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Article

Current Milestone and Emerging Trend of Carbon Capture and Storage (CCS) Technology: Bibliometric Analysis and Review of Risk-Hazard, Economic, and Numerical Assessments

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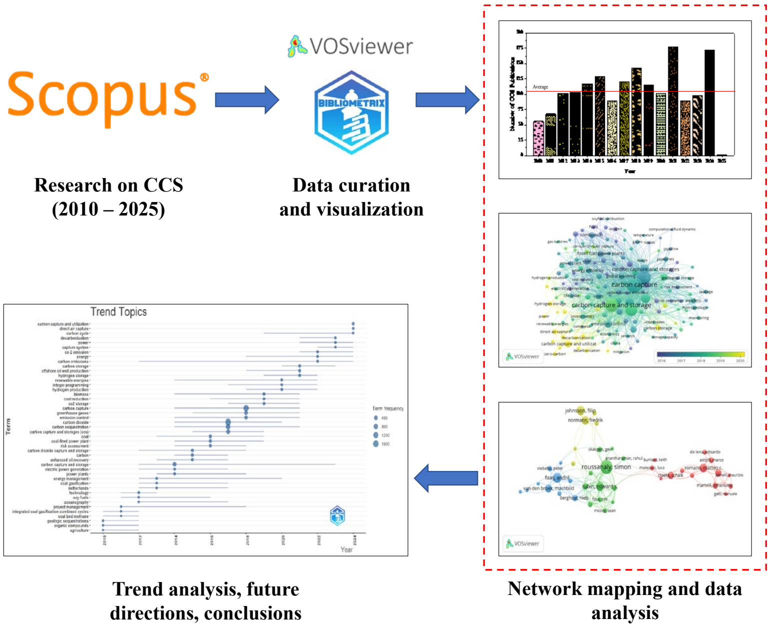
Abstract: Background: Carbon Capture and Storage (CCS) is emerging as a potential solution to reduce CO_2 emissions. This technology captures CO_2 for reuse or stores it safely underground, preventing pollution of the atmosphere. CCS is the best technology to control climate change and global warming. **Purpose**: This review aims to map the achievements that have been made and future research trends. **Methods**: This bibliometric review analyzes CCS-related research from 2010 to 2024 using the Scopus database. VOSviewer and Bibliometrix software are used for data processing and visualization. **Findings**: Significant advances have been made in CCS technology research. The growth of the number of publications, collaboration networks, the most influential contributors, and research trends has been mapped, which can be used as a reference for future research. **Conclusions**: The methodology used can still be refined to eliminate the potential bias in data interpretation. However, certain conclusions can be drawn from this bibliometric analysis. The research trend began to shift toward efforts to utilize CO_2 in useful products, improve safety, and reduce implementation costs. **Originality**: This bibliometric review provides an in-depth examination of the scientific literature on CCS, with a particular emphasis on risk assessment, economic perspectives, and numerical modeling. In contrast to previous bibliometric research, it stands out by integrating these three central themes while also highlighting the limitations and gaps in existing knowledge.

Keywords: carbon capture and storage; CCS risk-hazard assessment; CCS economic approaches; CCS numerical assessment; Bibliometric Analysis

Graphical Abstract



Highlights

- The release of CO_2 contributes to global warming, and carbon capture and storage (CCS) has been proposed as a promising way to help mitigate its effects.
- Research related to CCS has grown rapidly over the past fifteen years, particularly in the areas of risk–hazard, economics, and numerical assessment methods
- The collaborative CCS research network has expanded, with institutions from China, the USA, and the UK becoming the main contributors.
- Further research will focus on reducing costs, improving storage safety, and developing policies that support the implementation of CCS.

1. Introduction

Global warming, caused by high levels of greenhouse gases (GHGs) in the atmosphere, is a severe environmental problem. Increasing the average temperature of the Earth's surface can trigger climate change, melt polar ice, and raise sea levels to the point of damaging ecosystems and the environment (Bui *et al.*, 2018; Raza *et al.*, 2019). The world community has agreed to address this problem together. Several agreements, ranging from the Kyoto Protocol (1997) to the Paris Agreement (2015), have led to the development of various policies. One of the agreements currently being realized is the Net Zero Emissions (NZE) concept, which must be achieved by 2050 at the latest. This concept means that the amount of GHG emissions released must equal the amount absorbed or removed from the atmosphere in a given period. In other words, there is no increase in atmospheric emissions (International Energy Agency, 2016; Johnsson, Kjärstad and Rootzén, 2019).

Among the GHGs identified as triggering global warming, carbon dioxide (CO_2) is the most significant contributor (Fajri *et al.*, 2024; Perdana *et al.*, 2025). The current concentration of CO_2 in the atmosphere has reached 429 parts per million (ppm), or 0.0429% (Figure 1a). This number is well above the recommended safe threshold, below 350 ppm (0.035%) (Wennersten *et al.*, 2015). CO_2 emissions can be sourced from various sectors (Figure 1b). The most significant contributor is power generation, which still largely relies on burning fossil fuels such as coal, oil, and natural gas. The use of clean energy sources, such as hydro, nuclear, wind, and solar, for electricity and heat generation remains insufficient, further exacerbating emissions from this sector (Figure 2).

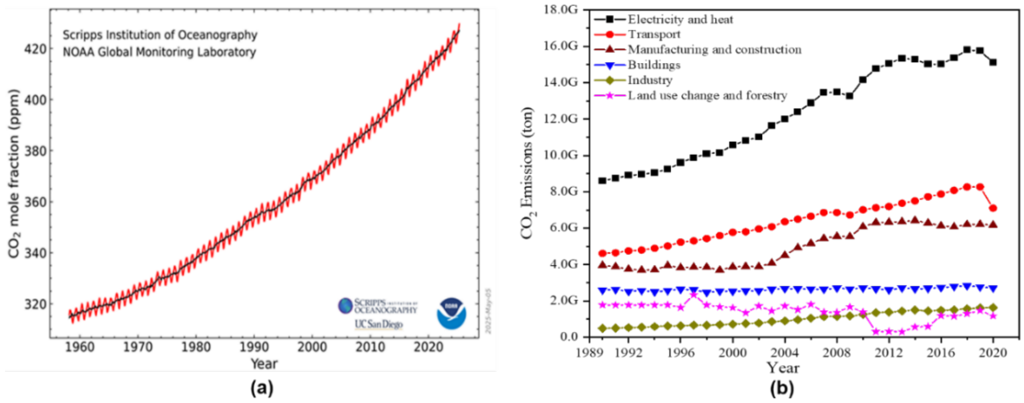


Figure 1. Statistics of (**a**) Atmospheric CO_2 monitoring result at Mauna Loa Observatory (Lan *et al.*, 2025) and (**b**) World CO_2 emissions by sector (Climate Watch, 2023).

The transportation sector is the second-largest contributor to carbon emissions. Vehicles that still rely on internal combustion engines continue to emit CO_2 as a result of the fuel-burning process during their engine cycles. This phenomenon occurs because fossil fuels, such as gasoline and diesel, release carbon dioxide when they are combusted to generate power. To illustrate, each combustion of one liter of diesel from an Internal Combustion Engine (ICE) can produce about 2.65 kg of CO_2 (Sharma and Maréchal, 2019). This emission figure is significant, given that transportation's dependence on ICE engines is still high. Even fuel cells that are considered clean still have the potential to produce CO_2 gas sourced from the process of reforming methanol into Hydrogen (Kappis *et al.*, 2021). The use of renewable energy in the transportation sector, such as solar energy, also still faces various technical challenges that have yet to be resolved (Kaneria and Reddy, 2025).

The construction and building sector also play a substantial role in contributing to global CO_2 emissions. These emissions stem not only from the operational phase of buildings over their life-cycle but also from the energy-intensive production of construction materials, particularly cement and steel (Al-Habaibeh *et al.*, 2025; Suman *et al.*, 2025). Cement production alone accounts for approximately 7–8% of global CO_2 emissions, mainly due to the calcination process and the combustion of fossil fuels. Additionally, the industrial sector that supports construction activities further amplifies emissions through high energy demand and carbon-intensive manufacturing processes (Barcelo *et al.*, 2014).

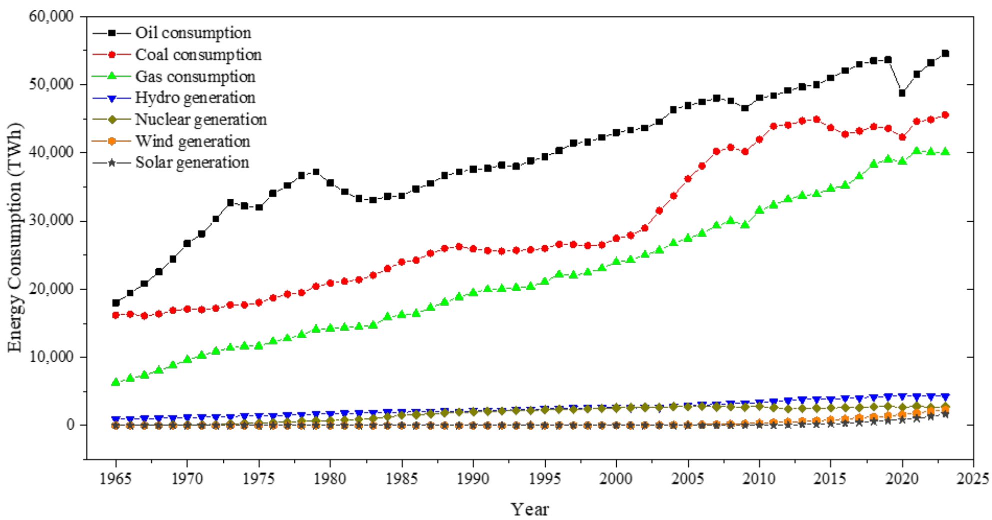


Figure 2. The world's primary direct energy consumption by source (The Energy Institute, 2024).

To achieve the NZE target, the International Energy Agency (IEA) estimates that the world needs to capture and store about 7-8 Gigatons of CO_2 per year. This amount equals 20% of total annual CO_2 emissions (International Energy Agency, 2021). Efforts such as forest conservation, transitioning to renewable energy sources, improving energy efficiency, implementing carbon tax schemes, and enforcing strict environmental regulations have been undertaken, but they still face significant obstacles.

The differences in economic interests and capabilities between countries lead to uneven implementation of emission-reduction policies. Transitioning to renewable energy sources requires considerable investment costs and still faces challenges related to efficiency and limited production capacity (Kutlu *et al.*, 2025; Ladokun, 2024; Rosli *et al.*, 2025). More sensible climate change mitigation solutions are needed to realize the NZE scenario. Carbon capture and storage (CCS) is the best solution in this situation. This technology will capture existing CO_2 emissions, which can be reused directly, processed into other products, or stored in a safe geological formation to prevent atmospheric pollution (Figure 3). CCS technology also enables the sustainability of sectors that rely on fossil fuels while transitioning to cleaner energy (Hammond *et al.*, 2011; Sakaguchi, 2010).

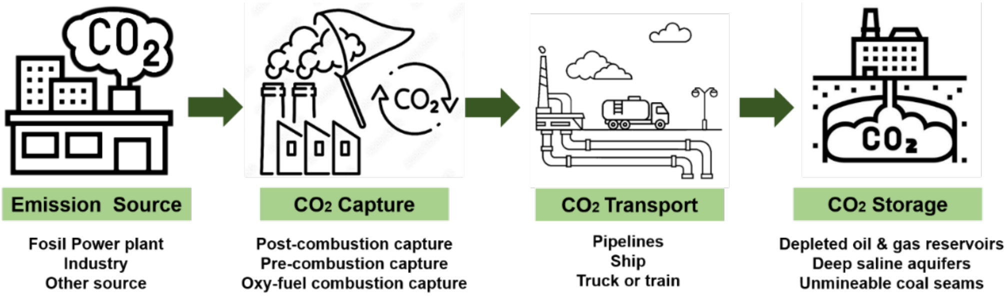


Figure 3. Carbon capture and storage technology.

Various policies and regulations have been issued to support the widespread implementation of CCS. For example, in the marine transportation sector, the Marine Environment Protection Committee (MEPC) under the International Maritime Organization (IMO) has approved various guidelines and regulations, such as the Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII). Another critical step is establishing a global carbon pricing mechanism for the shipping industry, effective in 2027. This mechanism requires vessels with a gross weight exceeding 5000 tons that exceed the emission threshold to pay an additional fee. In addition, more efficient and low-emission vessels can obtain tradable carbon credits (Bayraktar and Yuksel, 2023). This carbon-pricing mechanism drives the adoption of CCS in maritime-sector emission mitigation strategies.

However, adopting a new technology requires a relatively long research process. Despite its great potential, implementing CCS faces significant technical and non-technical challenges. From a technical perspective, the challenges include achieving efficiency in capturing, storing, and safely and sustainably reusing CO_2. Meanwhile, non-technical problems include the enormous investment costs and public acceptance of the risk of CCS hazards that may be caused (Rubin *et al.*, 2015). The data indicate that the estimated cost of capturing CO_2 from emission sources currently ranges from USD 50 to USD 100 per ton of CO_2. The price can be higher if Direct Air Capture (DAC) technology is used (Gutsch and Leker, 2024). Thus, meeting the NZE target would cost around USD 350–USD 700 billion annually. This fee is exclusive of transportation and storage costs and covers only the capture process.

Every year, thousands of studies are conducted to address issues related to CCS development. These studies need to be mapped using specific approaches to understand patterns and gaps that have not been addressed. A bibliometric review is one approach that can be used. This approach involves analyzing metadata from scientific publications, helping map research trends, identifying key contributors, and highlighting the field's evolution over time. A bibliometric review can show technological advancements, dominant research themes, and future research directions. These insights are essential for guiding research agendas, making policy, and identifying gaps in the literature (Casaban and Tsalaporta, 2023; Osman *et al.*, 2021).

This bibliometric study aims to provide a comprehensive review of research developments in CCS technology, with a particular focus on risk evaluation, economic perspectives, and numerical analysis. Drawing on publications indexed in the Scopus database over the past fifteen years, it investigates how the field has progressed, identifies the dominant themes shaping the discourse, and maps out the collaborative networks linking scholars, institutions, and nations. Scopus was chosen as the primary source due to its broad, reliable coverage of peer-reviewed scientific literature, ensuring access to high-quality literature relevant to this topic.

Compared to previous studies (Table 1), this study is novel in that it provides a more comprehensive mapping of scientific publications related to CCS within the context of risk assessment, economic approaches, and numerical evaluation. Previous bibliometric studies have covered CCS in general. However, no specific review has examined these three main areas of research activity, their limitations, or the associated knowledge gaps. The study not only focuses on the growth in the number of publications but also analyzes the geographical distribution of research by country, journal sources, active authors, and inter-institutional cooperation. This study will provide a more in-depth guide to understanding research trends, challenges faced, and future research directions.

Table 1. Previous bibliometric analysis related to carbon capture and storage.

No	Year	Reference	Database	Presented topic	Finding	Limitation
1	2018	(Viebahn and Chappin, 2018)	Scopus	Bibliographic coupling analysis of CCS deployment expectations vs. actual deployment	Found mismatch due to non-technical barriers (public perception, policy, economics); 69% technical focus vs. 31% non-technical research	Focus on peer-reviewed articles; excludes unpublished data from industry and government.
2	2019	(Li, Hou, *et al.*, 2019)	Web of Science (SCI-E, SSCI)	Bibliometric review on CCS project planning, investment, and operational decision-making	Identified cost analysis, investment evaluation, planning (cost curves, pipeline networks), and operation as key topics. Fossil fuel plants, pipelines, and oil fields are crucial links.	Need for updated cost data, expanded pipeline planning, and low-cost high-return project assessment; lacks operational mode studies for low-load systems.
3	2019	(Li, Jiang, *et al.*, 2019)	Web of Science (Core collection)	Bibliometric review of environmental, economic, and social aspects of CCS and modeling methods	Identified five hot topics: climate change mitigation, technology prospects, cost estimation, sectoral applications, and social attitudes. Primary methods: LCA, optimization, real options	Does not deeply analyze integration between topics; limited to 1997-2017 publications.
4	2024	(Apriantoro *et al.*, 2024)	Scopus	Bibliometric analysis of CCS research trajectory from 1998 to 2024	Observed growth linked to climate agreements and tech advances. Identified maturity or revitalization in 2024; need for integration with renewables and policy/ economic considerations	Potential bias from a single database; excludes non-indexed literature
5	2024	(Wang *et al.*, 2024)	Web of Science (Core Collection)	Bibliometric study of CO_2 geological storage research trends	Publication surge post-2009. Major contributors include the United States, China, and the United Kingdom. Key themes: physical/chemical dynamics, environmental/safety	Focus on English-language WOS publications; may omit relevant regional studies

No	Year	Reference	Database	Presented topic	Finding	Limitation
					assessments, site evaluation	

2. Methodology

This research was conducted according to the procedure outlined in Figure 4. Bibliometric analysis was employed to construct a comprehensive representation of publications related to CCS technology over the last 15-year period, from 2010 to 2024. This study used a literature search conducted on September 10, 2024, in the Scopus database. Scopus was selected because it is the most extensive database, offering broad disciplinary coverage with over 28,000 active titles. Scopus has a strict indexing system, ensuring that the articles it lists are of high quality. The data available in Scopus is quite detailed, enabling deeper analysis. The use of a single database, such as Scopus, also aims to maintain the consistency and accuracy of the data used in this analysis. Although WOS and other databases can enrich analysis results, they share significant overlap in the journals and articles they index, making Scopus already quite representative. To minimize potential database bias, the top 50 cited documents were cross-checked in Web of Science to ensure that no critical publications were omitted.

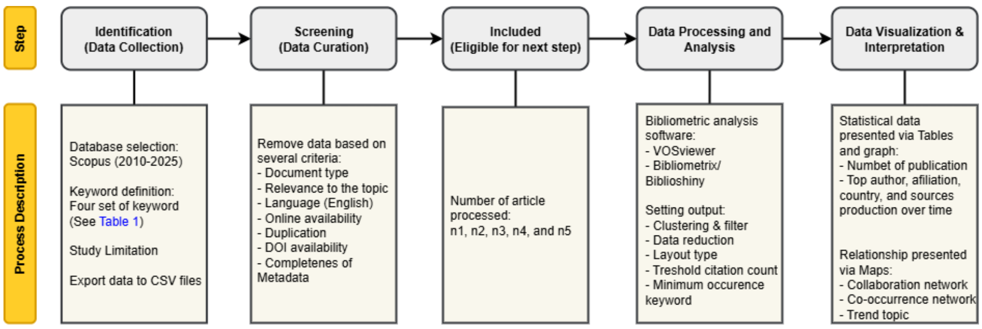


Figure 4. Research Procedure.

The paper publication periods from 2010 to 2024 were chosen to capture both historical developments and the latest innovations in CCS. In the early 2010s, awareness of the importance of climate solutions was growing, and CCS began to gain attention as a crucial technology. Since then, the volume of research has increased significantly, reflecting advances in technological innovation and the development of policy frameworks. Through bibliometric analysis, the review will map the most influential contributions in CCS, highlight research trends, and identify emerging areas of innovation. This analysis used the VOSviewer (Van Eck *et al.*, 2010; van Eck and Waltman, 2010) and Bibliometrix (Perianes-Rodriguez *et al.*, 2016) software to visualize collaboration networks and thematic clusters in the research.

Meanwhile, statistical analysis provides additional insights into publication trends, citation impact, and institutional collaboration. The search strategy uses four keywords: general CCS, risk assessment, economic analysis, and numerical investigation in CCS technology. The search strategy or query set is presented in detail in Table 2. As illustrated in Figure 4, the raw metadata were exported in CSV format and subsequently processed using Bibliometrix and VOSviewer (v1.6.20). Incomplete metadata fields, such as document type, publication year, total citations, abstract, authors, affiliation, keywords, digital object identifier (DOI), and corresponding author, were addressed through a two-step procedure. First, the records were manually cross-verified against the corresponding journal websites. Second, any records with more than 20% missing fields were excluded from the dataset. In VOSviewer, the minimum keyword occurrence threshold was set to 4, and the co-occurrence mapping utilized the fractional counting method with a LinLog/modularity layout. In Bibliometrix, analysis included annual scientific production, country collaboration networks, and thematic evolution mapping. The thematic map clustering was performed using a Callon centrality-density framework.

Table 2. Set keyword for search strategy.

Category	Query	Number of Documents (n)
General term	TITLE-ABS-KEY (carbon AND capture AND storage) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (EXACTKEYWORD , "Carbon Capture and Storage") OR LIMIT-TO (EXACTKEYWORD , "Carbon Capture and Storages (CCS)") OR LIMIT-TO (EXACTKEYWORD , "Carbon Capture and Storage (CCS)") OR LIMIT-TO (EXACTKEYWORD , "CCS") OR LIMIT-TO (EXACTKEYWORD , "Carbon Dioxide Capture And Storage")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p")) AND (LIMIT-TO (LANGUAGE , "English"))	1714
Risk Assessment	TITLE-ABS-KEY (carbon AND capture AND storage) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (EXACTKEYWORD , "Risk Assessment") OR LIMIT-TO (EXACTKEYWORD , "Accidental Release") OR LIMIT-TO (EXACTKEYWORD , "Accidental Releases") OR LIMIT-TO (EXACTKEYWORD , "Accidents") OR LIMIT-TO (EXACTKEYWORD , "Fracture") OR LIMIT-TO (EXACTKEYWORD , "Hazards") OR LIMIT-TO (EXACTKEYWORD , "Health Risks") OR LIMIT-TO (EXACTKEYWORD , "Leakage") OR LIMIT-TO (EXACTKEYWORD , "Leakage (fluid)") OR LIMIT-TO (EXACTKEYWORD , "Public Risks") OR LIMIT-TO (EXACTKEYWORD , "Risk") OR LIMIT-TO (EXACTKEYWORD , "Risk Analysis") OR LIMIT-TO (EXACTKEYWORD , "Risk Management") OR LIMIT-TO (EXACTKEYWORD , "Risk Perception") OR LIMIT-TO (EXACTKEYWORD , "Risks") OR LIMIT-TO (EXACTKEYWORD , "Risks Assessments") OR LIMIT-TO (EXACTKEYWORD , "Safety") OR LIMIT-TO (EXACTKEYWORD , "Safety Engineering")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p")) AND (LIMIT-TO (LANGUAGE , "English"))	424
Economic Approach	TITLE-ABS-KEY (carbon AND capture AND storage) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (EXACTKEYWORD , "Cost Analysis") OR LIMIT-TO (EXACTKEYWORD , "Cost Benefit Analysis") OR LIMIT-TO (EXACTKEYWORD , "Cost Effectiveness") OR LIMIT-TO (EXACTKEYWORD , "Cost Reduction") OR LIMIT-TO (EXACTKEYWORD , "Cost-benefit Analysis") OR LIMIT-TO (EXACTKEYWORD , "Costs") OR LIMIT-TO (EXACTKEYWORD , "Economic Analysis") OR LIMIT-TO (EXACTKEYWORD , "Economic And Social Effects") OR LIMIT-TO (EXACTKEYWORD , "Economics") OR LIMIT-TO (EXACTKEYWORD , "Profitability") OR LIMIT-TO (EXACTKEYWORD , "Techno-Economic Analysis")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p")) AND (LIMIT-TO (LANGUAGE , "English"))	1143
Numerical Assessment	TITLE-ABS-KEY (carbon AND capture AND storage) AND PUBYEAR > 2009 AND PUBYEAR < 2026 AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (EXACTKEYWORD , "Computational Fluid Dynamics") OR LIMIT-TO (EXACTKEYWORD , "Computer Simulation") OR LIMIT-TO (EXACTKEYWORD, "Numerical Methods") OR LIMIT-TO (EXACTKEYWORD , "Numerical Model") OR LIMIT-TO (EXACTKEYWORD , "Numerical Models") OR LIMIT-TO (EXACTKEYWORD , "Mathematical Modelling") OR LIMIT-TO (EXACTKEYWORD , "Equations Of State") OR LIMIT-TO (EXACTKEYWORD , "Computational Fluid Dynamics Modeling") OR LIMIT-TO (EXACTKEYWORD , "Computer Software") OR LIMIT-TO (EXACTKEYWORD , "Equation Of State") OR LIMIT-TO (EXACTKEYWORD , "Equation-of-state") OR LIMIT-TO (EXACTKEYWORD , "Numerical Investigations") OR LIMIT-TO (EXACTKEYWORD , "Numerical Simulation")) AND (LIMIT-TO (SRCTYPE , "j") OR LIMIT-TO (SRCTYPE , "p")) AND (LIMIT-TO (LANGUAGE , "English"))	444

3. Results and Discussion

3.1. Publication Trends

The search results were processed using Bibliometrix, and the results were presented as graphs and images. Figure 5 shows the trend in scientific publications on CCS. Each bar represents the number of publications per year, with a horizontal red line indicating the annual average for that period. Publication trends indicate fluctuating growth, but an overall increase from 2010 to 2024. In 2021 and 2024, the peak of publications was significantly above the annual average, suggesting a surge in research interest in CCS during those periods. Figure 5 illustrates the growing research interest in CCS technology, consistent with the increasing urgency of addressing global carbon emissions. Fluctuations in specific years suggest that external factors, such as policy or technological innovation, can influence the intensity of research on this topic.

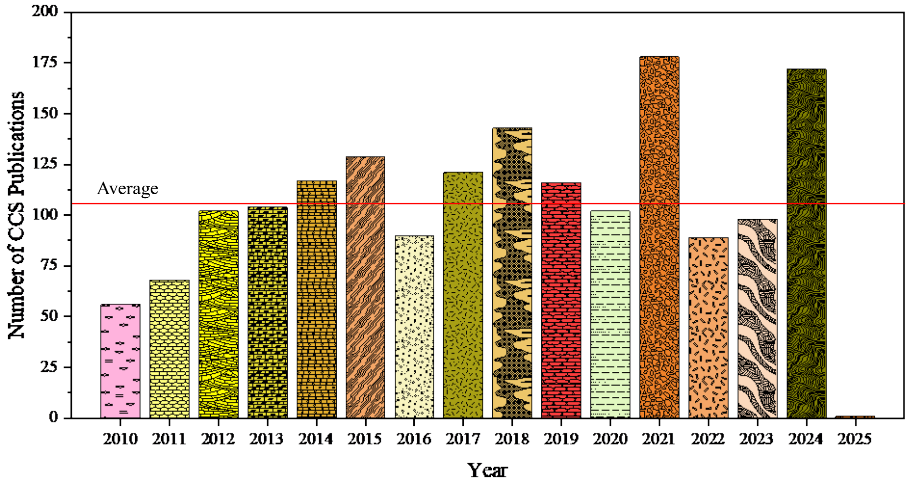


Figure 5. Number of Publications per Year from 2010 to September 2024.

The distribution of the most productive countries in the publication of scientific papers in the field of CCS is shown in Figure 6. The darker the colour, the higher the number of annual publications. Meanwhile, Figure 7 shows the top five countries in publications: China, the United Kingdom, the United States of America, Germany, and Norway. Overall, this graph reflects a global increase in CCS research, led by China and the United Kingdom, with a notable rise in publications expected to exceed 600 documents by 2025. Countries worldwide are also actively conducting joint research, as shown in Figure 8.

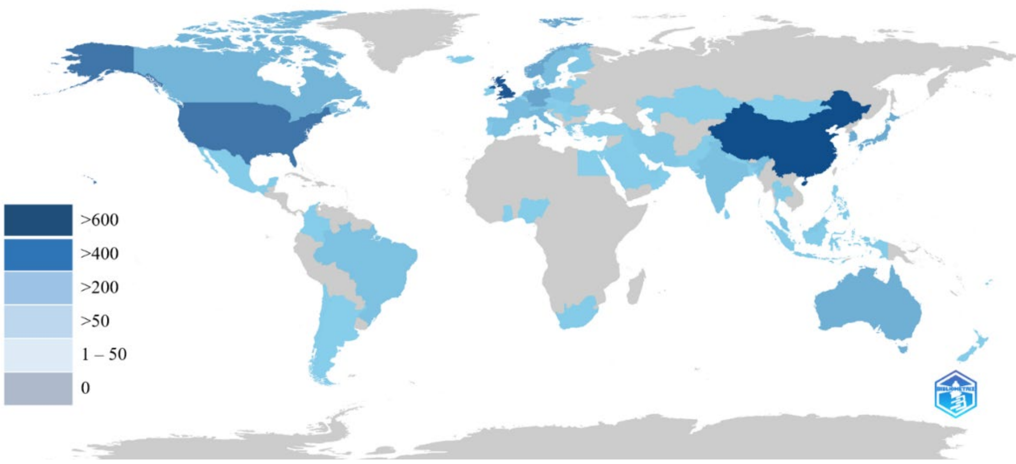


Figure 6. Map Distribution Country in Publication Number.

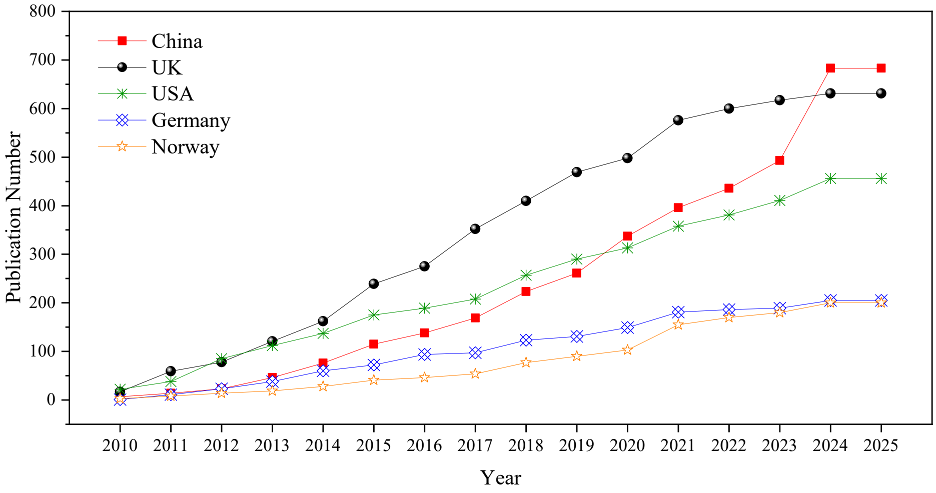


Figure 7. Top 5 Countries' Production in CCS Publication Over Time.

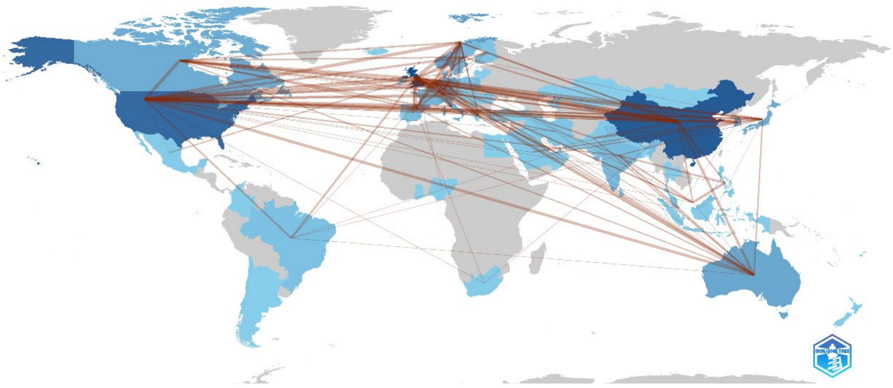


Figure 8. Map of the collaboration network between countries on CCS research.

Five leading research institutions have published scientific papers in the field of CCS, including Imperial College London, the University of Leeds, Chalmers University of Technology, the Chinese Academy of Sciences, and SINTEF Energy Research, as shown in Figure 9. Imperial College London topped the list, with a significant increase in publications, particularly since 2019, signaling its dominance in CCS research. In second place, the University of Leeds is also experiencing steady growth, though not as rapidly as Imperial College London. Meanwhile, Chalmers University of Technology, the Chinese Academy of Sciences, and SINTEF Energy Research also exhibit a positive trend, with their annual growth remaining relatively stable. This graph confirms that European institutions play a crucial role in developing CCS research globally.

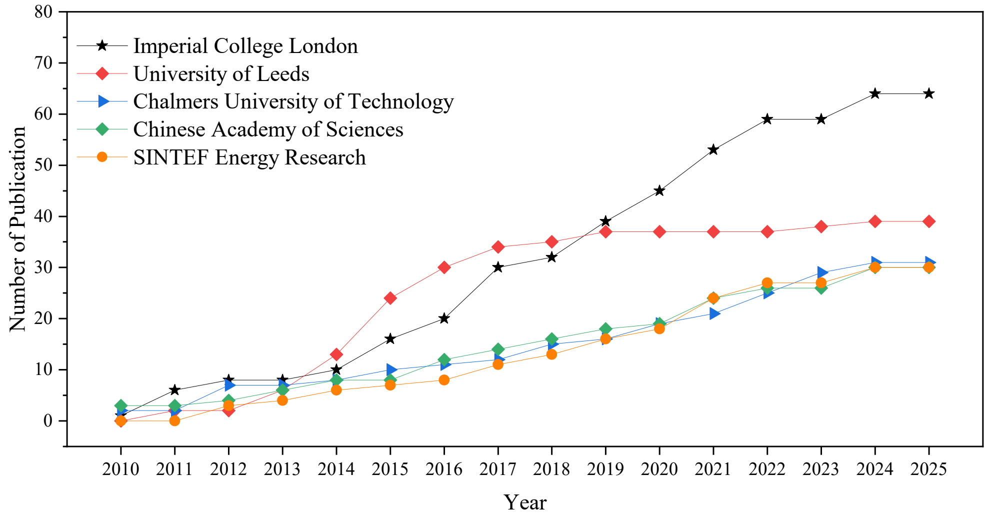


Figure 9. Top 5 Affiliations' Production over time.

Table 3 lists the 15 journals with the highest number of publications on CCS. The growth trend of the top five journals is shown in Figure 10. The International Journal of Greenhouse Gas Control topped the rankings with 514 publications and the highest total citations (18,168), demonstrating a strong influence in the field of CCS. Applied Energy and Energy also ranked at the top, focusing on energy and environmental engineering, and had high SJR scores of 2.82 and 2.11, respectively, indicating the quality of publications and influential research contributions. Most journals are in quartile 1 (Scimagojr), suggesting that CCS research is widely published in highly reputable journals focusing on Energy, chemical engineering, and environmental science.

Table 3. Top 15 Journals in publication number (n).

Rank	Journal Name	Publication Number (n)	Local H-Index	Total Cited	SJR	Scopus Sub-Subject Area	Quartile (SJR)
1st	International Journal of Greenhouse Gas Control	514	66	18168	1.21	Energy - Miscellaneous	1
2nd	Applied Energy	126	55	7582	2.82	Energy - Miscellaneous	1
3rd	Energies	101	23	1381	0.65	Energy - Miscellaneous	1
4th	Energy	99	39	3947	2.11	Energy - Miscellaneous, Environmental Sciences	1
5th	Journal of Cleaner Production	91	37	3733	2.06	Environmental Science - Miscellaneous	1
6th	Chemical Engineering Journal	35	17	1025	2.85	Chemical Engineering (miscellaneous)	1
7th	Industrial & Engineering Chemistry Research	35	22	1124	0.81	Chemical Engineering (miscellaneous)	1
8th	Applied Thermal Engineering	22	15	650	1.49	Energy Engineering and Power Technology	1
9th	Process Safety and Environmental Protection	20	14	546	1.29	Chemical Engineering, Environmental Science	1

10th	Chemical Engineering Science	13	8	446	0.82	Chemical Engineering (miscellaneous)	1
11th	Construction and Building Materials	10	6	351	2	Material Science (Miscellaneous)	1
12th	Applied Sciences (Switzerland)	9	6	118	0.51	Engineering - Miscellaneous	2
13th	Chemical Engineering and Technology	9	8	342	0.41	Chemical Engineering (miscellaneous)	2
14th	Journal of Engineering for Gas Turbines and Power	8	7	162	0.51	Energy Engineering and Power Technology	2
15th	Journal of Power Sources	7	5	139	1.86	Energy Engineering and Power Technology	1

The CCS-related publications are primarily concentrated in specialized journals. Bradford's Law (see Figure 11) categorizes sources within the same field into three zones. The first zone is core sources, which are often the most productive journals used as primary references. The International Journal of Greenhouse Gas Control (IJGHGC) is included in this core source. The second and third zones contain more journals, but the number of articles is the same as that of the core sources. For example, IJGHGC has published 514 articles. This amount is equivalent to a combination of the number of articles published in Applied Energy, Energies, Energy, Journal of Cleaner Production, Chemical Engineering Journal, Industrial & Engineering Chemistry Research, Applied Thermal Engineering, and Process Safety and Environmental Protection, totaling 529 articles. These journals are included in the second zone. The journal that has the least contribution is included in the third zone. Figure 10 shows the publication trends of each journal. Since 2010, the International Journal of Greenhouse Gas Control has consistently published the most papers, indicating that this journal is the primary center for CCS research publications.

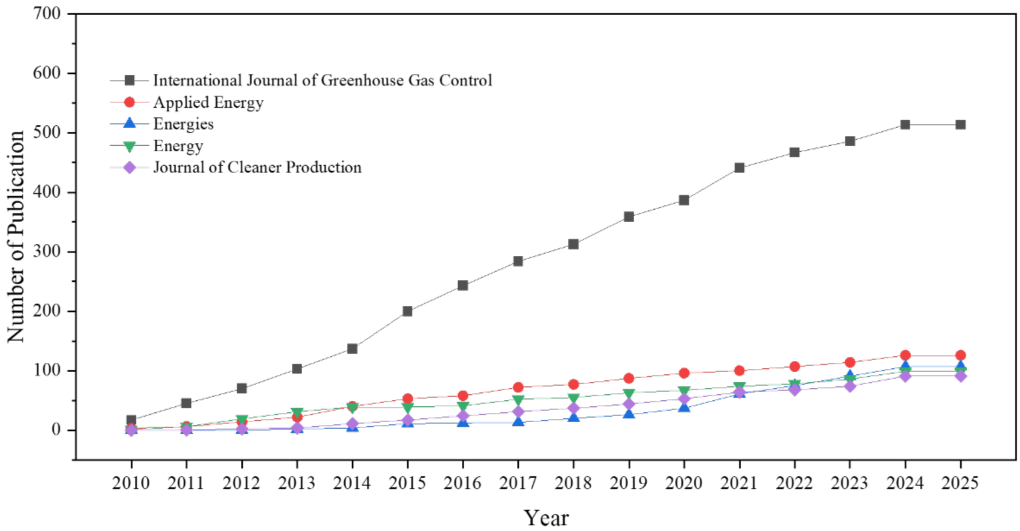


Figure 10. Sources of production over time.

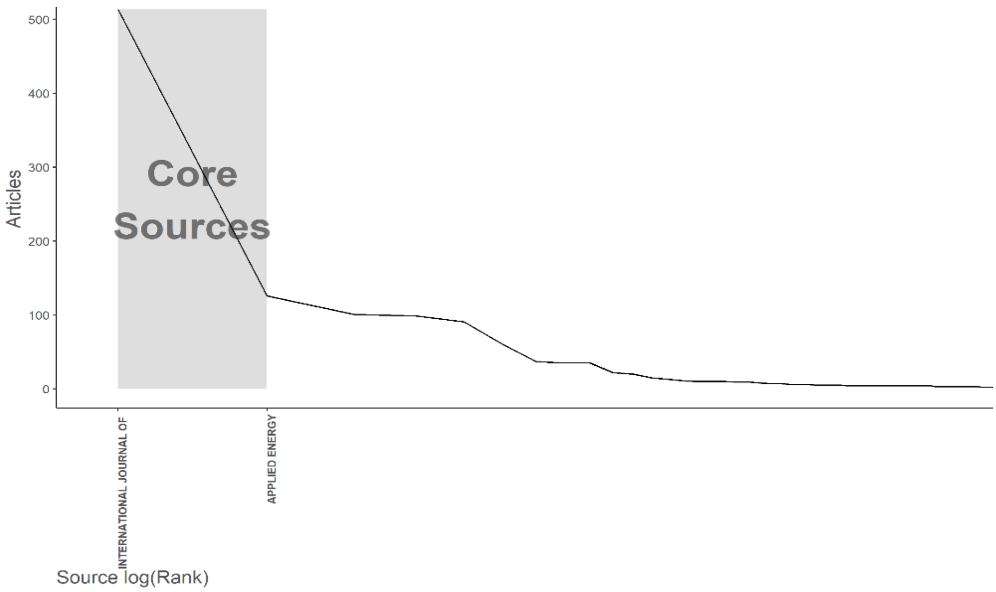


Figure 11. Core Sources by Bradford's Law.

The 15 most prolific authors in CCS research, ranked by publications, citations, and H-index, are shown in Table 4. The number of citations in this study refers to the total number of citations, including both self-citations and citations from other sources. Some researchers who had abnormal self-citations were excluded from the analysis. The H-Index is a bibliometric indicator that measures a researcher's productivity and scientific impact based on the number of citations and publications. The researcher has an H-index of *h,* meaning he has h publications that have been cited at least *h* times each. These incentives help assess research by combining quantity and quality. According to Table 4, Raymond R. Tan of De La Salle University, Philippines, ranked first with 17 publications and 849 citations. Simon Roussanaly of SINTEF Energy Research in Norway took second place with 16 publications and an H-index of 13. Calin-Cristian Cormos of Babes-Bolyai University, Romania, has the highest number of citations (959). Researchers from countries such as Japan, Korea, the United Kingdom, Sweden, and Italy made significant contributions, reflecting international cooperation in developing this technology.

Table 4. The top 15 authors most frequently publishing on CCS.

Rank	Author	Publication number	Citation	H-Index	Affiliation/ Country
1st	Raymond R. Tan	17	849	15	De La Salle University, Philippines
2nd	Simon Roussanaly	16	657	13	SINTEF Energy Research, Norway
3rd	Filip Johnsson	15	318	7	Chalmers University of Technology, Sweden
4th	Calin-Cristian Cormos	14	959	13	Babes-Bolyai University, Romania
5th	Cheol Huh	13	184	6	Korea Maritime and Ocean University, Republic of Korea
6th	Toru Sato	13	73	4	University of Tokyo, Japan
7th	Yong Yan	13	119	7	University of Kent, United Kingdom
8th	Jerry Blackford	11	288	7	Plymouth Marine Laboratory, United Kingdom
9th	Jonathan M. Bull	11	416	10	University of Southampton, United Kingdom
10th	Daejun Chang	11	219	6	KAIST, Republic of Korea
11th	Anna Lichtschlag	11	390	9	National Oceanography Centre, United Kingdom
12th	Youngkyun Seo	11	183	6	KAIST, Republic of Korea
13th	Henrik Stahl	11	425	10	Scottish Association for Marine Science, United Kingdom

14th	Fredrik Normann	10	168	6	Chalmers University of Technology, Sweden
15th	Matteo C. Romano	10	179	5	Politecnico di Milano, Italy

Figure 12 shows a visualization of a collaborative network among researchers generated with VOSviewer software. Each circle represents a researcher, and the lines connecting the nodes indicate collaborations based on joint publications. The size of the nodes reflects the frequency of the researcher's involvement in the partnership, while the different colours indicate separate groups or clusters of collaborations. Researchers like Toru Sato are clustered separately, with limited connections, suggesting that his cooperation is more exclusive with certain researchers, such as Yamaguchi. On the other hand, Henrik Stahl is at the centre of the collaboration network, connecting several researchers, including Jerry Blackford and Peter Taylor, with a large node indicating Stahl's significant role. Stuart M. V. Gilfillan appears involved in a smaller, limited cluster of collaborations but remains connected to other researchers. Overall, these visualizations show varying patterns of cooperation, with some researchers acting as critical linkages among the collaboration clusters.

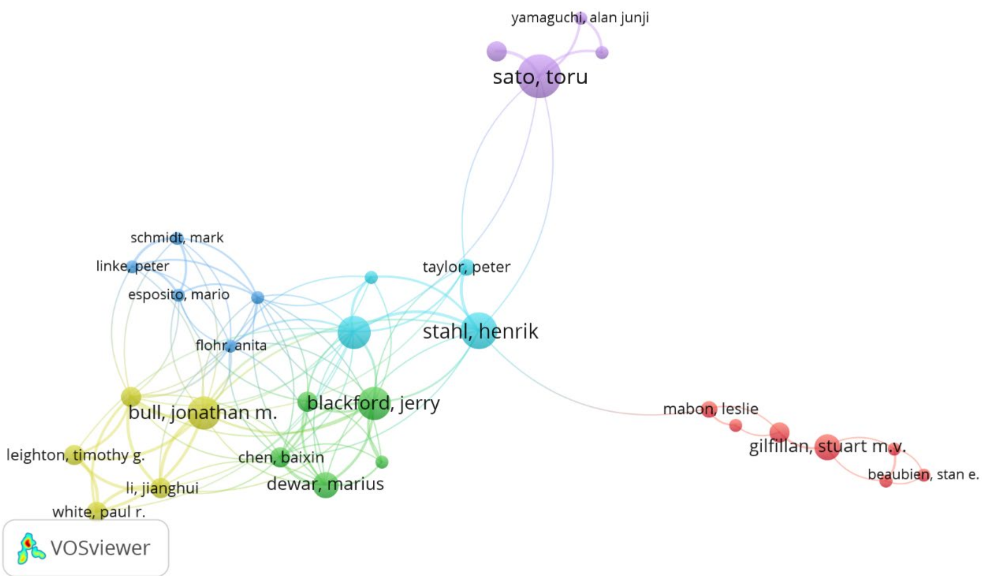


Figure 12. Author Collaboration Network.

Table 5 highlights the 15 most cited articles on CCS research. Article by Scrivener *et al.* (2018) became the most frequently cited article with 1,419 citations, demonstrating the importance of research on efficient solutions in the low-carbon cement-based materials industry. This study emphasizes that substituting Portland cement clinker with Supplementary Cementitious Materials (SCMs) is the most promising strategy for significantly reducing CO_2 emissions without requiring significant investments such as CCS. This approach is considered realistic for implementation in both developed and developing countries, making it a key reference in the literature on low-emission materials. Research on alternative cement materials was also conducted by Barcelo *et al.* (2014), who compared the mechanical performance and carbon emissions of Portland cement, calcium sulfoaluminate (CSA) cement, and alkali-activated fly ash–based geopolymers. The results demonstrated significant potential for reducing the carbon footprint of concrete without compromising structural strength.

Table 5. Top 15 Cited Articles.

Rank	References	Title	Year	Source Title	Cited By
1st	(Scrivener *et al.*, 2018)	Eco-efficient cement: Potential economically viable solutions for a low-CO_2 cement-based materials industry	2018	Cement and Concrete Research	1419

2nd	(Rubin *et al.*, 2015)	The cost of CO_2 capture and storage	2015	International Journal of Greenhouse Gas Control	686
3rd	(Michael *et al.*, 2010)	Geological storage of CO_2 in saline aquifers -A review of the experience from existing storage operations	2010	International Journal of Greenhouse Gas Control	528
4th	(Lin *et al.*, 2012)	In silico screening of carbon-capture materials	2012	Nature Materials	499
5th	(Barcelo *et al.*, 2014)	Cement and carbon emissions	2013	Materials and Structures	484
6th	(Leeson *et al.*, 2017)	A techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining, and pulp and paper industries, as well as other high-purity sources	2017	International Journal of Greenhouse Gas Control	375
7th	(Krevor *et al.*, 2015)	Capillary trapping for geologic carbon dioxide storage – From pore scale physics to field scale implications	2015	International Journal of Greenhouse Gas Control	367
8th	(Huisingh *et al.*, 2015)	Recent advances in carbon emissions reduction: policies, technologies, monitoring, assessment, and modeling	2015	Journal of Cleaner Production	343
9th	(Brouwer *et al.*, 2015)	Operational flexibility and economics of power plants in future low-carbon power systems	2015	Applied Energy	253
10th	(Vega *et al.*, 2020)	Current status of CO_2 chemical absorption research applied to CCS: Towards full deployment at industrial scale	2020	Applied Energy	252
11th	(Cormos, 2012)	Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS)	2012	Energy	250
12th	(Ou *et al.*, 2011)	Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China	2011	Applied Energy	241
13th	(Raynal *et al.*, 2011)	From MEA to demixing solvents and future steps, a roadmap for lowering the cost of post-combustion carbon capture	2011	Chemical Engineering Journal	228
14th	(Wennersten *et al.*, 2015)	The future potential for Carbon Capture and Storage in Climate Change Mitigation: An overview from perspectives of technology, economy, and risk	2015	Journal of Cleaner Production	209
15th	(Andrew *et al.*, 2014)	Pore-scale imaging of trapped supercritical carbon dioxide in sandstones and carbonates	2014	International Journal of Greenhouse Gas Control	205

From an economic perspective, Rubin *et al.* (2015) provide a comprehensive analysis of the costs of implementing CCS in fossil fuel–fired power plants, estimating capture costs at US$40–120 per ton of CO_2, with additional transportation and storage costs of US$10–30 per ton. This study has become a primary reference for researchers and policymakers in evaluating the financial feasibility of CCS. The cross-industry studied by Leeson *et al.* (2017) further expands the cost analysis of CCS to sectors such as steel, cement, oil refining, and pulp and paper, finding that the cost of avoided emissions ranges from US\$20 to US\$140 per ton of CO_2, depending on the technology and industry scale. This study integrates both economic and technical perspectives, making it widely used in the planning of carbon mitigation policies.

Other articles, such as those by Michael *et al.* (2010), which have garnered 528 citations, discuss the geological storage of CO_2 in saline aquifers, a crucial strategy for long-term CO_2 storage. This study provides an overview of several CO_2 storage projects, such as Sleipner and In Salah, which have been proven to be technically feasible with adequate monitoring systems. Article by Lin *et al.* (2012), published in Nature Materials, highlights research on materials for carbon capture, with 499 citations. These articles cover various aspects of CCS technology, including energy efficiency, implementation costs, and CO_2 storage methods. This study introduces an in silico method for high-throughput screening of carbon-capture materials, enabling the selection of porous structures, such as zeolites and zeolitic imidazolate frameworks (ZIFs), that exhibit higher energy efficiency than conventional carbon-capture technologies. Several of these publications occupy a crucial position in the literature, as they combine practical solutions, economic analyses, field-based technical evidence, and material innovations. The high number of citations they have received reflects the global relevance of their findings to efforts toward transitioning to a low-emission industry.

Figure 13 is a network visualization of the topics and keywords frequently appearing in CCS research. Each node represents a keyword, with its size indicating the frequency of its appearance in a publication. The connections between nodes depict the relationships among the identified keywords, reflecting the frequency with which they co-occur within the literature. The node colours correspond to the year of publication, ranging from dark blue for earlier works to bright yellow for more recent studies. Central to the network are keywords such as “carbon capture” and “carbon capture and storage”, indicating their pivotal role within the CCS research domain. Closely associated terms, including “fossil fuel power plants”, “geological storage”, “emission control”, and “renewable energies”, reveal the thematic breadth of CCS studies, encompassing areas such as energy efficiency, storage technologies, and strategies for reducing carbon emissions. The visualisation further underscores the field's thematic evolution, with concepts such as “hydrogen storage” and “renewable energies” gaining prominence in more recent publications. Collectively, this visual representation offers a detailed depiction of both the structural relationships and the developmental trajectory of CCS-related research in recent years.

Meanwhile, Figure 14 illustrates the trend of topics related to CCS research, based on the frequency of keyword usage over time. Each horizontal line represents the period during which the topic was present in the study, and the size of the circle reflects the topic's frequency or popularity in that year. Larger circles indicate higher frequencies. Keywords such as “carbon capture and utilization," “direct air capture,” and “carbon cycle” have appeared more frequently in recent years. This fact reflects a growing interest in carbon utilization and in innovative solutions to reduce direct emissions into the atmosphere. The relationship between Figures 13 and 14 is quite clear. Figure 13 visually shows the relationship between various CCS-related keywords, while Figure 14 shows the evolution of the use of those keywords over the years.

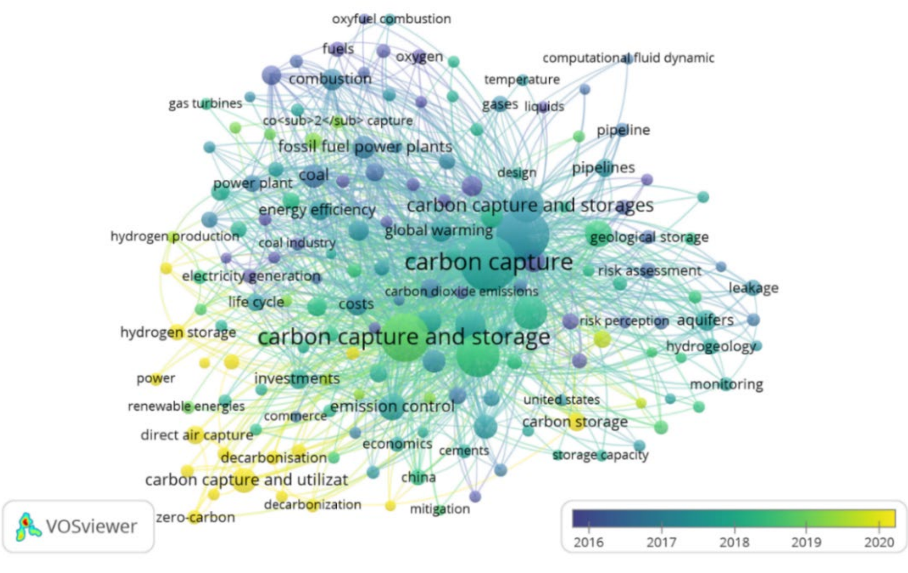


Figure 13. Co-occurrence network in CCS.

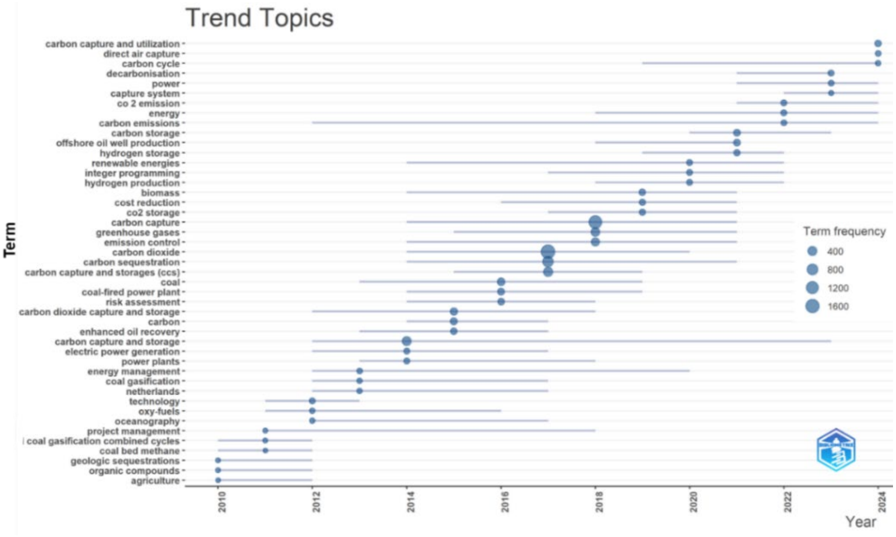


Figure 14. Trends in CCS-related research over the years.

3.2. Key Challenges in CCS Risk Perception

The trend in the number of publications on CCS across three main categories from 2010 to September 2024 is shown in Figure 15. The risk assessment category shows a fluctuating trend but has increased overall. This information highlights the importance of research into potential risks associated with CCS, including leakage and environmental impacts. The economic approach study shows stable and significant growth. This data shows the growing attention to cost-benefit analysis and economic studies when applying CCS at an industrial scale.

Meanwhile, publications on numerical evaluation, including mathematical models and simulations related to CCS, have become increasingly popular in recent years. Although not as numerous as in other categories, there has been consistent growth in publications in this field. Overall, research in these three categories continues to grow, with a significant focus on risk and economic aspects, suggesting that both are of primary concern in implementing CCS technologies.

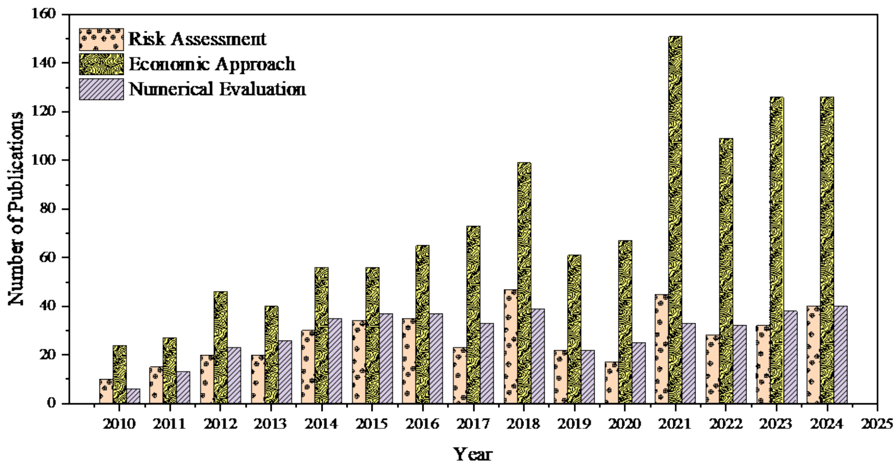


Figure 15. Number of CCS Publications in specific terms: Risk, Economic, and Numerical Evaluation per Year from 2010 to September 2024.

The author's collaborative network in CCS-related risk assessment research is shown in Figure 16. The Colours and lines indicate different clusters or groups of collaborations. The red cluster comprises authors such as Matthias Haeckel, Anita Flohr, Stefan Sommer, and James Strong, who collaborate closely on risk assessment research. The green cluster, which includes authors such as Jerry Blackford, Marius Dewar, and Baixin Chen, also exhibits strong collaboration within its groups but remains more distinct from the red cluster. On the other hand, the blue cluster of Marcella Dean and Christopher F. Brown appears to be more isolated from the broader network of collaborations, with fewer collaborations. Overall, this visualization reveals a complex pattern of cooperation in risk assessment research, with some groups of authors working intensively together. In contrast, others are more focused on limited or independent collaboration.

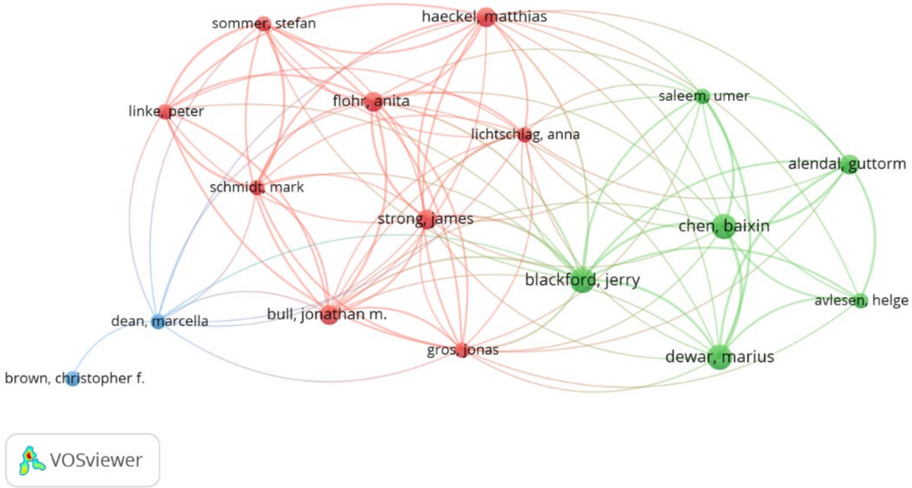


Figure 16. Author Collaboration Network in CCS Risk Assessment.

Figure 17 shows the keyword co-occurrence network in the risk assessment research related to CCS technology. The keywords "carbon dioxide" and "risk assessment" are central to the network, indicating that they are both significant topics in CCS research. These words are often associated with other important concepts, such as "carbon capture and storage," "leakage," and "underground storage," which are closely related to aspects of carbon storage and its potential risks, including CO_2 leakage from storage sites. In addition, keywords such as "carbon storage," "safety engineering," and "carbon utilization" also frequently appear in newer publications, indicating increased attention to these topics.

Research on CCS primarily examines methods for securely sequestering carbon dioxide in underground formations while exploring opportunities for its utilization in applications that enhance energy efficiency or advance environmentally sustainable technologies. As global environmental challenges intensify, concerns about the potential leakage or unintended release of stored carbon dioxide have become increasingly prominent, posing a substantial obstacle to long-term safety. In response, monitoring protocols use advanced detection technologies to identify early indicators of leakage. Equally important is the application of safety engineering principles to design storage systems that minimize the risk of failure. Effective risk management relies on informed decision-making, drawing upon monitoring data and comprehensive risk assessments to implement preventive measures. The growing body of scientific work in this domain highlights the crucial role of CCS risk management as a vital component of strategies to mitigate climate change.

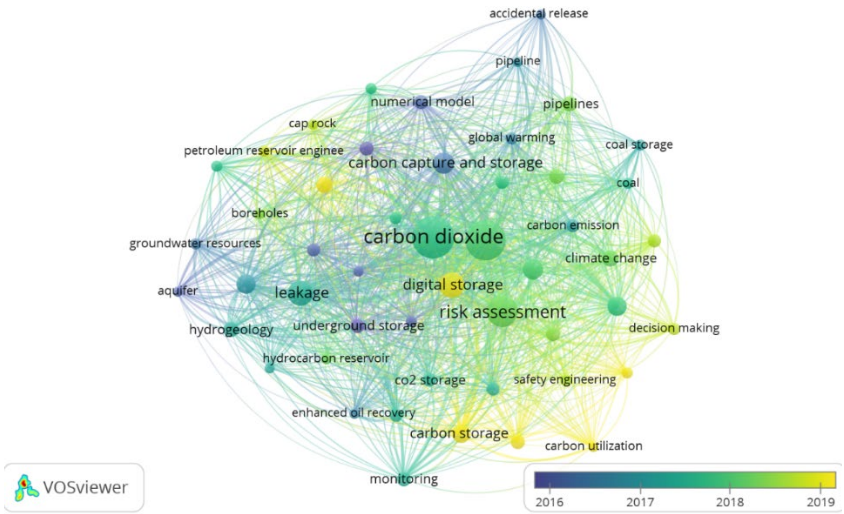


Figure 17. Co-Occurrence Network in CCS Risk Assessment.

3.3. Economic Barriers and Opportunities in CCS Deployment

The collaboration network among authors in research on economic approaches to CCS is shown in Figure 18. Simon Roussanaly and Edward Rubin are two authors at the centre of the network, suggesting they have a central role in the collaboration regarding the economic approach to CCS. They are connected to several other authors in various clusters, including Filip Johnsson and Fredrik Normann in the yellow cluster, with whom they also have close research collaborations. Matteo C. Romano also stands out for his extensive network of collaborations, particularly with authors such as Edoardo de Lena and Emanuele Martelli, highlighting a group of authors focused on specific research in the economics of CCS. André Faaij and Machteld van den Broek in the blue cluster appear to be more isolated from the main groups, though they still collaborate with other authors. The authors in the field of CCS economics collaborate in specific groups, with some key authors, such as Roussanaly and Rubin, playing a significant role in connecting the various clusters.

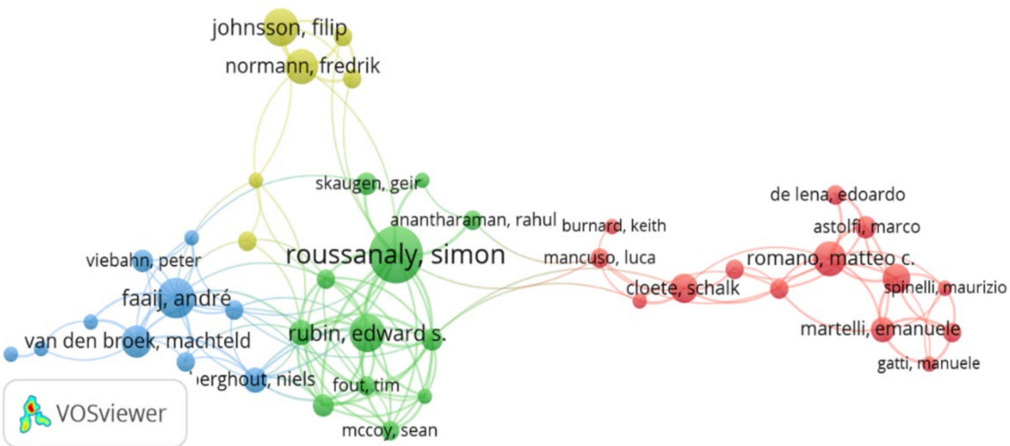


Figure 18. Author Collaboration Network in CCS Economic Approaches.

The co-occurrence network, or keyword linkage, in research on economic approaches to CCS is illustrated in Figure 19. The keywords "costs," "economic analysis," and "cost-benefit analysis" are at the centre of the network, indicating that the cost aspect and economic analysis are the main topics in CCS research. In addition, keywords such as "emission control," "investments," and "optimization" also have a strong correlation with this topic, indicating that aspects of emission control, technology optimization, and investment are also very relevant in the study of CCS economics.

Terms such as "coal," "natural gas," and "power plant" are frequently associated with economic considerations in the energy and CCS sectors, underscoring the pivotal role of fossil-fuel-based power generation in debates over cost and emission mitigation. Furthermore, concepts such as "cost-effectiveness” and “uncertainty analysis” have emerged as key elements in the economic evaluation of CCS, highlighting the growing emphasis on financial efficiency and the management of economic uncertainties in their deployment. Research adopting a monetary perspective primarily centers on cost assessment, emission-reduction strategies, optimization processes, and the interplay among diverse energy domains, including both fossil fuels and renewable energy sources.

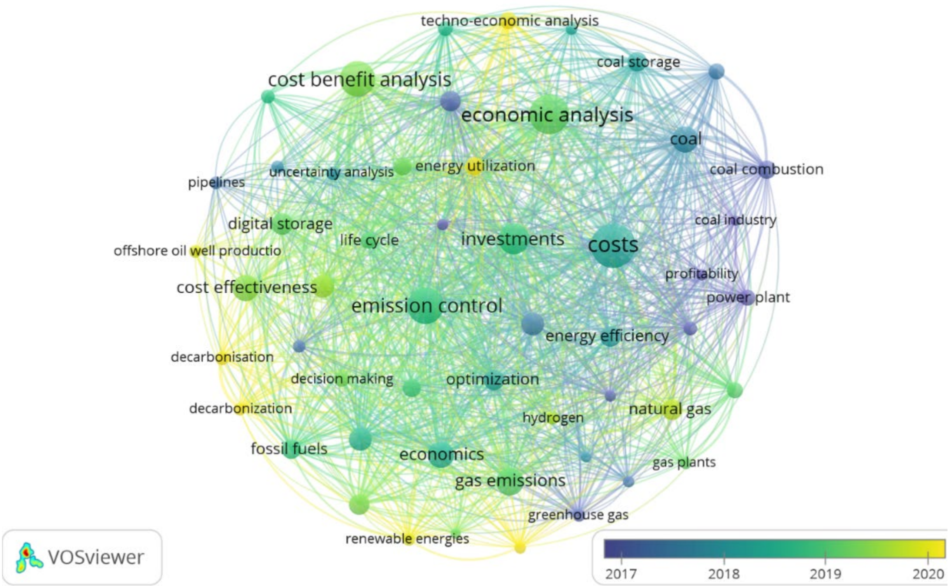


Figure 19. Co-Occurrence Network in CCS Economic Approaches.

3.4. Numerical Simulation Approaches for CCS Challenges

Figure 20 shows the collaboration network among authors in research on the numerical evaluation of CCS. Wang Yongsheng and Li Jun are the two prominent authors who serve as the centre of collaboration, connecting several smaller groups of writers. They are essential in bridging various research groups in CCS-related numerical assessment research. Authors such as Lei Hongwu and Li Xiaochun also play crucial roles in this network, as evidenced by the size of their nodes and their extensive connections with other researchers. Other author clusters, such as those of Liu Jianfeng and Liu Hejuan on the right, as well as Zhang Yuting and Wang Linlin on the left, exhibit smaller but active groups of researchers collaborating within their respective networks.

Figure 21 shows the co-occurrence network of keywords that often appear together in research on the numerical evaluation of CCS. The keywords “carbon capture," “numerical model,” and “carbon capture and storage” are at the centre of the network, suggesting that this topic is at the core of research using numerical evaluation. Other frequently cited topics include “numerical simulation," “computer simulation,” and “optimization,” which underscore the importance of computational simulation in modeling processes and optimizing these technologies. In addition, keywords such as “greenhouse gases," “emission control,” and “energy efficiency” also appear frequently, indicating that numerical evaluations are used to measure the impact of CCS technology in reducing greenhouse gas emissions and improving energy efficiency. Topics such as “leakage," “hydrogeology,” and “uncertainty analysis” appear at the edge of the network but remain essential in examining potential risks and uncertainties in the application of CCS. Overall, this visualization illustrates the interrelationship between the main topics in the numerical evaluation of CCS, with a primary focus on simulation and optimization in the application of carbon capture technologies.

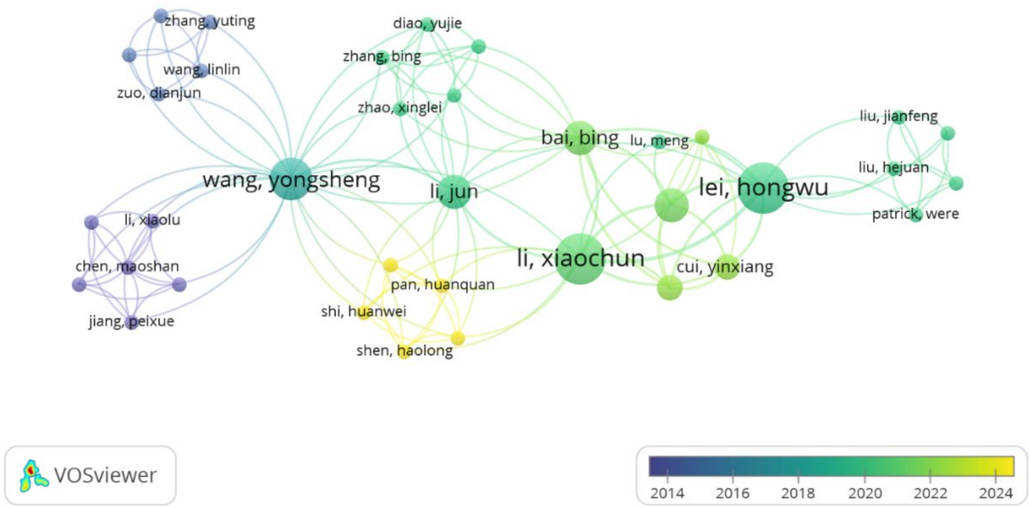


Figure 20. Author Collaboration Network in CCS Numerical Evaluation.

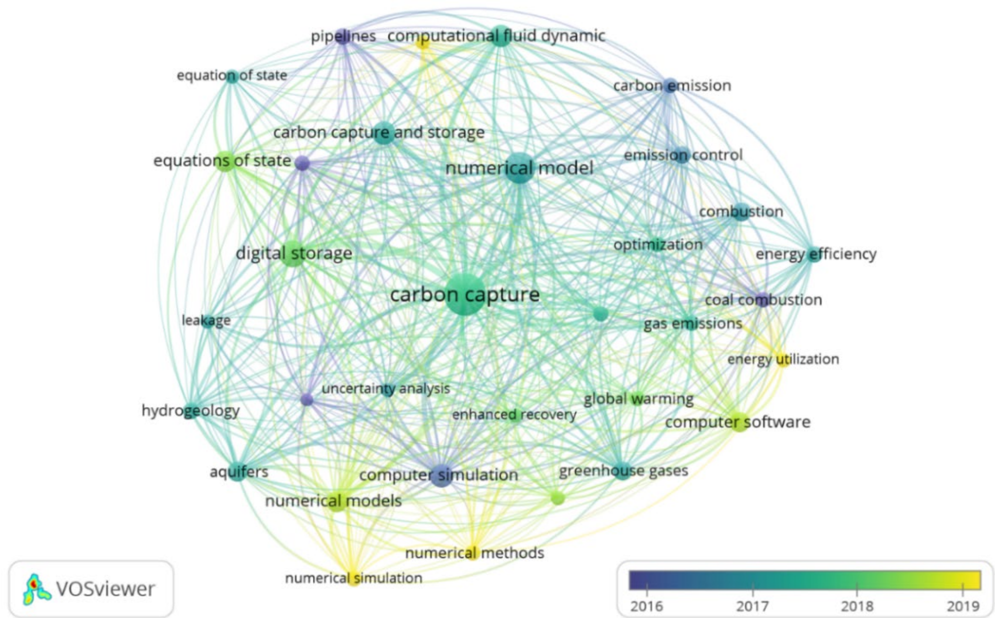


Figure 21. Co-Occurrence Network in CCS Numerical Evaluation.

4. Financial Support for CCS Research

Based on Figures 6 and 8, it can be observed that not all countries exhibit the same level of interest in developing CCS technology. Several developed countries, including the United States, China, Australia, and several Western European nations, have produced numerous publications and are actively engaged in international collaborations. Most other countries, especially those in Africa, South America, and Southeast Asia, show significantly smaller or no contributions. Not all countries are interested or have the capacity to contribute significantly to this research.

The future projections outlined in this article may change significantly, primarily due to political factors. The CCS research trends are closely tied to financial support (see Table 6) and are often influenced by government policies and political priorities. While the current analysis provides a clear picture of research outputs and regional focuses, political shifts can significantly affect the availability of research funding and priorities, which could ultimately change the scale and direction of future research. As political views evolve, particularly in response to increasingly pressing environmental issues, the pace and scope of research are likely to undergo rapid transformation, making it a dynamic area of study that will continue to evolve in the coming years.

Table 6. The Most Influential Sponsor in CCS Publications Based on the Scopus Database.

No	Sponsor	Country/ Region	Number of Publications
1	National Natural Science Foundation of China	China	200
2	Ministry of Science and Technology of the People's Republic of China	China	116
3	Engineering and Physical Sciences Research Council	UK	97
4	European Commission (Horizon 2020 Framework Programme)	Europe	178
5	U.S. Department of Energy	USA	72
6	Natural Environment Research Council	UK	49
7	UK Research and Innovation	UK	49
8	Norges Forskningsråd	Norway	46
9	National Key Research and Development Program of China	China	44
10	National Research Foundation of Korea	Korea	34
11	Ministry of Education of the People's Republic of China	China	33
12	National Energy Technology Laboratory	USA	33
13	Energimyndigheten	Sweden	21
14	Japan Society for the Promotion of Science	Japan	17
15	Conselho Nacional de Desenvolvimento Científico e Tecnológico	Brazil	16

5. Concluding Remark

5.1. Key Findings

The result of this bibliometric analysis indicates that CCS remains a key technology in global climate change mitigation efforts, with significant progress in capture efficiency, storage methods, and research collaborations. However, barriers such as high costs, regulatory uncertainties, and long-term storage security risks continue to limit large-scale deployment. Overcoming these challenges will require cross-disciplinary innovation, robust policy support, and sustained international cooperation. By highlighting the interconnection between risk assessment, economic evaluation, and numerical modeling, this review provides a strategic foundation for guiding future CCS research and accelerating its practical implementation.

5.2. Limitations

This study has mapped the development of CCS technology based on publications from the Scopus database over a specific period. Nevertheless, the methodology used still has limitations. An in-depth review of the research substance cannot rely solely on quantitative data. The use of VOSviewer and Bibliometrix can provide a general overview of publication patterns, but does not allow for an analysis of the quality and relevance of the research conducted. In addition, although fairly representative, using Scopus as the sole data source also has its drawbacks. While relevant to the topic discussed, literature publications that are not yet indexed or are local cannot be included in the analysis. This condition has the potential to introduce bias, as non-Scopus publications could significantly influence the analysis results.

5.3. Future Research Directions

Future research could benefit from refining the methodology by thoroughly reassessing the substantive elements of existing studies, with particular emphasis on risk assessment, economic evaluation, and quantitative analysis. Such an appraisal would help determine the current depth and quality of research in the field. Analytical approaches may also be strengthened by integrating advanced techniques, including those underpinned by artificial intelligence (AI). Expanding the scope of data sources to include alternative databases would facilitate comparative analysis. Incorporating locally produced or non-indexed literature, subject to rigorous selection criteria, could further enrich the evidence base. Collectively, these strategies are expected to yield a more comprehensive understanding of global trends in CCS research.

Beyond technical dimensions, future investigations into CCS technologies should also consider non-technical factors, including government policy frameworks, regulatory mechanisms, and societal acceptance. Recent findings indicate growing scholarly interest in using CO_2 to produce specific value-added products. This domain warrants deeper exploration from both technical and economic standpoints. As emerging technologies advance, it is essential to assess their potential to reduce operational costs and enhance the efficiency of CCS systems. Furthermore, more detailed research should be undertaken on related thematic areas, including climate change mitigation strategies, renewable energy integration, and the promotion of low-emission transportation systems.

Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

CRediT author statement

Aprianur Fajri: Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft. **Aditya Rio Prabowo:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Ristiyanto Adiputra:** Conceptualization, Methodology, Investigation, Resources, Writing - Review & Editing, Supervision. **Nurul Muhayat:** Visualization, Supervision. **Sören Ehlers:** Conceptualization, Writing - Review & Editing. **Moritz Braun:** Conceptualization, Writing - Review & Editing.

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References

Al-Habaibeh, A., Manu, E., Clement, T., Shakmak, B., Selvam, J. and Lin, T.-H. (2025), “Accelerating Whole Life Carbon Assessment in Construction with Artificial Intelligence”, *Energy Catalyst*, Vol. 1, pp. 54–67. https://doi.org/10.61552/EC.2025.004.

Andrew, M., Bijeljic, B. and Blunt, M.J. (2014), “Pore-scale imaging of trapped supercritical carbon dioxide in sandstones and carbonates”, *International Journal of Greenhouse Gas Control*, Vol. 22, pp. 1–14. https://doi.org/10.1016/j.ijggc.2013.12.018.

Apriantoro, M.S., Dartim and Andriyani, N. (2024), “Bibliometric Analysis of Carbon Capture and Storage (CCS) Research: Evolution, Impact, and Future Directions”, *Challenges in Sustainability*, Vol. 12 No. 2, pp. 152–162. https://doi.org/10.56578/cis120205.

Barcelo, L., Kline, J., Walenta, G. and Gartner, E. (2014), “Cement and carbon emissions”, *Materials and Structures/Materiaux et Constructions*, Vol. 47 No. 6, pp. 1055–1065. https://doi.org/10.1617/s11527-013-0114-5.

Bayraktar, M. and Yuksel, O. (2023), “A scenario-based assessment of the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations”, *Ocean Engineering*, Vol. 278 No. March 2023, p. 114295. https://doi.org/10.1016/j.oceaneng.2023.114295.

Brouwer, A.S., van den Broek, M., Seebregts, A. and Faaij, A. (2015), “Operational flexibility and economics of power plants in future low-carbon power systems”, *Applied Energy*, Vol. 156, pp. 107–128. https://doi.org/10.1016/j.apenergy.2015.06.065.

Bui, M., Adjiman, C.S., Bardow, A., Anthony, E.J., Boston, A., Brown, S., Fennell, P.S., *et al.* (2018), “Carbon capture and storage (CCS): The way forward”, *Energy and Environmental Science*, Vol. 11 No. 5, pp. 1062–1176. https://doi.org/10.1039/c7ee02342a.

Casaban, D. and Tsalaporta, E. (2023), “The impact of direct air capture during the last two decades: A bibliometric analysis of the scientific research Part II”, *Sustainable Chemistry for Climate Action*, Vol. 2 No. December 2022, p. 100021. https://doi.org/10.1016/j.scca.2023.100021.

Climate Watch. (2023), “World CO_2 Emisions by Sector”, available at: https://www.climatewatchdata.org (accessed 16 October 2024).

Cormos, C.C. (2012), “Integrated assessment of IGCC power generation technology with carbon capture and storage (CCS)”, *Energy*, Vol. 42 No. 1, pp. 434–445. https://doi.org/10.1016/j.energy.2012.03.025.

Van Eck, N.J. and Waltman, L. (2010), “Software survey: VOSviewer, a computer program for bibliometric mapping”, *Scientometrics*, Vol. 84 No. 2, pp. 523–538. https://doi.org/10.1007/s11192-009-0146-3.

Van Eck, N.J., Waltman, L., Dekker, R. and Van Den Berg, J. (2010), “A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS”, *Journal of the American Society for Information Science and Technology*, Vol. 61 No. 12, pp. 2405–2416. https://doi.org/10.1002/asi.21421.

Fajri, A., Jurkovič, M., Kandimba, E.M., Lutanto, A., Falah, F., Adiputra, R. and Firdaus, N. (2024), “Recent

Advancements in Ocean Current Turbine Blade Design: A Review of Geometrical Shape, Performance and Potential Development using CAE", *Mekanika: Majalah Ilmiah Mekanika*, Vol. 23 No. 2, pp. 108–123. https://doi.org/10.20961/mekanika.v23i2.87374.

Gutsch, M. and Leker, J. (2024), "Co-assessment of costs and environmental impacts for off-grid direct air carbon capture and storage systems", *Communications Engineering*, Vol. 3 No. 1, pp. 1–14. https://doi.org/10.1038/s44172-023-00152-6.

Hammond, G.P., Akwe, O.S.O. and Williams, S. (2011), "Techno-economic appraisal of fossil-fuelled power generation systems with carbon dioxide capture and storage", *Energy*, Elsevier Ltd, Vol. 36 No. 2, pp. 975–984. https://doi.org/10.1016/j.energy.2010.12.012.

Huisingh, D., Zhang, Z., Moore, J.C., Qiao, Q. and Li, Q. (2015), "Recent advances in carbon emissions reduction: Policies, technologies, monitoring, assessment and modeling", *Journal of Cleaner Production*, Vol. 103 No. 2015, pp. 1–12. https://doi.org/10.1016/j.jclepro.2015.04.098.

International Energy Agency (IEA). (2016), *20 Years of Carbon Capture and Storage*, *20 Years of Carbon Capture and Storage*, OECD.

International Energy Agency (IEA). (2021), "Net Zero by 2050: A Roadmap for the Global Energy Sector".

Johnsson, F., Kjärstad, J. and Rootzén, J. (2019), "The threat to climate change mitigation posed by the abundance of fossil fuels", *Climate Policy*, Taylor & Francis, Vol. 19 No. 2, pp. 258–274. https://doi.org/10.1080/14693062.2018.1483885.

Kaneria, P. and Reddy, K.S. (2025), "Minimizing shadow effects to optimize solar energy input in the World Solar Challenge", *Green Technology & Innovation*, Vol. 1 No. 1.

Kappis, K., Papavasiliou, J. and Avgouropoulos, G. (2021), "Methanol Reforming Processes for Fuel Cell Applications", *Energies*, Vol. 14 No. 24, p. 8442. https://doi.org/10.3390/en14248442.

Krevor, S., Blunt, M.J., Benson, S.M., Pentland, C.H., Reynolds, C., Al-Menhali, A. and Niu, B. (2015), "Capillary trapping for geologic carbon dioxide storage - From pore scale physics to field scale implications", *International Journal of Greenhouse Gas Control*, Vol. 40, pp. 221–237. https://doi.org/10.1016/j.ijggc.2015.04.006.

Kutlu, C., Erdinc, M.T., Ehtiwesh, A., Bottarelli, M., Su, Y. and Riffat, S. (2025), "Evaluation of operation control parameters of a residential solar organic Rankine cycle with effects of expander-generator coupling", *Journal of Global Decarbonisation*, Vol. 2025 No. 1, pp. 1–19. https://doi.org/10.17184/eac.9437.

Ladokun, L.L. (2024), "Hydrodynamic Performance Assessment of Straight and Helical Hydrokinetic Turbine Hydrofoil-Blade Sections in River Oyun, North-Central Nigeria", *Mekanika: Majalah Ilmiah Mekanika*, Vol. 23 No. 2, pp. 168–177. https://doi.org/10.20961/mekanika.v23i2.92527.

Lan, X., Tans, P. and Thoning, K.W. (2025), *Trends in Globally-Averaged CO_2 Determined from NOAA Global Monitoring Laboratory Measurements*.

Leeson, D., Mac Dowell, N., Shah, N., Petit, C. and Fennell, P.S. (2017), "A Techno-economic analysis and systematic review of carbon capture and storage (CCS) applied to the iron and steel, cement, oil refining and pulp and paper industries, as well as other high purity sources", *International Journal of Greenhouse Gas Control*, Vol. 61, pp. 71–84. https://doi.org/10.1016/j.ijggc.2017.03.020.

Li, H., Jiang, H.D., Yang, B. and Liao, H. (2019), "An analysis of research hotspots and modeling techniques on carbon capture and storage", *Science of the Total Environment*, Vol. 687 No. 5, pp. 687–701. https://doi.org/10.1016/j.scitotenv.2019.06.013.

Li, J., Hou, Y., Wang, P. and Yang, B. (2019), "A Review of carbon capture and storage project investment and operational decision-making based on bibliometrics", *Energies*, Vol. 12 No. 1. https://doi.org/10.3390/en12010023.

Lin, L.C., Berger, A.H., Martin, R.L., Kim, J., Swisher, J.A., Jariwala, K., Rycroft, C.H., *et al.* (2012), "In silico screening of carbon-capture materials", *Nature Materials*, Vol. 11 No. 7, pp. 633–641. https://doi.org/10.1038/nmat3336.

Michael, K., Golab, A., Shulakova, V., Ennis-King, J., Allinson, G., Sharma, S. and Aiken, T. (2010), "Geological storage of CO_2 in saline aquifers-A review of the experience from existing storage operations", *International Journal of Greenhouse Gas Control*, Vol. 4 No. 4, pp. 659–667. https://doi.org/10.1016/j.ijggc.2009.12.011.

Osman, A.I., Hefny, M., Abdel Maksoud, M.I.A., Elgarahy, A.M. and Rooney, D.W. (2021), "Recent advances in carbon capture storage and utilisation technologies: a review", *Environmental Chemistry Letters*. Vol. 19 No 2, pp. 797-849. https://doi.org/10.1007/s10311-020-01133-3.

Ou, X., Xiaoyu, Y. and Zhang, X. (2011), "Life-cycle energy consumption and greenhouse gas emissions for electricity generation and supply in China", *Applied Energy*, Vol. 88 No. 1, pp. 289–297. https://doi.org/10.1016/j.apenergy.2010.05.010.

Perdana, M.M.G., Andika, R., Susanto, B.H., Steven, S., Nishiyama, N. and Sophiana, I.C. (2025), "Transforming CO_2 emissions into fuel: An energy analysis of dimethyl ether production pathways", *Results in Engineering*, Vol. 25 No. February, p. 104330. https://doi.org/10.1016/j.rineng.2025.104330.

Perianes-Rodriguez, A., Waltman, L. and van Eck, N.J. (2016), "Constructing bibliometric networks: A comparison between full and fractional counting", *Journal of Informetrics*, Vol. 10 No. 4, pp. 1178–1195. https://doi.org/10.1016/j.joi.2016.10.006.

Raynal, L., Bouillon, P.A., Gomez, A. and Broutin, P. (2011), "From MEA to demixing solvents and future steps, a roadmap for lowering the cost of post-combustion carbon capture", *Chemical Engineering Journal*, Vol. 171 No. 3, pp. 742–752. https://doi.org/10.1016/j.cej.2011.01.008.

Raza, A., Gholami, R., Rezaee, R., Rasouli, V. and Rabiei, M. (2019), "Significant aspects of carbon capture and

storage – A review", *Petroleum*. Vol. 5 No. 4, pp. 335-340. https://doi.org/10.1016/j.petlm.2018.12.007.
Rosli, M.A.M., Mahadi, A.A., Harsito, C. and Prasetyo, S.D. (2025), "Design of a Solar Power Plant System for Government Buildings in the Ibu Kota Nusantara of Indonesia Using HOMER Optimization", *Mekanika: Majalah Ilmiah Mekanika*, Vol. 24 No. 1, pp. 7–19. https://doi.org/10.20961/mekanika.v24i1.92798.
Rubin, E.S., Davison, J.E. and Herzog, H.J. (2015), "The cost of CO_2 capture and storage", *International Journal of Greenhouse Gas Control*, Vol. 40, pp. 378–400. https://doi.org/10.1016/j.ijggc.2015.05.018.
Sakaguchi, J. (2010), "Best mix of primary energy resources by renewable energy and fossil fuel with CCS in view of security, stability and sustainability-A vision on hydrogen supply chain by organic chemical hydride method", *Science in China Series E: Technological Sciences*, Vol. 53 No. 1, pp. 62–68. https://doi.org/10.1007/s11431-010-0008-5.
Scrivener, K.L., John, V.M. and Gartner, E.M. (2018), "Eco-efficient cements: Potential economically viable solutions for a low-CO_2 cement-based materials industry", *Cement and Concrete Research*, Vol. 114 No. March, pp. 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015.
Sharma, S. and Maréchal, F. (2019), "Carbon Dioxide Capture From Internal Combustion Engine Exhaust Using Temperature Swing Adsorption", *Frontiers in Energy Research*, Vol. 7 No. December, pp. 1–12. https://doi.org/10.3389/fenrg.2019.00143.
Suman, S., Kaiser Calautit, J., Wei, S., Wenbin Tien, P., Chen, X., Wang, Z. and Sun, H. (2025), "Assessing the Energy-Saving Potential of Passive Strategies in Commercial Buildings in the Top Upcoming Megacities", *Energy Catalyst*, Vol. 1, pp. 1–21. https://doi.org/10.61552/EC.2025.001.
The Energy Institute (EI). (2024), *Statistical Review of World Energy 2024*, Vol. 73.
Vega, F., Baena-Moreno, F.M., Gallego Fernández, L.M., Portillo, E., Navarrete, B. and Zhang, Z. (2020), "Current status of CO_2 chemical absorption research applied to CCS: Towards full deployment at industrial scale", *Applied Energy*, Vol. 260. https://doi.org/10.1016/j.apenergy.2019.114313.
Viebahn, P. and Chappin, E.J.L. (2018), "Scrutinising the gap between the expected and actual deployment of carbon capture and storage - A bibliometric analysis", *Energies*, Vol. 11 No. 9. https://doi.org/10.3390/en11092319.
Wang, C., Zhang, S., Hua, T., Zeng, J. and Lan, M. (2024), "CO_2 geological storage: A bibliometric analysis of research trends", *Heliyon*, Vol. 10 No. 14. https://doi.org/10.1016/j.heliyon.2024.e34479.
Wennersten, R., Sun, Q. and Li, H. (2015), "The future potential for Carbon Capture and Storage in climate change mitigation – an overview from perspectives of technology, economy and risk", *Journal of Cleaner Production*, Vol. 103, pp. 724–736. https://doi.org/10.1016/j.jclepro.2014.09.023.