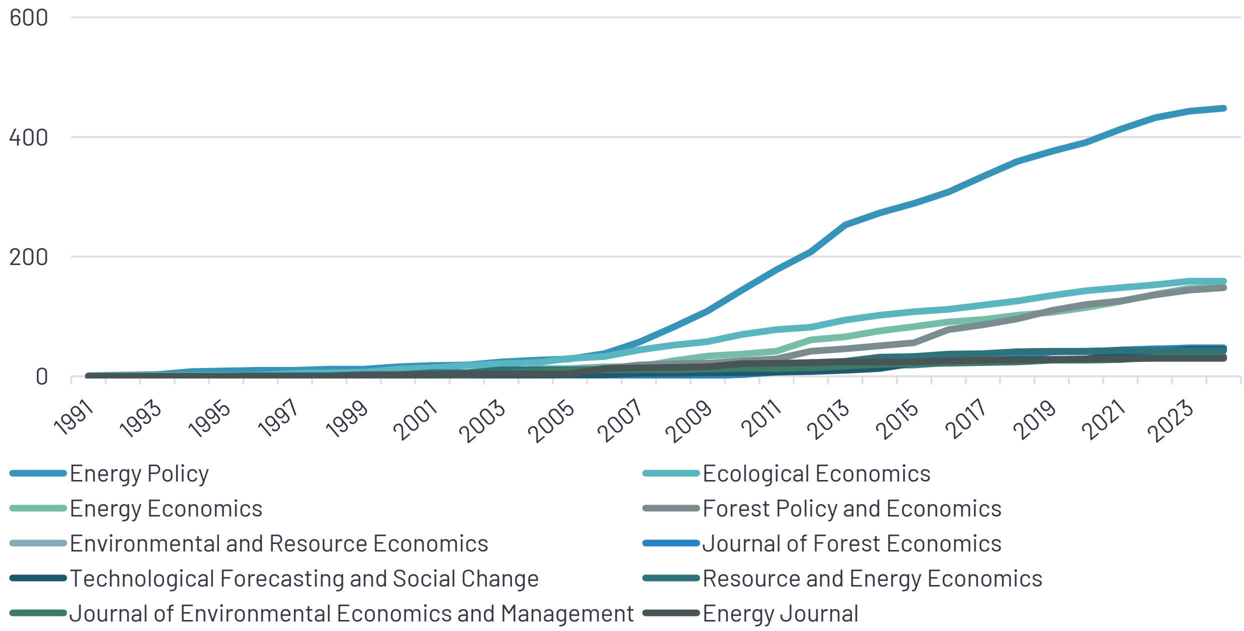

Figure 4. Source growth.

COUNTRIES' PRODUCTION OF CCUS RESEARCH OVER TIME

Production by country has been led by the USA since 2000. The United Kingdom held the second spot until 2021, but were then replaced by China, as seen in Figure 5. Germany, France, the Netherlands, and Australia complete the top seven. Denmark, on the other hand, has seen limited development, only taking up the 20th place.

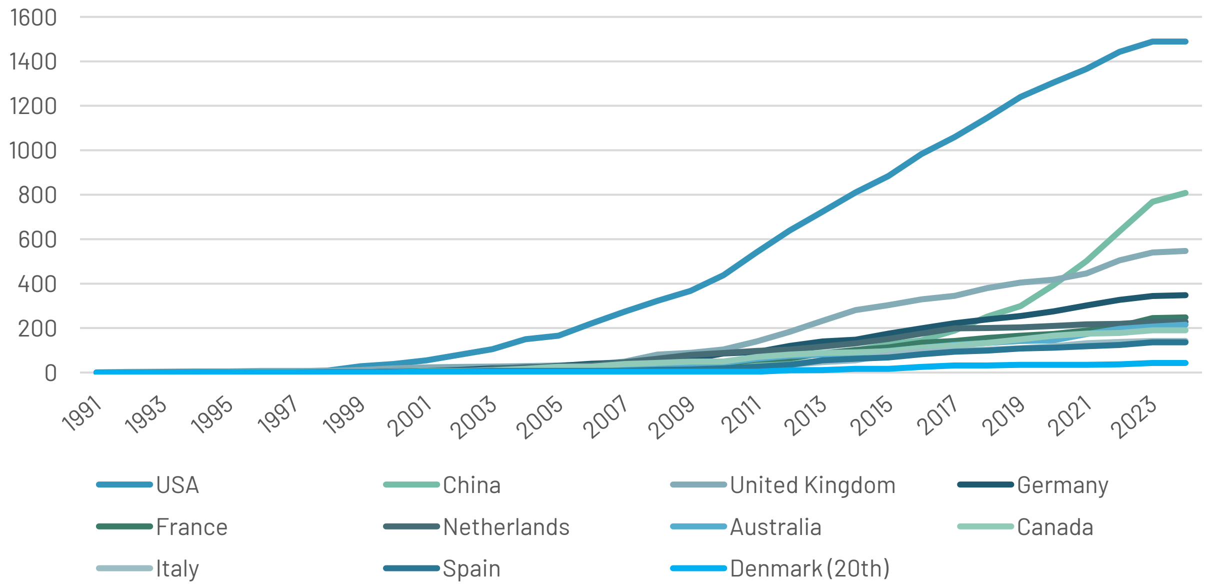

Figure 5. Top ten countries' production over time.

AFFILIATIONS LEADING IN TERMS OF CCUS PUBLICATIONS

At the affiliation level, we observe that the top ten universities leading on research into CCUS are located in four countries, i.e., USA (5 universities), UK (2), Netherlands (2), and China (1). The sole Chinese university, Tsinghua University, is, however, most prolific (with 49 publications), closely followed by Oregon State University.

Affiliation	Country	Articles
Tsinghua University	China	49
Oregon State University	USA	48
University of Edinburgh	UK	40
Stanford University	USA	37
Ohio State University	USA	36
Vrije University Amsterdam	Netherlands	34
Carnegie Mellon University	USA	33
Utrecht University	Netherlands	33
University of Maryland	USA	32
University of Cambridge	UK	31

Table 5. Affiliations leading in terms of CCUS publications.

Examining the production growth profiles of the affiliations in Figure 6, Oregon State University had been leading since 2016. However, Tsinghua University has shown a steep increase in the past five years, and currently predominates in terms of relevant publication numbers, a place previously held by Oregon State University until 2022.

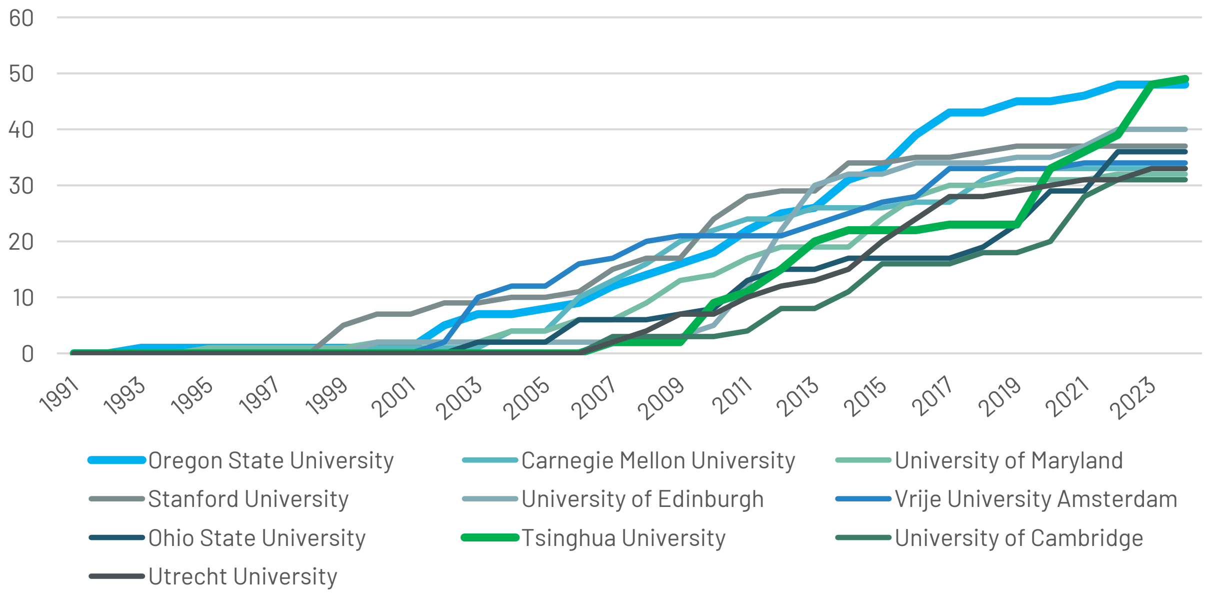

Figure 6. Affiliations' production over time.

CONCEPTUAL STRUCTURE OF CCUS RESEARCH

Transitioning from analysis of document metadata, which provided insight into the evolution of publications, their sources, and the geographical and institutional distribution of CCUS research, we now shift the focus to the intellectual core of the field. This section delves into the conceptual structure of CCUS research, using author's keywords as the primary unit of analysis in order to grasp the content of the papers. By examining these keywords, we uncover the thematic underpinnings and topical trends that characterize the current state-of-the-art within CCUS.

MOST FREQUENT WORDS

Identifying the most frequently occurring author's keywords offers insights into prevailing research topics and focus areas within the CCUS domain. This is illustrated through two distinct visual representations, Table 6 and Figure 7 (a treemap chart). These visualizations serve as foundational elements in understanding the conceptual structure of CCUS research, facilitating a deeper exploration of the field's current state and evolving trends.

The table lists the top ten author's keywords, ranked in descending order, based on their number of occurrences. This concise format provides a straightforward overview of the primary topics that dominate current academic discussions, such as climate change, carbon sequestration, carbon capture and storage (CCS), and climate policy.

Author keywords	Occurrences	Percentage
climate change	181	11%
carbon sequestration	160	10%
carbon capture and storage (CCS)	133	8%
climate policy	77	5%
carbon	64	4%
ecosystem services	46	3%
China	42	3%
energy	42	3%
uncertainty	40	2%
carbon abatement	35	2%

Table 6. Most relevant author's keywords.

Complementing Table 6, a treemap chart displaying the top fifty author's keywords offers a more comprehensive and nuanced perspective. In this chart, each keyword is represented as a proportionally sized rectangle, with larger sizes indicating a higher frequency of occurrence—the relative proportions are also displayed as percentage values. Thus, Figure 7 provides a hierarchical visualization of research topics, including not only the main focus areas but also emerging themes and less dominant topics within the CCUS research landscape.

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Figure 7. Treemap with the top 50 author's keywords.

Observing the occurrence numbers and percentages of the author's keywords, the focus falls on how to capture and store carbon, as well as its component, i.e., carbon sequestration (Figure 7). *Climate change* and *carbon sequestration* are the top two keywords, showing a steady increase every year, while *CCS* has been growing in parallel in third spot (Figure 8). *Climate policy* still represents a topic of interest in the CC(U)S context, as the governmental and institutional factors continue to be developed. *Carbon*, *ecosystem services*, *China*, *energy*, *uncertainty*, and *carbon abatement* complete the top ten keywords. *Ecosystem services* show the link between ecological ecosystems and environmental economics in the context of CCUS. *China* represents an empirical context which is gaining increasing research attention. The inclusion of *uncertainty* as a top author's keyword is worth noting and reasonable, indicating that CCUS, as an emerging industry, involves many uncertainties and risks related to financing, emerging underdeveloped technologies, and future climate change mitigation strategies and policies.

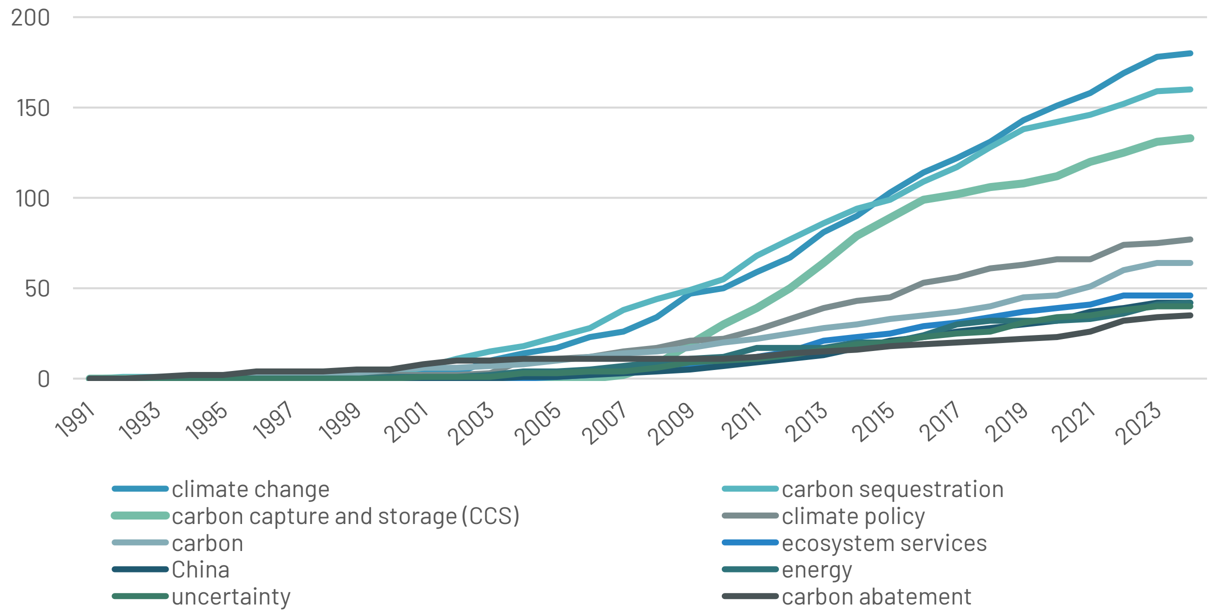

Figure 8. Cumulative dynamics of top ten author's keywords.

The main research focus remains on carbon capture and storage, while carbon utilization or the overall CCUS attracts less attention (i.e., the 87th spot). Although *carbon sequestration* was at the forefront of academic research until 2015, *climate change* has now taken the top spot.

CO-OCCURRENCE NETWORK

The co-word network analysis serves as a vital tool for mapping and visualizing the interconnectedness of CCUS and other relevant concepts within the dataset. By using author's keywords as the method parameter, we create the semantic map that delineates the landscape of the CCUS field. This map is not merely an array of isolated terms, but rather a dynamic network where the size and connections between nodes (keywords) revel the depth of their relationship and thematic relevance.

Figure 9 offers a visualization of the CCUS field, delineating two main clusters along with four minor ones. The dominant blue cluster emphasizes the synergy between *climate change* and *carbon sequestration*, underscoring the robust co-occurrence and thematic overlap between these two concepts. *Climate change* represents the most substantial network node, signifying its central role in the discourse. Notably, this node is more strongly associated with *carbon sequestration* than with *CCS*. However, weaker links can be observed with the minor clusters, such as ecology (green cluster) and afforestation (light green cluster), as well as mitigation (purple cluster) and uncertainty (light blue cluster). These relationships indicate a strong environmental and ecological dimension within the CCUS discourse, as well as the field's engagement with broader strategies for addressing climate change and the inherent uncertainties in predicting and managing its impact.

Conversely, the red cluster encapsulates the *CCS* domain, which appears underdeveloped and dispersed compared to the blue cluster. This section of the network includes a wide variety of keywords with diverse foci, such as *decarbonization*, *innovation*, *technology*, *climate policy*, and *(renewable) energy*, indicating a multifaceted but less cohesive area of research. The dispersion and variety within this cluster suggests that the CC(U)S field is still evolving, with a primary focus on *CCS* and multiple sub-themes that have yet to coalesce into a unified strand of academic inquiry.

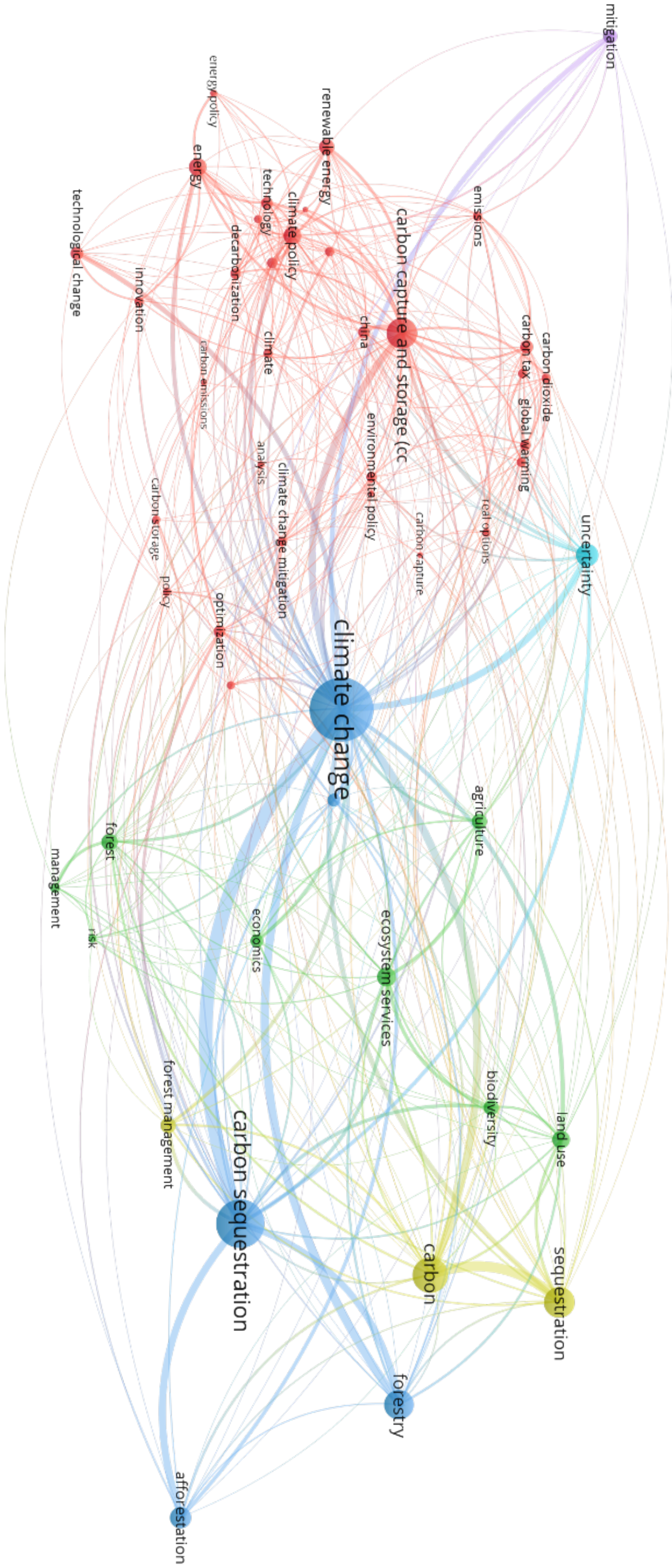

Figure 9. Keyword co-occurrence network.

THEMATIC MAPPING

This section utilizes co-word network analysis to explore the conceptual structure of CCUS research, by mapping and categorizing themes based on their development degree (density) and relevance degree (centrality). The development degree on the vertical axis refers to the internal strengths of a theme (its cohesiveness), indicating how well-developed and coherent the research within a particular cluster is. In contrast, the relevance degree on the horizontal axis represents the centrality of a theme within the network, reflecting its importance and influence on the field as a whole.

In this analysis, we set a minimum threshold of including author's keywords that appear in the cluster at least five times per thousand documents. This condition ensures that only the most significant themes are mapped. In Figure 10, under the basic quadrant which represents well-established and influential themes, *climate change*, *carbon sequestration* and *energy* emerge. The largest theme, *climate change*, serves as a nexus connecting diverse but related concepts such as *CCS* and *climate policy*, *uncertainty*, *(renewable) energy efficiency*, *emissions*, and *carbon pricing*. The theme of *carbon sequestration* is predominantly associated with *carbon* and *ecosystem services*, signifying a strong link to environmental conservation efforts. This illustrates that carbon sequestration is perceived more as an integral part of broader ecological and sustainability discussions, rather than being perceived as a technical solution.

Energy, as another significant theme, bridges the gap between *carbon abatement* strategies and practical implementation, linking *innovation*, *decarbonization*, and *technology* with the operational aspects of electricity generation. This highlights the critical role of technological advancement and innovation in furthering the CCUS agenda.

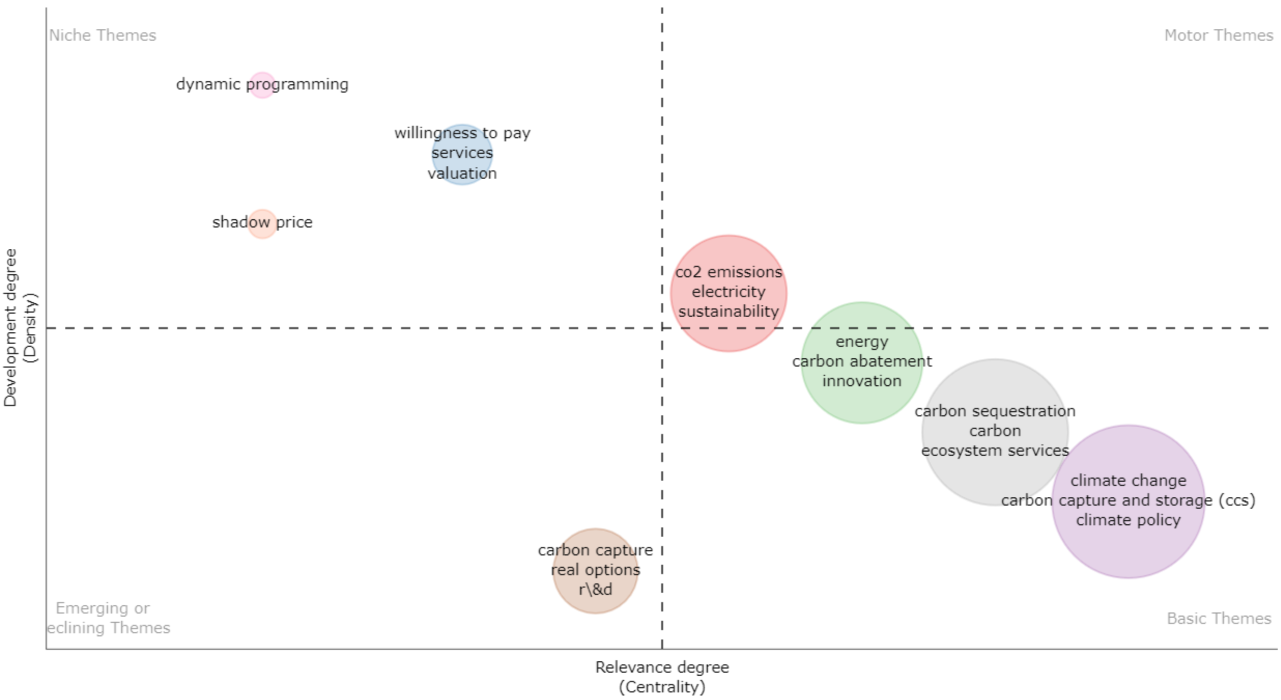

Figure 10. Thematic map.

Specifically focusing on *carbon capture*, this theme is intriguingly positioned under emerging or declining themes, which may be either new areas of research that have not yet established strong connections within the field, or older areas that are losing relevance. The positioning of *carbon capture* indicates its importance within the overall CCUS research landscape in terms of recognized potential and impact. The low development degree of the *carbon capture* theme suggests that the research in this area requires further development to create a coherent body of research or a high degree of internal consistency among studies. Moreover, *carbon capture* is closely tied to *research and development (R&D)* within the CCUS sphere, emphasizing the need for ongoing innovation and investigation to enhance the efficiency and viability of carbon capture technologies in order to ensure the delivery of *real options*.

Turning our attention to niche or less-explored themes, which are more weakly connected with the rest of the research landscape, *willingness to pay*, *shadow price*, and *dynamic programming* (a computational method of analysis) emerge. *Shadow price* refers to an implicit or non-market price for assessing the cost-effectiveness, economic value, and feasibility of CO_2 emission reduction strategies, technologies, and policies. The capital and human cost of climate change emerges. *Willingness to pay*, on the other hand, represents the monetary value that individuals, communities, or societies are prepared to pay for environmental services, carbon abatement, and other ecosystem benefits. This economic measure is crucial for understanding the extent of social value towards environmental improvements, carbon reduction, and conservation activities, including social acceptance of CCUS deployment.

SUMMARY OF KEY FINDINGS

CCUS PUBLICATION RELEVANCY

Annual CCUS-related scientific production has grown steadily in the past decade with an annual percentage growth rate of 9.66%. The first peak was noted in 2012 and it has gained momentum ever since. The past couple of years have shown a slightly higher surge, which is roughly maintained. These findings indicate a couple of positive insights: firstly, the rising publication outputs suggest that there is a growing interest, but also relevant recognition of CCUS-related studies within the scientific community—this relevancy could be attributed to both social and ecological concerns, but may also be due to recent CCUS-related technological breakthroughs; and secondly, such scientific production growth often mirrors an increase in interest by the public sector, and thus possibly reflects an increase in public funding support. This, in turn, accelerates research interest momentum.

Yet, despite these findings, we should also note that while publication output increases steadily, there is no guarantee of publications' quality over quantity, nor of content richness and progress. Thus, it is crucial to analyze the rigor and impact attributes of these publications in much greater depth.

AFFILIATIONS DRIVING CCUS RESEARCH

The publication by countries is of relevant interest as it provides insights into the distribution of CCUS-related publications, and also into the global efforts and priorities when addressing climate change-related challenges. It can also aid in:

1. Identifying key research leaders and promoting global cooperation, which allows relevant stakeholders to pinpoint key players to collaborate with, and to extract valuable expertise and resources.
2. Tracking CCUS publication output can also possibly help in trailing business-related progress by different countries/companies.
3. Reflecting policy priorities and R&D investments, including funding allocations and CCUS deployment strategies.
4. Potentially capitalizing on CCUS emerging market opportunities, as countries that are leading in CCUS research may also attract the interest of businesses and investors.

The analysis indicates that the USA is currently leading CCUS research with five universities in the top ten. In second place, China has shown a rapid interest growth since 2020, with Tsinghua University leading the list of global publications.

MAIN TOPICS OF CCUS RESEARCH AND FUTURE DIRECTIONS

The findings show that the main keywords include the following: climate change, carbon sequestration, carbon capture and storage (CCS), climate policy, carbon, ecosystem services, China, energy, uncertainty, and carbon abatement. These leading keywords suggest that *climate change* remains as the dominant focus of academic research which is still more concerned with climate policy and carbon sequestration rather than CC(U)S. This confirms that CCUS is an underdeveloped field which requires further investigation. However, it also indicates the urgency of addressing climate change and the need for designing appropriate policy interventions to promote sustainability within this field. While CCUS may encompass carbon sequestration, the latter has a narrower attention on ecological ecosystems and afforestation. On the other hand, carbon capture studies focus more on R&D of the technology, showing that the field is still immature and under development to understand the first steps of <u>CC</u>US.

CCS has also attracted research attention with particular emphasis on decarbonization, carbon technology, renewable energy, and climate policy. However, it is important to note that the keyword *carbon utilization* does not appear as a standalone author's keyword. This does not necessarily entail that there is a lack of research interest in this field, but rather that is currently underdeveloped. With that understanding, we should note that more research is needed in all aspects of CC<u>U</u>S areas, and *carbon utilization* in particular, as business leaders and investors need to envision a return on their investments before commitment. Thus, more carbon utilization-related research is needed, to facilitate clarification of the conversion process of CO_2 into viable offerings and/or materials such as chemicals and fuels.

Another finding to be mentioned is China as a prominent empirical context for researching CCUS. This highlights China's interest in understanding (and advancing) this field, particularly through Tsinghua University, the top university performer in CCUS-related research. The emphasis on China as an empirical context is also justifiable considering its status as a major emitter and its addressing moves towards carbon neutrality, which provides a rich context for studying CCUS at scale. However, expanding empirical contexts beyond China and integrating more diverse geographical and economic perspectives can enrich the global understanding and applicability of CCUS technologies.

Despite the predominant focus on climate change, policy, and the empirical context of China, seven review articles were also included in the dataset. These reviews focus on various crucial aspects such as the development of carbon technology, the impact and structure of carbon taxes, the broad effects of climate change, the intricacies of policy design for carbon emissions and sequestration, the dynamics of climate finances, and forecasting developments in the hydrogen economy. Although these reviews are relatively diverse in topics, this report represents a timely endeavor to synthesize the latest research and development in the field of CCUS. While the interplay between the technological advancements, policy formations, and business implementation in the realm of CCUS is critical, this link highlights a significant gap. Thus, comprehensive policy analyses can ensure the alignment of incentives and regulations, while business studies can explore viable economic models for CCUS deployment and implementation.

CONCLUSION

In summary, CCUS is a field under development, and it is not surprising that the policies and climate impact awareness are being introduced first, as they indicate relevancy. Academic researchers have been focusing on investigation of policies and R&D processes in regard to CCUS, rather than on its economics side; this is despite the nature of the publication sources, which primarily focus on energy and environmental economics. Moreover, emphasis on CCS tells only part of the story, and the conversion of captured CO_2 into "X" can pave the way for business leaders and investors to join, invest, and introduce new business models and related offerings. Clearly, there is still a long way to go, both in studying CC<u>U</u>S as a system and through the operationalization of the *utilization* term into practical feasibility. This calls for more exploration and clarification of all the components of CCUS and its business aspects, rather than understanding it solely as a cost with institutional or policy impacts. Thus, we are marching into the unknown, with a lot of uncertainties, risks, and policy/research discrepancies, but as this field of study is following a steady growth curve of interest by scholars, policy designers, and practitioners alike, it seems that it is here to stay.

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