Carbon Capture, Utilization, and Storage: A Literature Synthesis and Bibliometric Analysis

Lukas Mueller

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Lukas Mueller
Technical University of Darmstadt

1. Introduction

Carbon Capture, Utilization, and Storage (CCUS) is a comprehensive approach aimed at mitigating greenhouse gas emissions, particularly carbon dioxide (CO2), from industrial processes and power generation. The fundamental concept involves capturing CO2 emissions at their source, such as power plants or industrial facilities, preventing them from entering the atmosphere. Captured CO2 can be either utilized for various industrial purposes or stored underground, reducing its impact on the environment. Today, around 90% of the captured CO2 is stored in depleted oil and gas fields, but saline reservoirs promise the largest potential (Ma et al., 2022).

According to the Intergovernmental Panel on Climate Change (IPCC) in 2014, the implementation of CCUS is deemed essential for mitigating CO2 emissions from both power generation and industrial sources. The IPCC (2023) states that carbon dioxide removal, including CCS from bioenergy and direct air capture, is essential to achieve both the 1.5°C and 2°C targets. However, investment in CCS has not matched studies simulating the cost-effective pathway to the Paris Agreement target, see e.g., IEA (2018), Golombek et al. (2023). Public acceptance stands out as a primary obstacle hindering the broader adoption of CCS technologies, according to Zuch and Ladenburg (2023). Golombek et al. (2023) briefly summarize the literature, identifying key factors contributing to the limited investments in CCS deployment. These factors include uncertainties in investment costs, a shortage of professionals dedicated to research and development in CCS due to competition with oil and gas projects, legal complexities, public opposition to storage coupled with concerns about potential leakages, and flawed model predictions.

The prospectus paper attempts to comprehensively summarize and synthesize the existing literature in the field of CCUS. By the end of this paper, readers should have gained an in-depth understanding of the current landscape of CCUS technology, with a focus on the status quo in Europe. The synthesis aims to highlight key findings, trends, and challenges and provide a concise but comprehensive overview that will serve as a valuable resource for those seeking a clear and informed perspective on the current state of CCUS in the European context.

The remainder of the paper is structured as follows. Section 2 outlines the methodology and research framework. Section 3 aggregates and summarizes existing review articles. Section 4 presents the results of a bibliometric analysis. Section 5 explains CCUS from a techno-economic perspective. Section 6 reviews the socio-economic literature on CCUS. Section 7 provides a summary of the current project landscape in Europe. Section 8 concludes.

2. Methodology

This review is intended to provide a comprehensive overview of the topic of carbon capture (utilization) and storage. In particular, we provide an overview of the current assessments from a techno-economic perspective. Against this backdrop, we use a mixed-methods approach. Specifically, we aggregate and synthesize the perspectives illustrated in recently published review articles. These articles naturally differ in scope, foci, and contribution, and we illustrate these differences in detail.

To obtain a more objective overview of the incumbent literature on CCUS, we also conduct a bibliometric analysis following Donthu et al. (2021). The first step in conducting the bibliometric analysis was the acquisition of relevant scholarly literature from the World of Science (WoS) database using the following search string: **(AB=(Carbon Capture and Storage)) OR (AB=(Carbon Capture Utilization and Storage)) OR (AK=(CCS)) OR (AK=(CCUS))**. The search yields an extensive corpus of 12,348 documents, of which 9,117 are scientific articles and 1,034 review articles. In addition, the documents must be in English and published in journals belonging to Elsevier, Wiley, or Springer Nature. This leaves us with a final sample of 6,361 articles. We provide some descriptive statistics on this initial sample below. We also derive a subset of 304 articles from "Business and Economics," "Governmental Law," and "Social Sciences - Other Topics." We exported the search results as plain text files, which we then saved for further analysis. We use the software package Bibliometrix to process and analyze the data in R (Aria & Cuccurullo, 2017).

3. Existing Reviews

As a starting point, we briefly examine the existing review articles and summarize their findings. A brief overview of the articles' scope and individual contribution is provided in Table 1.

Hong (2022) offers a broad techno-economic review of the current global status of CCUS, providing a technological description of incumbent and innovative technologies of CCUS as well as a brief economic appraisal. The study focuses on both established and innovative technologies and provides a comprehensive overview of their advantages and disadvantages. The study takes an in-depth look at the capture processes, including the techno-economic aspects and the state of the art. In addition, the analysis covers the areas of transport, utilization, and storage, thus offering a broad but well-founded perspective on the current state of CCUS. Ma et al. (2022) highlight the central role of advanced countries in promoting technological innovation, cost reduction, and risk mitigation efforts. Their review covers the historical development and key projects of CCUS and provides insights into the breakthroughs that have shaped its development. The authors discuss classification systems and emphasize the importance of large scientific and technological infrastructures in advanced countries. They address critical issues of CO2 capture, such as the cost associated with low-concentration emissions and considerations of space, water, and other resources. In examining geological storage, the authors highlight that 90% of storage to date is in petroleum reservoirs, but deep saline aquifers hold significant untapped potential. Yadav and Mondal (2022) specifically discuss the progress and various configurations of CCS based on oxyfuel combustion, highlighting its cost-effective CO2 capture, major components, energy penalties, auxiliary energy consumption, CO2 purity, and capture efficiency, as well as addressing advanced oxyfuel configurations and techno-economic and thermodynamic aspects.

Zuch and Ladenburg (2023) have authored a review article on the topic of acceptance of CCS technology from a socio-technological perspective. Specifically, they synthesize findings from 23 studies on the acceptance of CCUS and explore the impact of information effects. The analysis reveals that providing detailed information on climate change positively influences CCS acceptance, while the effects of risk information remain ambiguous. Moreover, familiarity with existing project details emerges as a factor that enhances acceptance. The limited number of randomized controlled trials (RCTs) poses challenges in making definitive policy recommendations, emphasizing the need for further empirical research to inform strategies for promoting CCS acceptance effectively.

Likewise, McLaughlin et al. (2023) also examine the literature on carbon capture, utilization, and storage (CCUS) through a socio-technological lens, exploring new technologies for carbon capture in combustion processes, new innovations such as direct capture from air, and evolving storage systems. Despite technological progress, the deployment and diffusion of CCUS are hampered by economic and socio-technical barriers, including issues of international cooperation and societal perceptions. The authors propose policy solutions, such as grants, subsidies, carbon pricing, and demand-side measures, and highlight China and

Europe as potential models for policy implementation. By incorporating a socio-technical perspective, the report emphasizes the interplay between technical, economic, social, and environmental factors in the development of CCUS and challenges the notion of a simple separation between technology and policy or scaling and uptake. The findings argue in favor of an interdisciplinary research approach to comprehensively understand and address the complex dynamics of CCUS in the broader context of the energy transition.

Dütschke and Duscha (2022), in a proceedings article, assess the societal preparedness for Carbon Capture, Utilization, and Storage (CCUS) in specific European countries. They focused on a combined analysis of political and societal perspectives. The selected countries for analysis were the Netherlands and the U.K. as frontrunners, along with Poland, Germany, Spain, and France, which are highly industrialized and among the highest CO2 emitters in Europe. The analysis included the examination of ongoing activities, the overarching political framework, and climate goals in these countries. Additionally, the authors investigated specific regulations and goals for CCUS, existing funding instruments, and the state of knowledge regarding public acceptance of CCUS in each country. The findings suggested that none of the countries were on a straightforward path toward implementing CCUS, and questions about social acceptance were particularly open in most cases.

There are some additional reviews that are not included in our overview but should be mentioned for the sake of completeness. Bahman et al. (2023) review the current strand of literature on CCUS globally and across different industries. Osman et al. (2020) provide a comprehensive literature review of carbon capture and storage technologies from a chemical perspective. Further well-established literature reviews on CCUS are Leung et al. (2014), Boot-Handford et al. (2014), Bui et al. (2018), Haszeldine et al. (2018), and Wennersten et al. (2015).

Table 1: This table summarizes the scope and contribution of the most recent review articles on Carbon Capture, Utilization, and Storage.

Article	**Scope**	**Contribution**
Hong (2022)	• „Current" status of CCUS-Technology and Networks (as of September, 2021) • Extensive overview of technologies (advantages/disadvantages) • Capture, separation in great detail (techno-economic aspects and technology-readiness), transportation, utilization, and storage narratively reviewed	• Broad overview, rich in technological details • Covers economic aspects and technological readiness
Ma et al. (2022)	• History and development of CCUS; Historical key projects and breakthroughs • Classification schemes of CCUS (specifically capture and storage) • Key issues of CO2 capture: cost of capture, especially in low concentration emissions, space, water and resources, and other flue gas components. • Key issues of geological storage: ensuring and examining risk; 90% of storage to date is in oil reservoirs, but deep saline aquifers have the largest potential.	• Project-centered evaluation offers detailed insights into how CCUS and projects have developed. • Outlines past, present, and future challenges of CCUS
Yadav & Mondal (2023)	• Detailing and reviewing CCUS technology, specifically focusing on oxyfuel combustion	• In-depth analysis of oxyfuel combustion, especially detailing construction and components of plants • Reviewing current literature on energy penalty (10-12%)

Zuch & Ladenburg (2023)	• Review of 23 studies on CCS acceptance and information effects. • The theoretical model highlights prior knowledge, learning, and varied information stimuli.	• Climate change details increase acceptance, risk info effects are ambiguous, and existing project details boost acceptance. Limited RCTs make policy recommendations challenging.
McLaughlin et al. (2023)	• Examines the current status of CCUS (carbon capture, utilization, and storage) technologies and their deployment on a global scale. • Explores the technical aspects, including various carbon capture processes and storage systems, as well as utilization pathways for captured carbon. • Considers the economic and socio-technical barriers, such as international cooperation, infrastructure limitations, and social perceptions, that constrain the widespread adoption of CCUS.	• Identifies policy-driven solutions to economic and socio-technical barriers, including grants, subsidies, carbon pricing, demand-side measures, and risk mitigation. • Highlights national frameworks in China and Europe as potential models for implementing CCUS policies while acknowledging challenges related to geopolitics and trade. • Advocates for a socio-technical perspective, emphasizing the interconnectedness of technical, economic, social, and environmental factors in the evolution of CCUS, challenging the need for simplified divides between technology and policy or scaling and acceptance.
Tcvetkov et al. (2019)	• Systematic literature review of 135 articles on public perception of CCS • 9 key aspects of public perception	• Provides an overview of the societal implications and challenges of CCS • Argues that most of the literature focuses on storage, while there is a lack of research on transportation and capture • Studies focus mostly on general public perception, neglecting areas with active projects

4. Bibliometric Analysis

This section provides the results of the bibliometric analysis. Table 2 summarizes the most productive journals. Specifically, we include journals with more than 25 publications on the topic. The leading journal was the *International Journal of Greenhouse Gas Control* (n = 902), a peer-reviewed journal focusing primarily on CCUS. *Applied Energy* and *Energy* follow at some distance (n = 319 and n = 237 resp.) The latter journal also exhibits the third-highest SJR value among the listed journals.

In terms of country productivity, as shown in Table 3, China is the most productive country with 1,234 published articles, followed by the U.S. (n = 835) and the U.K. (n = 677). The first country to be part of the European Union is Germany, with 343 identified records. However, considering European countries compared to China and the U.S., European countries are far more productive in aggregate, as they contribute a total number of 1609 articles (based on the table exhibited below). This is also reflected in a higher level of multi-country productivity (MCP); i,e., the highest values of the MCP-Ratio index were found for the Netherlands (MCPR = 0.393) and Spain (MCPR = 0.382) followed by Italy (MCPR 0.354), Germany (MCPR = 0.332) and the U.K. (MCPR = 0.321).

The aim of performance analysis is to evaluate the research output and impact of individual authors, journals, or institutions based on various bibliometric indicators. The great advantage of the bibliometric analysis, however, is the possibility of carrying out a co-citation analysis. Instead of quantitatively evaluating the output of each country, journal, or author, co-citation analysis is focused on exploring the relationships between documents (e.g., articles, journals) based on the co-citation patterns of references. Figure 1 shows the network of co-citations based on the respective journals. It is interesting to note that the flagships from Nature, namely Nature and Science, appear here in particular. Especially since elite journals generate a lower output in quantitative terms, it is important to recognize that the articles published there seem to play an important role in the overall scientific discourse. Figure 2 shows the country network and confirms the previously tabulated results. Additionally, Figure 3 shows the most productive authors in the field over time.

Table 2. This table presents a compilation of the most significant journals based on the number of publications related to Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS), where N denotes the number of publications exceeding 25. Two journals with missing SJR (Scientific Journal Rankings) scores have been omitted, and the entry for Computer Graphics Forum has been manually excluded. The data is derived from a web of science (WoS), providing insights into the scholarly landscape of CCS and CCUS research.

Journal	Number of Pubs	SJR
International Journal of Greenhouse Gas Control	902	1.067
Applied Energy	319	3.062
Energy	237	2.041
Journal of Cleaner Production	231	1.921
Energy Policy	168	2.126
Renewable and Sustainable Energy Reviews	146	3.678
Fuel	144	1.514
Energy Conversion and Management	131	2.829
Greenhouse Gases-Science and Technology	130	0.499
International Journal of Hydrogen Energy	97	1.201
Chemical Engineering Journal	93	2.419
Journal of CO2 Utilization	81	1.392
Science of the Total Environment	61	1.806
Climatic Change	57	1.357
Energy Economics	50	2.549
Environmental Science and Pollution Research	49	0.831
Applied Thermal Engineering	42	1.584
Journal of Natural Gas Science and Engineering	39	1.091
Energy Research and Social Science	37	2.551
Journal of Environmental Chemical Engineering	36	1.042
Journal of Environmental Management	36	1.481
Journal of Petroleum Science and Engineering	35	1.062
Computers and Chemical Engineering	34	1.017
Energy Reports	34	0.894
Clean Technologies and Environmental Policy	33	0.756
Applied Geochemistry	32	0.829
International Journal of Energy Research	32	0.811
Mitigation and Adaptation Strategies for Global Change	32	0.810
Separation and Purification Technology	32	1.197
Renewable Energy	29	1.877
Fluid Phase Equilibria	28	0.606
Resources Conservation and Recycling	28	2.589
Chemical Engineering Science	27	0.870
Global Change Biology	27	3.685
Process Safety and Environmental Protection	27	1.256

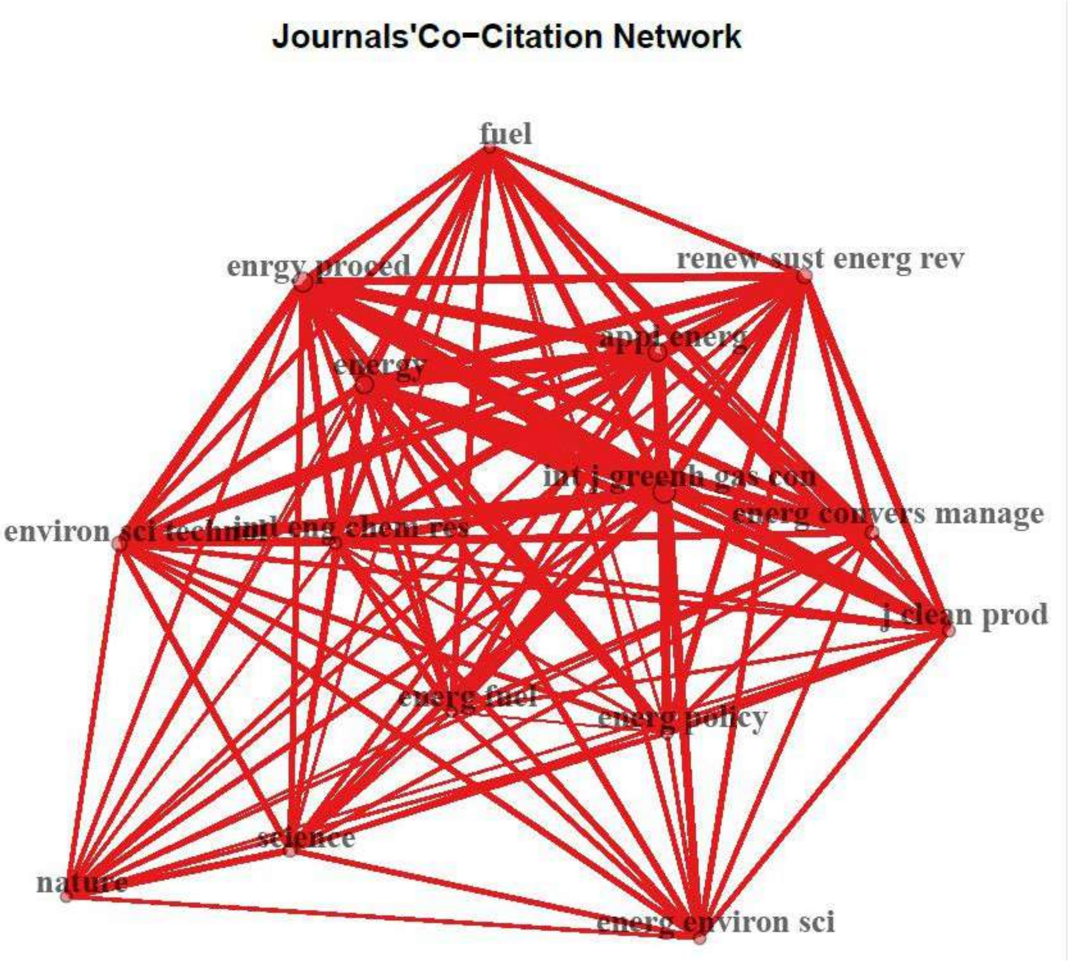

Figure 1: Nodes represent journals, and edges denote co-citation relationships between journals. The thickness of edges reflects the frequency of co-citation, with thicker lines indicating stronger connections. Node size corresponds to the impact or importance of each journal, and node transparency represents the intensity of co-citation.

Table 3: This table displays the statistical breakdown for the number of articles, Fractional Count (Frac), Share of Collaborative Publications (SCP), Main Collaboration Partner (MCP), and the corresponding MCP Ratio in the context of research output by country. The metrics offer a comprehensive overview of collaborative patterns and contributions, providing valuable insights into the global landscape of scholarly publications.

Country	**Articles**	**Freq**	**SCP**	**MCP**	**MCP_Ratio**
China	1234	0.1966	899	335	0.271
USA	835	0.1330	642	193	0.231
United Kingdom	677	0.1078	460	217	0.321
Germany	343	0.0546	229	114	0.332
Australia	258	0.0411	181	77	0.298
Korea	228	0.0363	167	61	0.268
Spain	204	0.0325	126	78	0.382
Canada	196	0.0312	136	60	0.306
Netherlands	196	0.0312	119	77	0.393
Italy	189	0.0301	122	67	0.354

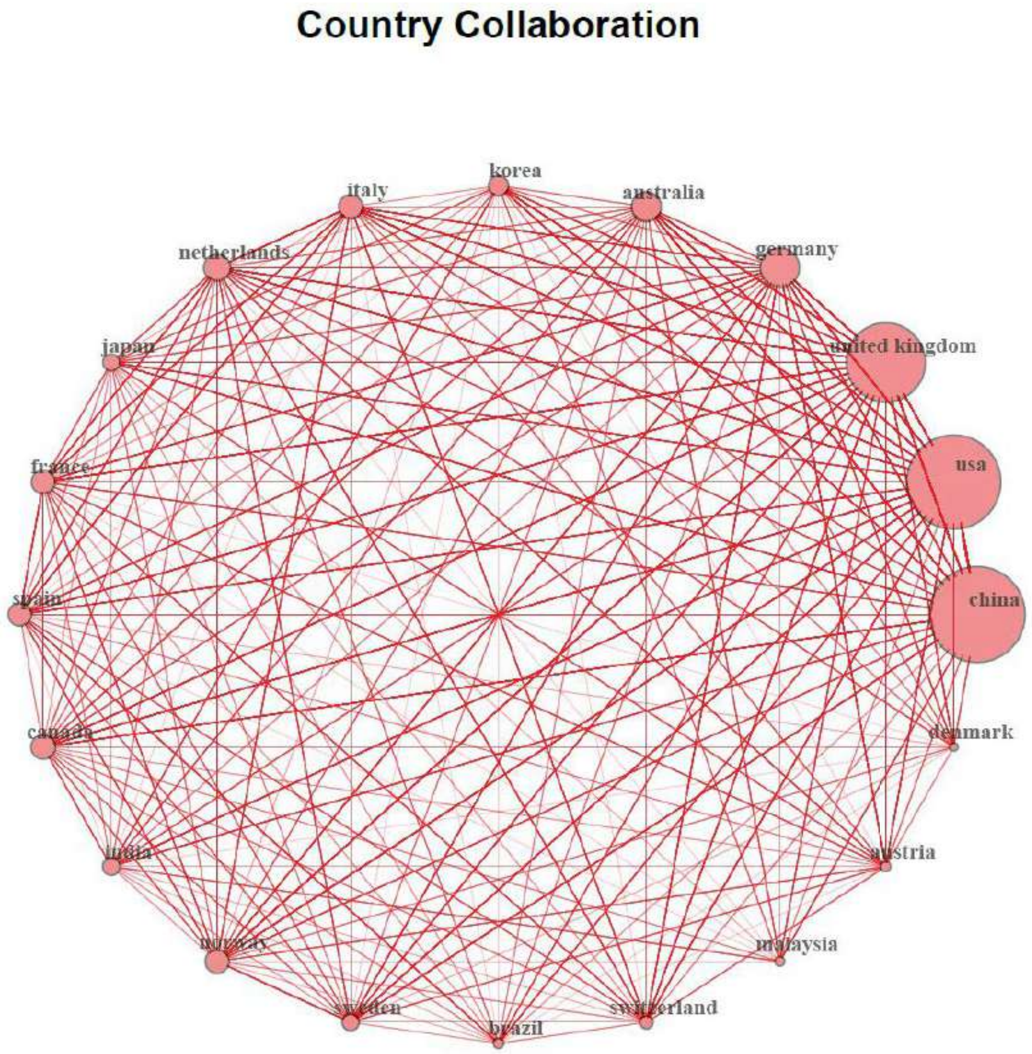

Figure 2: Country Collaboration Network of the 20 Most Productive Countries. The edges represent collaborations between countries, with the thickness indicating the strength of collaboration. Node size corresponds to the productivity of each country, and node transparency reflects the intensity of collaboration. Larger nodes represent more productive countries, and more transparent nodes indicate higher collaboration intensity.

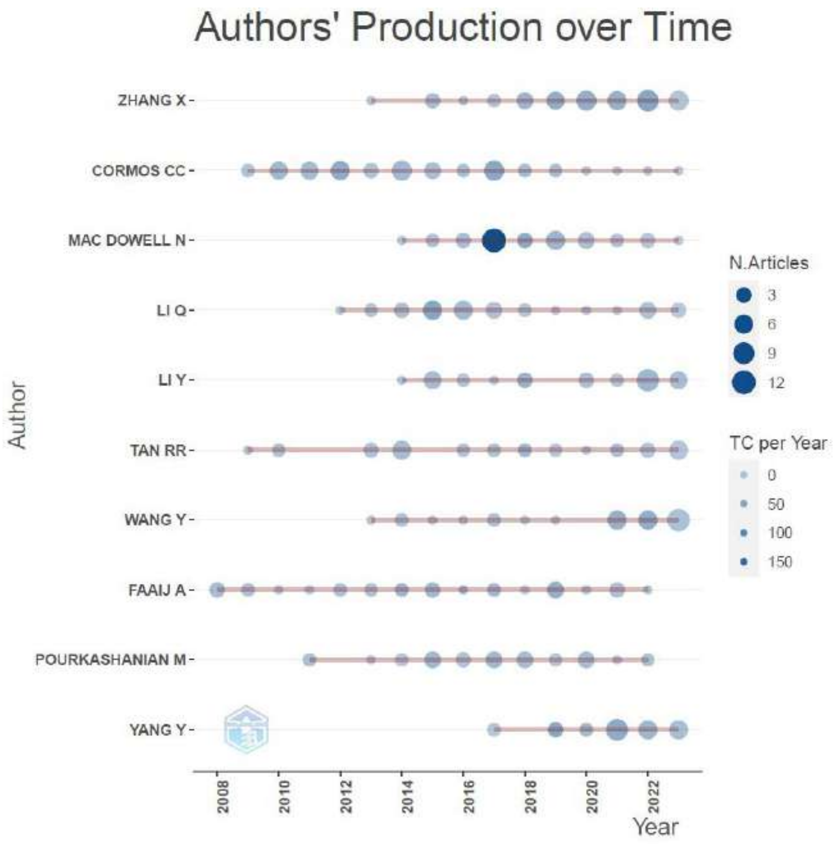

Figure 3: This figure visually shows the temporal development of the productivity of the ten most productive authors in our sample. The diagram illustrates the number of articles (N) as the size of the nodes and the color gradient of the corresponding node for the total number of citations (T.C.), thus providing a dynamic representation of the authors' scientific output and the impact of their contributions over time.

From the quantitative macro perspective, we now turn to the individual study level. We provide initial insights on the content of the published papers from the keyword analysis in Table 4. Analyzing the author's keywords does not provide a clear picture, as it largely reveals alternative terminology and acronyms. The keywords-plus analysis is, therefore, more enlightening: The majority of publications deal with the topics of "capture" and "sequestration," which together are well ahead of the topic of "storage." The results thus clearly reflect the scope of the previously analyzed review articles, which predominantly focus on the various technologies for capturing CO2 and usually address storage for the sake of completeness.

Table 5 exhibits the ten most influential documents published in relation to CCS or CCUS. The first two papers, Leung et al. (2014) and Figueroa et al. (2008), provide an extensive review of carbon capture and storage technologies at that time. The following articles are rather technical, i.e., J.R. Li et al. (2011) investigated the use of metal-organic frameworks for CO2 adsorption and separation, focusing on both experimental results and molecular simulations to assess their potential. The youngest article in the list is Scrivener et al. (2018). The main conclusions from the study suggest that substantial reductions in global CO2 emissions related to cement and concrete production can be achieved over the next 20-30 years through increased use of low-CO2 supplements (SCMs) as partial replacements for Portland cement clinker, more efficient use of Portland cement clinker in mortars and concretes, and the potential exploration of alternative cement technologies, potentially mitigating the need for costly investment in carbon capture and storage (CCS) over the next 20–30 years.

Table 4: This table presents the most cited author keywords and keywords plus, providing a concise snapshot of pivotal terms that have garnered significant attention in the research domain. The inclusion of both author keywords and keywords plus offers insights into the breadth and depth of scholarly discussions, outlining specific areas of research focus and interest within the field.

Author Keywords	Articles	Keywords-Plus	Articles
CCS	892	Storage	752
Carbon capture and storage	518	CO2 capture	577
Carbon capture	283	Carbon-dioxide	483
CO2 capture	276	Capture	443
Climate change	217	Sequestration	419
Carbon capture and storage (CCS)	213	Energy	408
Carbon dioxide	212	Performance	387
CCUS	211	Carbon capture	382
CO2	177	CO2	363
CCS concepts	155	Model	280

Table 5: This table displays the top ten most cited articles, including Paper title, DOI, Total Citations (T.C.), Citations per Year (T.C./Year), and Total Number of Citations (NTC). The Normalized Total Citations (NTC) are calculated by dividing the total number of citations of an article by the average number of citations of all articles published in the same year; this measure takes into account the differences in citation practice between disciplines.

Paper	DOI	TC	T.C. / Year	NTC
Leung DYC, 2014, Renew Sust Energ Rev	10.1016/j.rser.2014.07.093	1848	184.8	38.14
Figueroa JD, 2008, Int J Greenh Gas Con	10.1016/S1750-5836(07)00094-1	1763	110.2	12.23
Li J.R., 2011, Coordin Chem Rev	10.1016/j.ccr.2011.02.012	1672	128.6	20.45
Li C.W., 2014, Nature	10.1038/nature13249	1184	118.4	24.44
Thomson AM, 2011, Climatic Change	10.1007/s10584-011-0151-4	1097	84.4	13.41

Scrivener KL, 2018, Cement Concrete Res	10.1016/j.cemconres.2018.03.015	965	160.8	25.16
Wang M, 2011, Chem Eng Res Des	10.1016/j.cherd.2010.11.005	949	73.0	11.60
Cuéllar-Franca RM, 2015, J CO2 Util	10.1016/j.jcou.2014.12.001	901	100.1	19.46
Bondeau A, 2007, Global Change Biol	10.1111/j.1365-2486.2006.01305.x	864	50.8	8.57
Blamey J, 2010, Prog Energ Combust	10.1016/j.pecs.2009.10.001	783	55.9	10.69

Eventually, in Figure 4, we illustrate the research clusters in a conceptual structure map. The results show one research cluster (purple) which is analyzing the sequestration of CO2, especially using metal-organic frame frameworks, materials that are widely used in CO2 catalytic reduction because of their porous structures, large specific surface areas, regular pore morphologies, and flexible tunability in terms of components and structure (Zhang et al., 2023). The second research cluster (yellow) investigates the topic of sequestration and separation of CO2 from flue gasses. The third cluster (red) is focused on the chemical compositions and characteristics of the separated gases, along with an exploration of solubility, kinetics, and other chemo-physical characteristics. The fourth cluster is devoted to storage and the injection of CO2 into reservoirs. Permeability refers to the ability of a substance or material to allow the passage or flow of another substance through it, describing the property of a material to permit the movement of fluids, gases, or other substances through its structure. The fifth and largest cluster covers techno-economic modeling, scenario analyses, and policy themes.

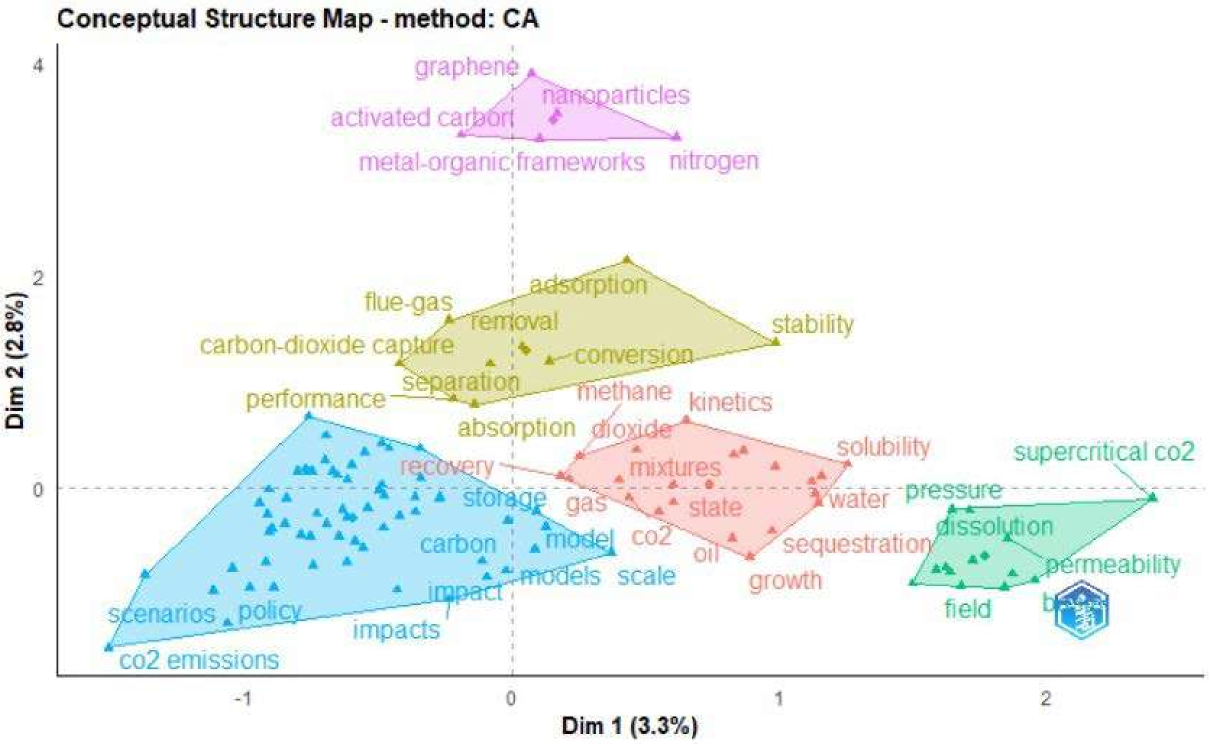

Figure 4: Conceptual Structure Map illustrating the relationships among various elements, generated using the Correspondence Analysis (C.A.) method. The map visually represents the conceptual structure within the dataset, offering insights into associations or clusters among different research areas.

„CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources provided geological storage is available. When CO2 is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO2 capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological storage capacity is estimated to be on the order of 1000 GtCO2, which is more than the CO2 storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO2 can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C to 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers.“ (IPCC, 2023, p. 86)

5. Techno-Economic Summary

After providing an overview of current surveys in this domain and an objective and predominantly quantitative summary of established research, we will explain the concept of CCUS in the following chapter.

5.1 General Introduction

The consumption of fossil resources such as coal, oil, and gas is the main source of anthropogenic carbon dioxide emissions, thus contributing substantially to human-induced climate change (Cook et al., 2013; Haustein et al., 2017). Accordingly, mitigation of global warming and climate change through reduced atmospheric CO_2 concentration is primarily based on three concepts: (i) reducing the consumption of fossil resources, thereby eliminating the generation of carbon emissions, (ii) preventing generated emissions from entering the atmosphere, thereby allowing the continued depletion of fossil fuels with minimal impact on climate, and (iii) removing residual carbon dioxide emissions from the atmosphere ex-post to counterbalance continued emissions from the energy sector (IPCC, 2021).

While the former is inevitably related to the extension of alternative energy sources such as renewable energies and nuclear power, the latter is both concerned with mitigating the climate impacts of the continued use of fossil fuels. Since fossil fuels are a finite resource (at our current rate of consumption), CCUS is considered a complementary element in the energy transition in the short and medium term rather than a substitute for renewable energies (Haszeldine et al., 2018)[1]. Carbon Capture, Utilization, and Storage are often used synonymously with carbon (capture and) sequestration, broadly encompassing the technologies used to remove carbon dioxide from the atmosphere ex-post. However, in scientific literature, the established terminology for the latter has become Carbon Dioxide Removal (CDR) (e.g., Hong, 2022). While there is inevitable overlap, CCUS technologies provide only the storage and transport components for CDR concepts, which are otherwise distinct concepts. This review, however, focuses primarily on CCUS. Note that the term CCUS encompasses utilization approaches compared to CCS, while they are otherwise identical. Figure 5 provides a schematic representation of the life cycle chain of fossil fuel utilization. Fossil fuels are extracted and burnt in power plants to generate electrical energy. The resulting CO2 is sequestered and captured in the power plants, transported via pipelines, and injected into geological reservoirs under the seabed.

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[1] Short and Medium Term in a sense that is unexpected to contribute much to archiving targets by 2040 yet will eventually make the difference between 2° and 4.5° by 2100.

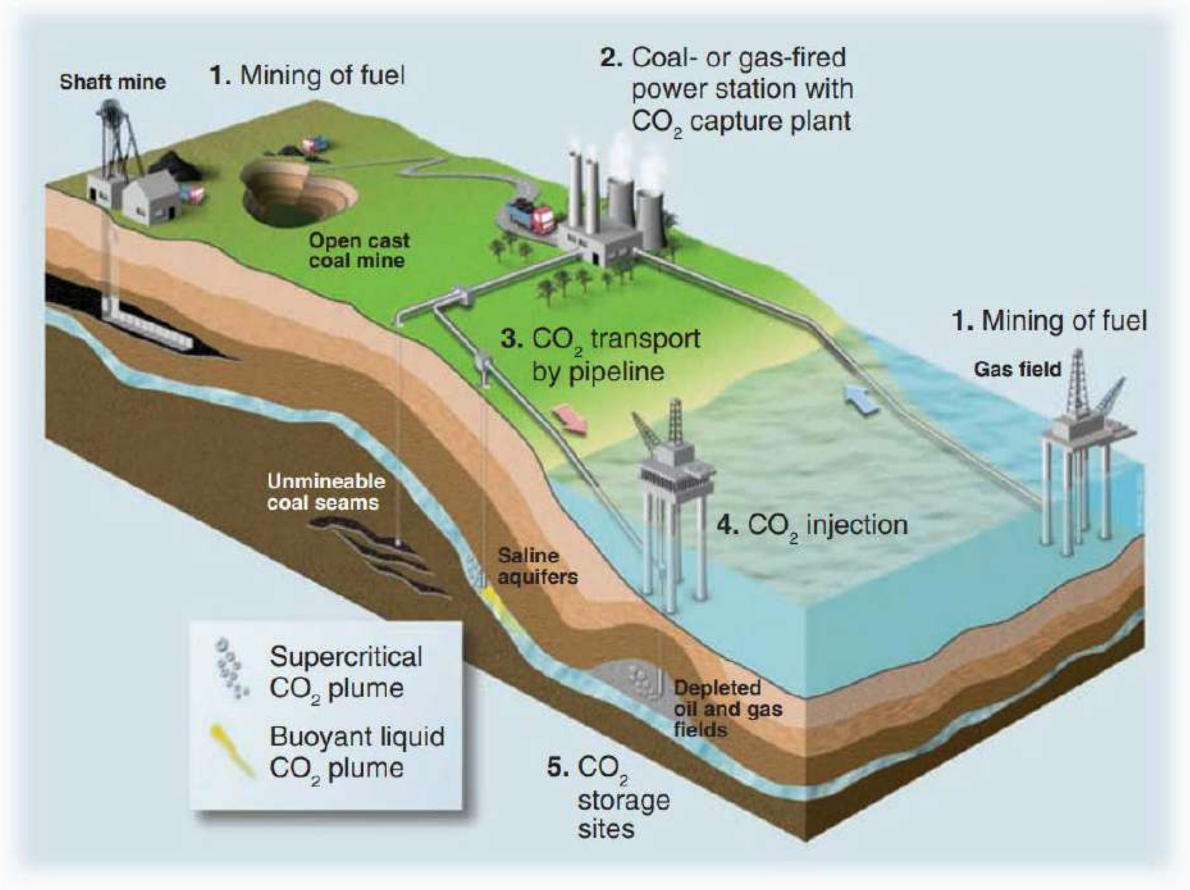

Figure 5: Schematic representation of the life cycle chain of fossil fuel utilization. Source: Haszeldine (2009).

Figure 6, adapted from McLaughlin et al. (2023), illustrates the elements of the general socio-technical system for CCUS. The linkages shown in the figure illustrate the interconnectedness of these elements while acknowledging that the actual relationships are likely to be more complex than is presented for the sake of simplicity. The diagram includes various components, possibly including technological processes, economic factors, policy elements, and environmental aspects, which collectively contribute to the socio-technical system for CCUS.

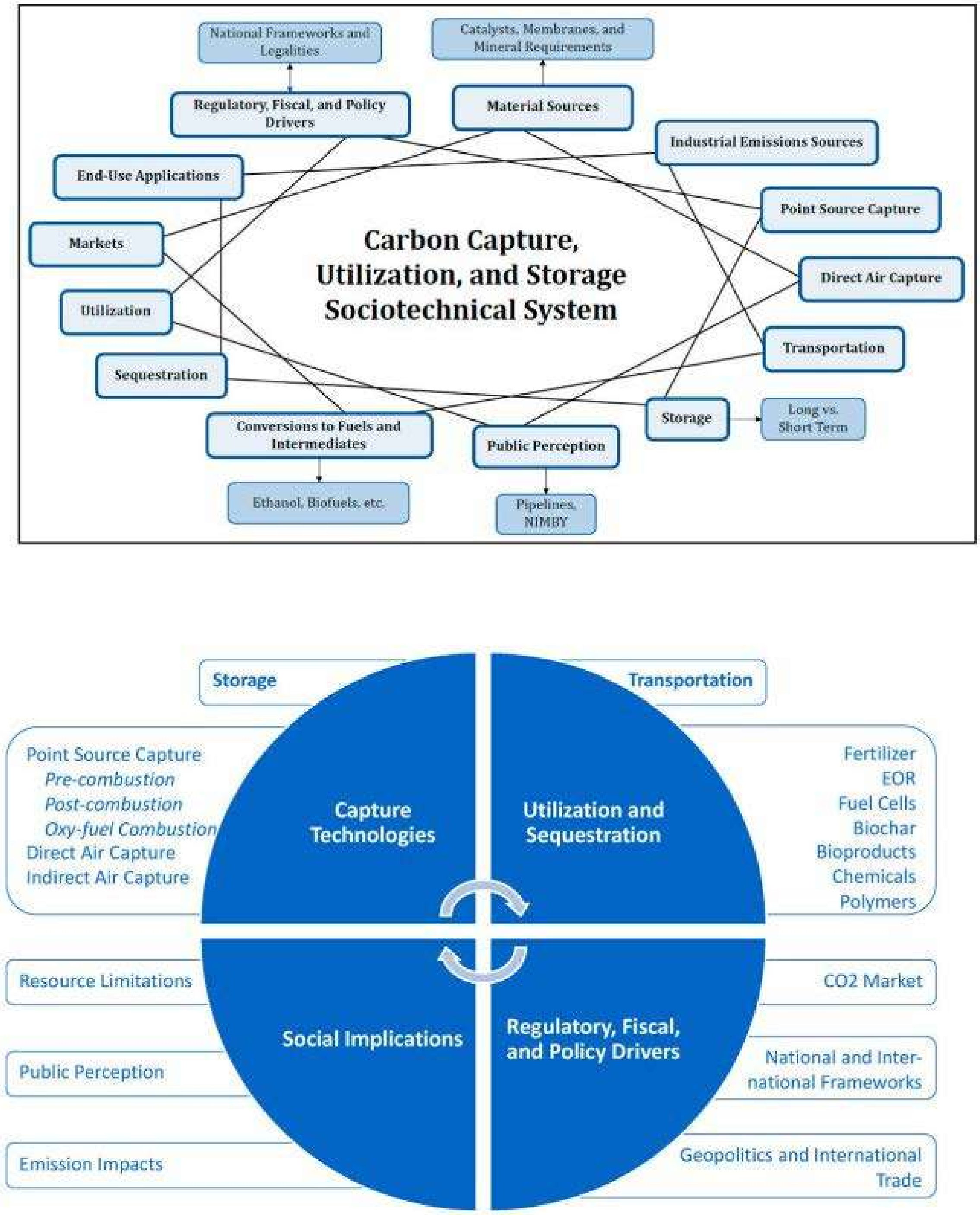

Figure 6: Elements of the socio-technical system for CCUS (connections are meant to illustrate the interconnected nature of these systems and are likely more complex than represented). EOR = Enhanced Oil Recovery. Source: McLaughlin et al. (2023)

Starting with the main challenge in CCUS, capturing CO2 from flue gas is the step that consumes the most energy and generates the highest costs (Haszeldine, 2009). According to House et al. (2009), as cited by Haszeldine (2009), early separation technologies were predicted to consume 25 to 40% of the fuel energy of a power plant and be responsible for 70% or more of the additional costs after scale-up. Such numbers are also reported in more recent analyses, with Yadav and Mondal (2022) reporting that capturing CO2 is responsible for 75% of the total CCS cost. Haszeldine (2009) predicted that the developments currently underway should result in tangible improvements toward a 10 to 20% energy penalty. Yadav and Mondal (2022) note that energy penalty is still a major drawback of CCS technologies and that reduction in plant efficiency is in the range of 7 to 15% (in the case of oxyfuel combustion).

It is generally accepted that transportation is not a major challenge to the advancement of CCUS technology (Haszeldine, 2009). Depending on the location of the plant and the affiliated storage facility, conventional pipelines can be used to transport carbon dioxide (Haszeldine, 2009), which is considered a mature technology (Hong, 2022). Other approaches may include alternative transportation, e.g., by ship, rail, or road, which may result in additional costs and emissions (McLaughlin et al., 2023). Utilization of carbon dioxide encompasses algae cultivation for biodiesel production and C02-derived chemicals (technologies at the lab-scale and pilot plant stage, respectively) and CO2-derived methanol and urea yield boosting (both at the commercial scale), *inter alia* (Hong, 2022).

Figure 7 presents a depiction of the present development trajectory of various CCUS technologies and components with regard to their Technological Readiness Level (TRL). The TRL framework, consisting of research (TRL 1 to 3), development (TRL 4 to 6), and demonstration (TRL 7 to 9) stages, provides a comprehensive lens through which to assess the current state of advancement in CCUS. This nuanced analysis of technological progress not only elucidates the evolving landscape of these technologies but also establishes a crucial foundation for strategic decision-making. The delineation into research, development, and demonstration stages offers a nuanced understanding of the maturity and applicability of

CCUS innovations, thereby informing research agendas, guiding investment strategies, and shaping policy initiatives for sustainable carbon management solutions.

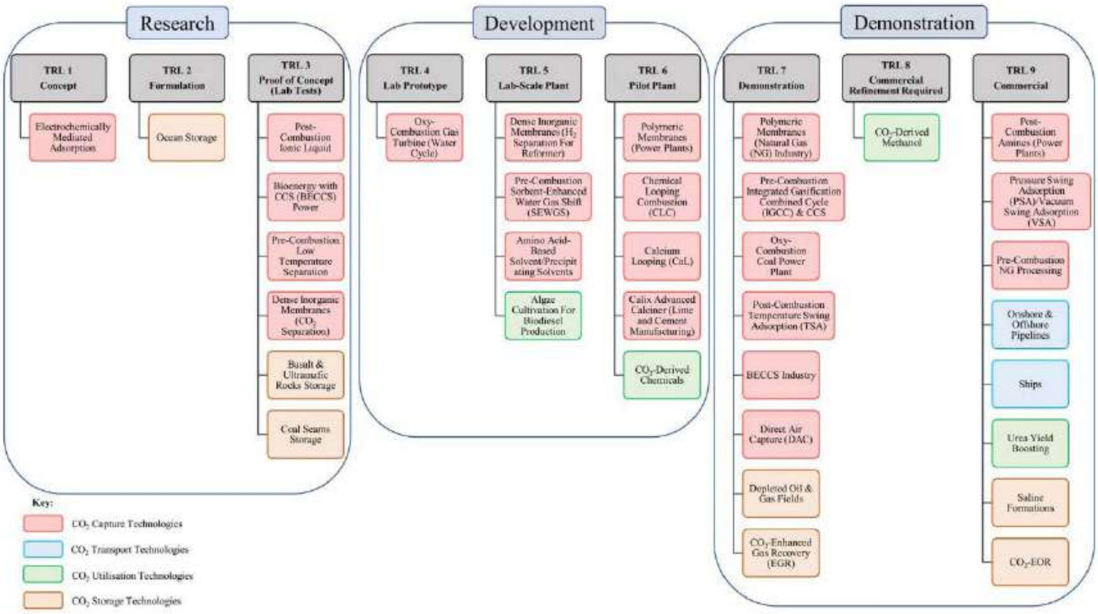

Figure 7: Technology readiness level (TRL) of some CCUS technologies. Source: Hong, 2022; adapted from Bui et al. (2018) and Kearns et al. (2021).

The figure clearly reveals where the current bottleneck remains, particularly in the area of storage. The process of injecting carbon dioxide (CO2) for storage into the minuscule pore spaces of sedimentary rocks is rooted in the extensive industrial experience gained through the injection of CO2 into hydrocarbon fields for enhanced oil recovery (EOR) purposes, a practice that has been in operation commercially since the 1970s (Haszeldine, 2009). In addition, enhanced gas recovery and general storage in depleted oil and gas fields are already in the demonstration phase. Another commercially available method is storage in saline formations, i.e., underground geological structures that contain salt water. At depths where pressure is sufficient to maintain CO2 in a dense, liquid state (approximately 74 bar), saline formations must have sufficient porosity and permeability for CO2 injection and storage. An effective cap rock, an impermeable layer, is essential to prevent the upward migration of CO2. The suitability of saline formations for CCUS depends on factors such as depth, storage capacity, and the ability to monitor and verify the safe containment of CO2. Other storage options, especially ocean storage, are still in the early stages of development.

5.2 Capture and Sequestration Technologies

The previous chapter provided a general introduction to CCUS, a suite of technologies and processes developed to counter climate change by reducing the release of carbon dioxide into the atmosphere directly at the primary sources, e.g., fossil fuel-fired power plants and industrial facilities (Haszeldine, 2009). This chapter examines the technologies for capturing and sequestering CO2 in greater detail.

There are several different technologies to capture CO2, which are post-combustion, pre-combustion, and oxyfuel combustion (see, e.g., Hong, 2022; Bahman et al., 2023; Haszeldine, 2009; Yadav and Mondal, 2022). Hong (2022) also lists industrial separation, chemical looping combustion (CLC), and CDR as distinct approaches. The former is fundamentally similar to the three aforementioned approaches but is specifically tailored to the needs of industries, e.g., in the production of aluminum. Chemical looping combustion is an emerging technology that is attractive in terms of cost, yet substantially more complex and not yet commercially applicable (Hong, 2022). Similar to the majority of studies reviewed, we will focus on post-combustion, pre-combustion, and oxyfuel combustion in the remainder of the study.

In pre-combustion capture, carbon dioxide (CO2) is captured before the combustion process. This involves the gasification of fossil fuels to produce syngas, which are then converted into CO2 and hydrogen through a water shift reaction. This allows for the easy separation of CO2. In post-combustion capture, CO2 is captured from the exhaust flue gas after combustion using chemical solvents. Oxyfuel combustion involves using pure oxygen for combustion, and some of the flue gas is recycled to lower the flame temperature, referred to as recycled flue gas (RFG). The resulting flue gas primarily contains CO2 and water vapor, making it relatively easy to separate the CO2. We provide a layout of all three technologies in Figure 8 (adapted from Yadav and Mondal, 2022) and a comprehensive overview in Table 6 (adapted from Hong (2022) and extended).

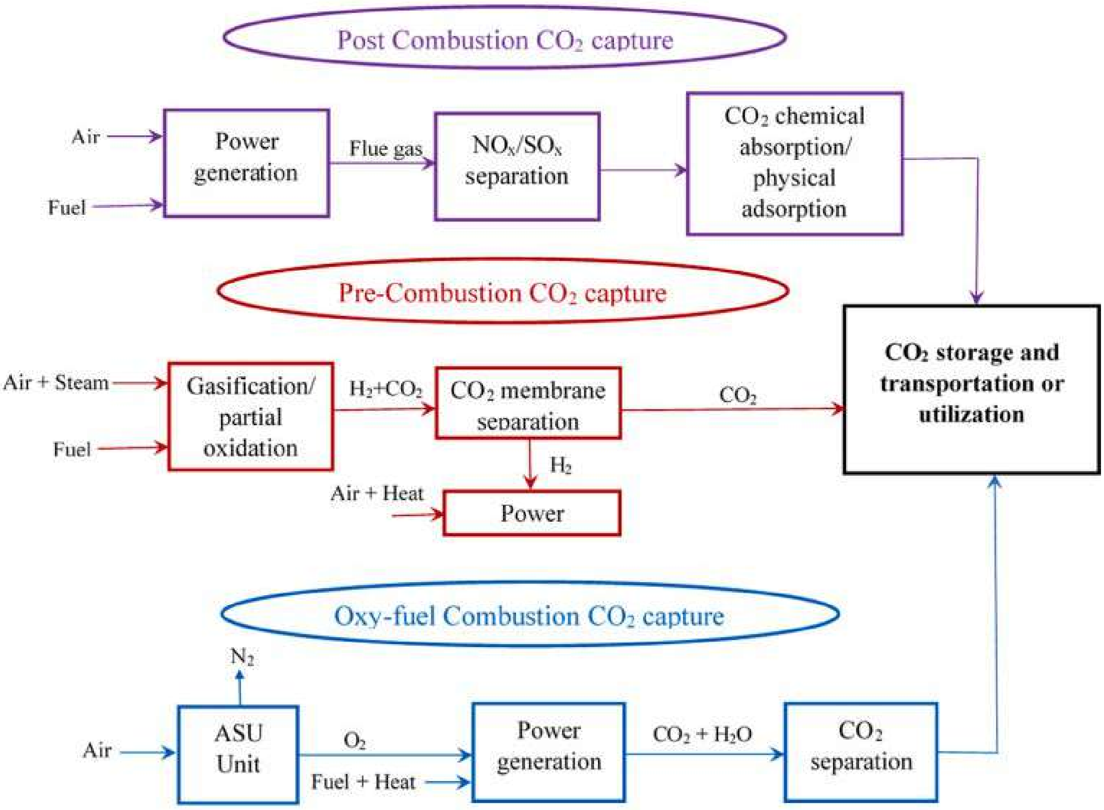

Figure 8: Schematic flow diagram of various CO2 capture technologies (Source: Yadav and Mondal, 2022; modified from Spigarelli and Kawatra (2013) and Valluri et al. (2022).

Table 6: Overview of carbon capture technologies based on Hong (2022), whose overview has been adapted and extended. For a more comprehensive overview on technical details, we refer the interested reader to Hong (2022

	Advantages	Disadvantages	Use in Industry
Post-Combustion	• More mature technology compared to other alternatives • Can easily retrofit to existing plants	• Low CO2 concentration and partial pressure reduce capture efficiency • CO2 concentration needs to be increased after separating the CO2 in order to be transported and stored • High energy requirement • High capital and operating costs • Electricity costs increase twice as much for coal-fired plants as for gas-fired plants	• Cement Manufacturing • Stainless steel Factories • Gas-fired Power Plants • Coal-fired Power Plants
Pre-Combustion	• High CO2 concentration and partial pressure enhance sorption efficiency • Fully developed technology, commercially deployed in some industries • Possible for retrofit to existing plants • Cheaper solvent (Selexol, Rectisol) when using physical absorption • Allows the use of coal with lower emissions of air pollutants	• Temperature (associated with heat transfer) and efficiency losses (7-8%) (associated with H2-rich gas turbine fuel) • High energy requirement for sorbent regeneration • High capital and operating costs for current sorption systems • Mainly applicable to power plants with an Integrated Gasification Combined Cycle (IGCC)	• Hydrogen production • Chemical commodities production • Petroleum industry
Oxyfuel Combustion	• Very high CO2 concentration enhances absorption efficiency • Mature air separation technologies available • Possibility of compact boiler and other equipment with reduced volume of flue gas to be treated	• High-efficiency drop • Costly and energy-intensive oxygen separation • May have corrosion problems (high SO2 concentration) • Retrofit is often unattractive due to significant plant changes needed	• Glass • Aluminium • Cement • Steel • Incineration

6. Socio-Economic Review

In this section we narrow in on the economic literature of CCUS technologies. Exploring the economic literature on CCUS technologies is critical for sustainable policy-making, guiding investment and fostering innovation to combat climate change, as it provides insights into the financial viability, cost-effectiveness and economic impact of widespread adoption of CCUS. To this end, this, we first report the results of the bibliometric analysis drawing from the subsample of 304 articles published in the fields of "Business and Economics," "Governmental Law," and "Social Sciences - Other Topics." The results are presented in a similar fashion compared to the first analysis to maintain comparability.

Table 7 exhibits the most significant journals in the field. *Energy Policy* clearly dominates with 168 publications, followed by Energy Economics at 50 publications. The results indicate that the discussion of CCUS is primarily policy-oriented, while the economic and social sciences take a back seat. In particular, we have not come across a comprehensive study focusing primarily on the economic aspects of CCUS in our analysis.

Regarding the geographical distribution of articles presented in Table 8, the results are relatively similar to the results of the first analysis. The top four most productive countries remain the same, but the order has changed. The United States dominates (n = 58), closely followed by the United Kingdom (n = 44), China (n = 32), and Germany (n = 21).

The results of the keyword analysis (in Table 9) do neither provide a clear picture nor a common theme. The most frequently occurring terms in the "Author Keywords" column include "Carbon Capture and Storage," "CCS," "Climate Change," and "Climate Policy." Similarly, in the "Keywords-Plus" column, terms such as "Storage," "CO2 Capture," and "Energy" are prevalent. More interesting and clear are the results of the co-occurrence analysis shown in Figure 9. Three distinct clusters emerge. The first cluster (green) consists of literature that addresses public perception and policy implications, i.e., the socio-economic aspects. The second and largest cluster (blue) comprises literature that models and optimizes CCS investments and their costs. The third cluster (red) is not clearly interpretable.

Table 7: This table presents a compilation of the most significant journals based on the number of publications related to Carbon Capture and Storage (CCS) and Carbon Capture, Utilization, and Storage (CCUS), where N denotes the number of publications exceeding four. The data is derived from web of science (WoS), providing insights into the scholarly landscape of CCS and CCUS research in the field of politics and economics.

Journal	Number of Pubs	SJR
Energy Policy	168	2.126
Energy Economics	50	2.549
Technological Forecasting and Social Change	17	2.336
Ecological Economics	6	1.778
European Journal of Operational Research	6	2.354
Journal of Environmental Economics and Management	5	3.476

Table 8: This table displays the statistical breakdown for the number of articles, Fractional Count (Frac), Share of Collaborative Publications (SCP), Main Collaboration Partner (MCP), and the corresponding MCP Ratio in the context of research output by country. The metrics offer a comprehensive overview of collaborative patterns and contributions, providing valuable insights into the global landscape of scholarly publications.

Country	Articles	Freq	SCP	MCP	MCP_Ratio
USA	58	0.1927	46	12	0.2069
United Kingdom	44	0.1462	36	8	0.1818
China	32	0.1063	25	7	0.2188
Germany	21	0.0698	17	4	0.1905
France	20	0.0664	11	9	0.4500
Netherlands	19	0.0631	11	8	0.4211
Australia	13	0.0432	11	2	0.1538
Norway	12	0.0399	11	1	0.0833
Japan	10	0.0332	9	1	0.1000
Austria	8	0.0266	3	5	0.6250

Table 9: This table presents the most cited author keywords and keywords plus, providing a concise snapshot of pivotal terms that have garnered significant attention in the research domain. The inclusion of both author keywords and keywords plus offers insights into the breadth and depth of scholarly discussions, outlining specific areas of research focus and interest within the field.

Author Keywords	Articles	Keywords-Plus	Articles
Carbon Capture and Storage	53	Storage	37
CCS	35	CO2 Capture	31
Climate Change	29	Energy	31
Climate Policy	23	CCS	30
Carbon Capture and Storage (CCS)	16	Emissions	27
China	15	Capture	24
Uncertainty	10	Policy	24

Carbon Capture	9	Technologies	21
Innovation	8	Cost	20
Real Options	8	Model	20

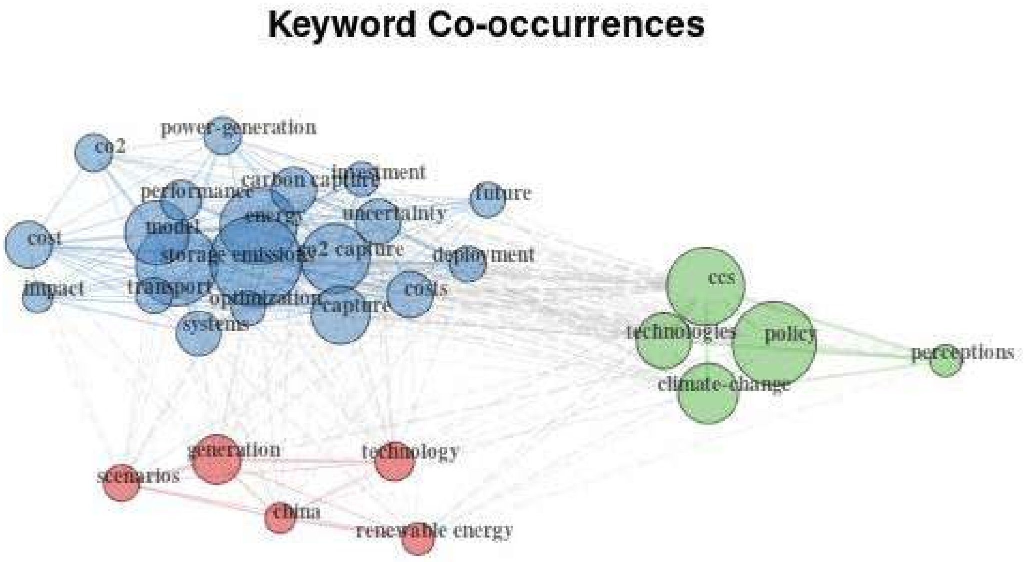

Figure 9: Keyword Co-occurrence Analysis: This figure illustrates the co-occurrence of keywords as identified by the authors. Node size corresponds to keyword frequency, while clusters of similar topics are visually grouped by color.

Turning to the individual studies (see Table 10), we find that Edwards (2008) appears to be the most influential article. However, the article is primarily concerned with the current status of key scientific and technical challenges, and the projection of hydrogen and CCUS is only mentioned as an indispensable component for sustainable hydrogen production from fossil fuels. The second article, Gibbins and Chalmers (2008), provides a brief review of the current status of CCS and barriers to commercial deployments at that time. The remaining studies also appear to be relatively diverse in terms of scope. Wei et al. (2010) review 15 studies on the job creation potential of renewable energy, energy efficiency, and low carbon sources such as carbon capture and sequestration (CCS) and nuclear power. Chen and Xu (2010) provide an overview of the development of clean coal in China and conclude that CCS technologies, *inter* *alia*, are crucial for promoting sustainable development in China as coal still accounts for a significant share of the energy mix.

Table 10: This table displays the top ten most cited articles, including Paper title, DOI, Total Citations (T.C.), Citations per Year (T.C./Year), and Total Number of Citations (NTC). The Normalized Total Citations (NTC) are calculated by dividing the total number of citations of an article by the average number of citations of all articles published in the same year; this measure takes into account the differences in citation practice between disciplines.

Paper	**DOI**	**TC**	**T.C. / Year**	**NTC**
Edwards Pp, 2008, Energ Policy	10.1016/j.enpol.2008.09.036	714	44.6	3.069
Gibbins J, 2008, Energ Policy	10.1016/j.enpol.2008.09.058	594	37.1	2.553
Wei M, 2010, Energ Policy	10.1016/j.enpol.2009.10.044	397	28.4	5.510
Chen Wy, 2010, Energ Policy	10.1016/j.enpol.2009.06.003	278	19.9	3.858
Riahi K, 2015, Technol Forecast Soc	10.1016/j.techfore.2013.09.016	240	26.7	5.120
Middleton Rs, 2009, Energ Policy	10.1016/j.enpol.2008.09.049	206	13.7	4.128
Odeh Na, 2008, Energ Policy	10.1016/j.enpol.2007.09.026	187	11.7	0.804
Huijts Nma, 2007, Energ Policy	10.1016/j.enpol.2006.12.007	185	10.9	2.207
Herzog Hj, 2011, Energ Econ	10.1016/j.eneco.2010.11.004	172	13.2	4.717
Abadie Lm, 2008, Energ Econ	10.1016/j.eneco.2008.03.008	168	10.5	0.722

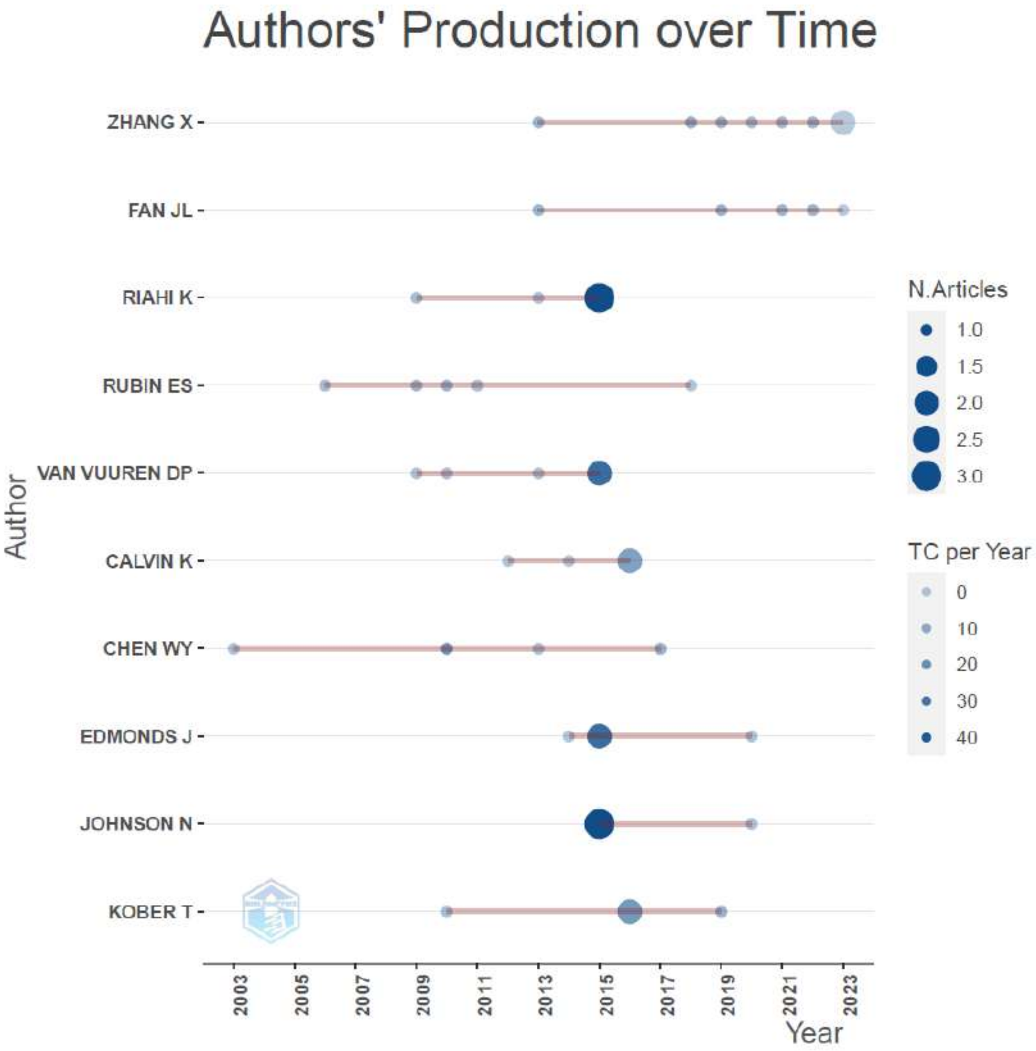

Figure 10: This figure visually shows the temporal development of the productivity of the ten most productive authors in our sample. The diagram illustrates the number of articles (N) as the size of the nodes and the color gradient of the corresponding node for the total number of citations (T.C.), thus providing a dynamic representation of the authors' scientific output and the impact of their contributions over time.

The key challenges associated with scaling up CCS initiatives are explored in Herzog et al. (2011), published in Energy Economics. These challenges encompass the imperative to decrease costs, establish essential infrastructure, mitigate subsurface uncertainty, and navigate complex legal and regulatory landscapes. The literature has thus far examined various factors contributing to the limited investments in CC(U)S (see, e.g., Golombek et al. (2023)). These factors encompass uncertainties surrounding investment costs (Lohwasser and

Madlener, 2012), a scarcity of professionals dedicated to Research and Development (R&D) due to competition with oil and gas projects (Budins et al., 2018), legal complexities (Herzog, 2011), public opposition to storage coupled with concerns about potential leakages (van der Zwaan and Gerlagh, 2016), and flawed model predictions regarding future development. The latter is attributed to either the underestimation of CCS costs or the overestimation of costs associated with alternative mitigation options (Durmaz, 2018).

So far, this article has covered three of the aspects shown in Figure 6, namely capture technologies, storage and transport, and economics. The last aspect, however, is imperative for the widespread adoption of CCUS. Kräusel and Möst (2012) note that support for CCS and thus a stable legal framework for it depends to a large extent on public attitudes towards CCS. Another key question in environmental economics is how to value natural capital in monetary terms. Researchers have developed a number of tools in the past to determine the market value of non-marketed assets, such as stated-preference techniques (see Spash & Hanley, 1995; Hanley & Czajkowski, 2019). However, in order to obtain valid and reliable results, participants must demonstrate a certain level of awareness and knowledge of the underlying concepts and issues. Accordingly, in the remainder of the chapter, we assess the current state of the literature on public perceptions of CC(U)S. Tcvetkov et al. (2019) provide a systematic review of 135 articles anaylzing the public perception of CCS. On a general level, the authors note that the existing literature is largely focused on assessing publics perceptions of the storage component compared to transport and capture. The authors further note that prior literature is predominantly assessing the general publics perceptions on CCS. However, analysing the perceptions of people in areas with existing or planned projects could provide additional insights.

We provide an overview of the societal barriers and challenges associated with CCUS in Table 11.

Table 11: This table summarizes the current stand of literature on societal challenges of CCUS

Term	Comment / Sources
Awareness	General public understanding is poor (Tcvetkov et al., 2019; Dütschke et al., 2023)
Public Perception	Largely negative (Germany and other countries) (see Dütschke et al., 2016)
Not-in-my-backyard (NIMBY)	Advancing CCS-technologies is subseptible to NIMBY; perception largely neutral before the development of concrete projects (Tcvetkov et al., 2019)
Willingness-to-pay	Lower than for renewable energies (Kräusel and Most, 2012). Literature is developing (Tcvetkov et al., 2019)

Although various aspects of CCUS have been extensively reviewed, including its global context, technological innovations and development, and societal perspectives, a noticeable gap remains: a focused review addressing the economic and policy dimensions of CCUS. Summarizing the existing reviews, it is clear that a specific examination of the economic and political aspects is required to drive the ongoing discourse on the development and deployment of CCUS.

7. Recent Development in Europe

Hong (2022) shows that as of September 2021, there have been 63 CCUS projects in Europe with a maximum capacity of 30 to 60 Mt. Considering the dynamic development of the CCS sector, especially in recent years, we draw on a dataset provided by the Global CCS Institute

(GCCSI, 2023) to provide insights into the (expected) growth of installed capacity of CCUS technologies across Europe. Note that there are only three operating CCUS systems in Europe (two in Norway and one in Iceland), while the remaining projects are still in the planning phase.

We keep the verbatim explanations short and concise to avoid elaborating on lengthy and superfluous information. Figure 11 reveals a consistent uptick in the annual number of newly announced CCUS projects throughout Europe. Prior to 2020, this number remained consistently below 10, but since 2021, it has surged, with more than 20 new projects being announced annually. A similar trend is evident in the cumulative capacity, as depicted in Figure 12. A more detailed look at the country level is provided in Figures 13 and 14. The United Kingdom, Norway, and the Netherlands clearly emerge as the frontrunners, exhibiting the highest number of announced projects and the most extensive planned capacity. This is in line with the findings of Dütschke and Duscha (2022) and also correlates with the concentrated academic research activity in these countries, which is evident in the bibliometric analysis. In Table 11 (Appendix), we provide an overview of the most recent and significant projects in Europe. The CCUS projects analysed result from a comparison of mentions in the Reuters[2] and IOGP[3] presentations of the most important CCSU projects in Europe. The resulting projects can therefore be found in all three lists and can therefore be considered relevant. For the detailed analysis, only projects that were started or completed between 2022 and 2024 were considered. The data and entries were compared with Reuters (2023) and industry statements, press releases, and media articles. The database is available upon request.

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[2] https://www.reuters.com/markets/carbon/carbon-storage-projects-across-europe-2023-03-31/
[3] https://www.iogp.org/bookstore/product/map-of-ccs-projects-in-europe/

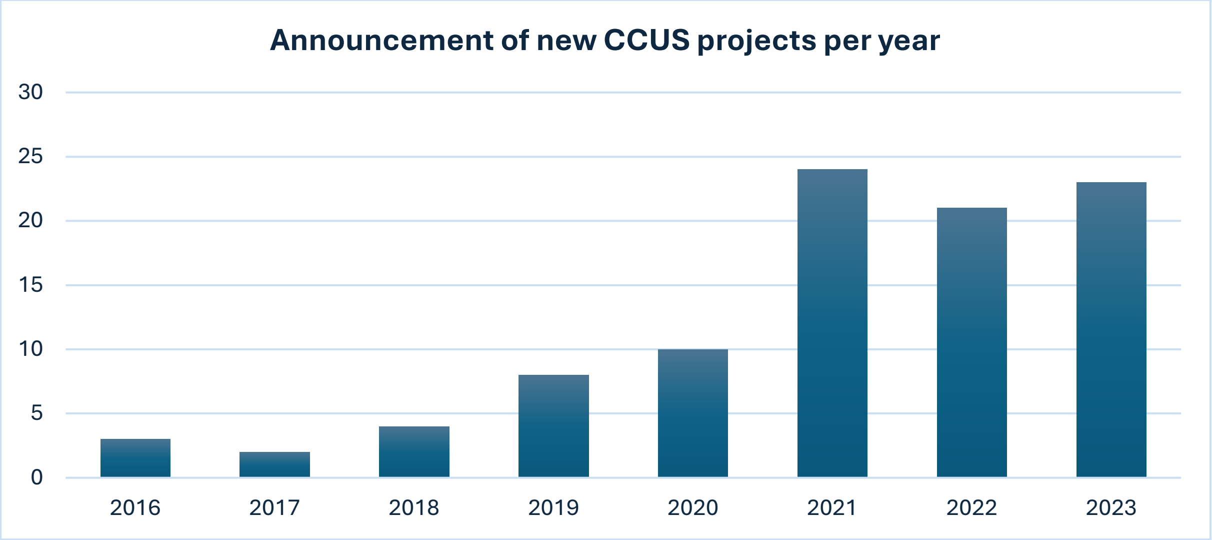

Figure 11: Announcement of new CCUS projects per year.

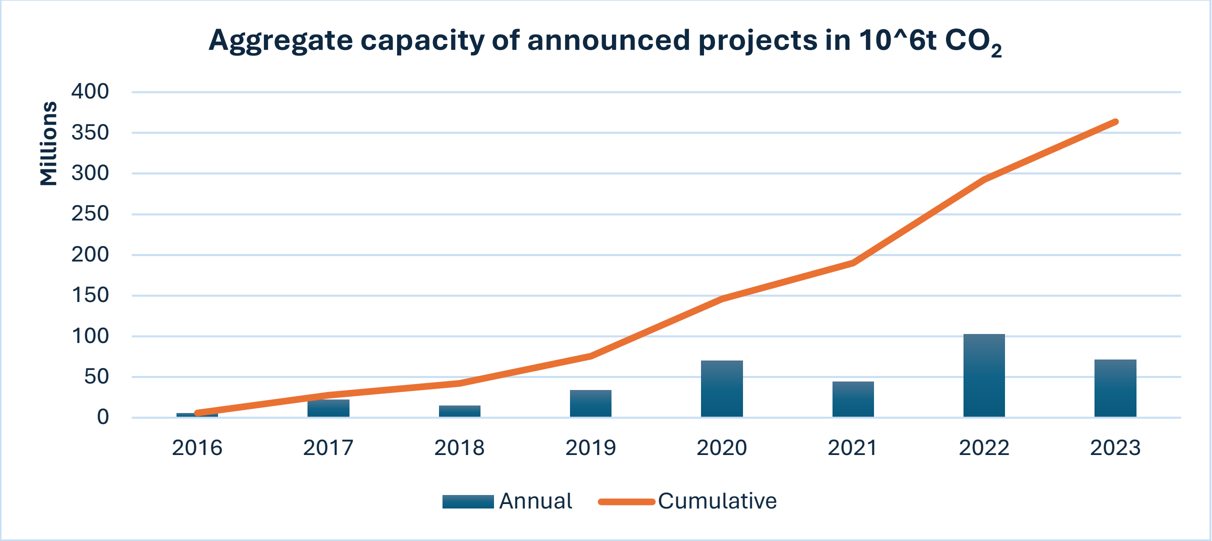

Figure 12: Aggregate capacity of announced projects in 10^6t CO_2

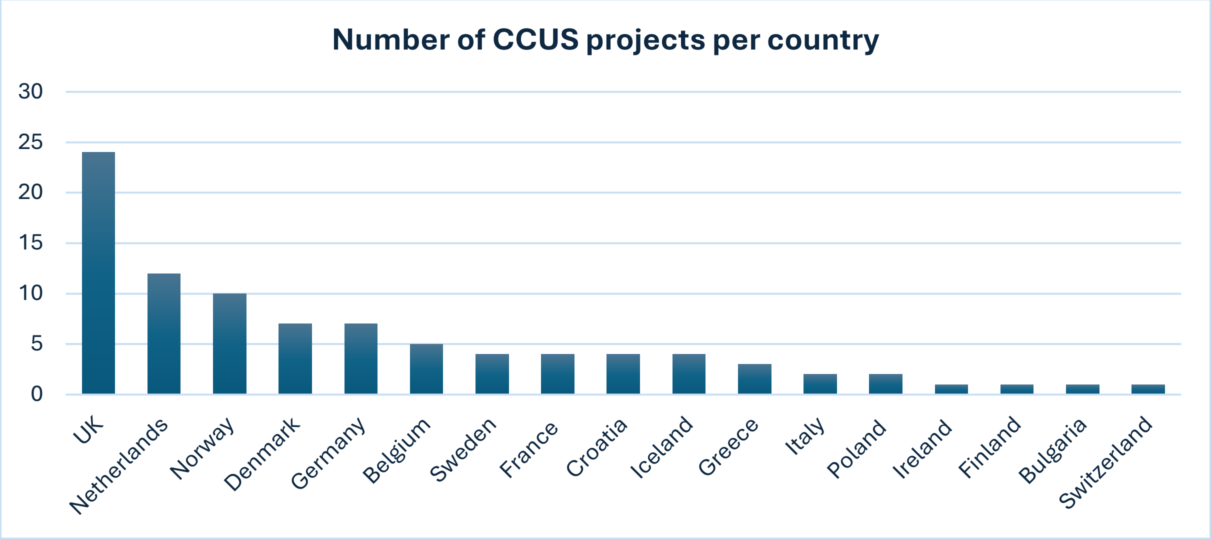

Figure 13: Number of CCUS projects per country

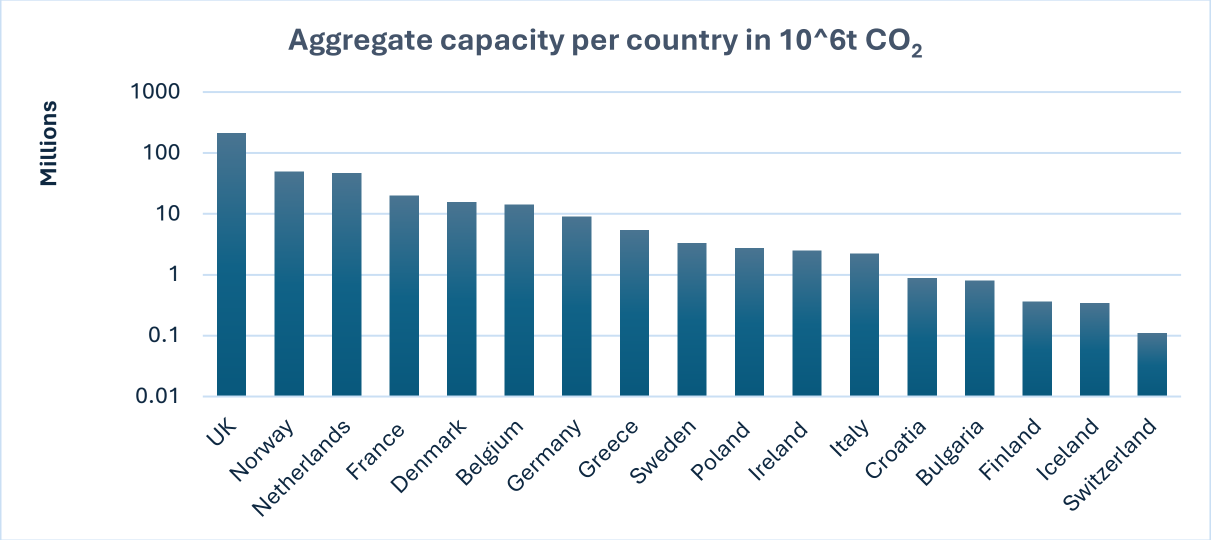

Figure 14: Aggregate capacity per country in 10^6t CO_2

8. Conclusion

This article provides a comprehensive overview of the current state of CCUS research and development. Firstly, the existing review articles are summarised, and their respective scope and contribution are illustrated. In the second part, the literature corpus is quantitatively analyzed using bibliometric analysis. In particular, we present the primary power analysis and the secondary co-citation analysis. We then describe CCUS from a techno-economic perspective, drawing heavily on the established literature, especially the most recent review articles. A review of the socio-economic literature reveals a notable research gap. On the one hand, there is an established strand of research in the social sciences, particularly on societal acceptance and implications. The current state of literature implies that public perception and awareness regarding CCUS is still limited.

There is a strong concentration of scientific discussion in the journal Energy Policy. On the other hand, the economic hurdles are clearly emphasized in individual studies. However, the bibliometric analysis did not provide a clear picture here, and no specialized review article was identified. Understandably, ex-post analyses are difficult to impossible due to the early stage of development and the small number of projects in the operational phase. Nevertheless, a precise summary of the economic literature could offer considerable added value. We hope that interested readers from research, policy, and practice will find our overview helpful in familiarizing themselves with the literature on CCUS. We are confident that we provide a comprehensive overview, both qualitative and quantitative and identified a significant gap in the literature.

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Appendix

Table 12: Overview of selected and significant CCUS projects in Europe.

Name	Start	Capture	Transportation	Storage	Funding	Notes	Links
Northern Lights	2024	CO2 is captured by industrial plants. The annual capacity is 1.5 million tons of CO2, with plans to increase capacity as demand in Europe increases. Of this, 0.8 million tons are reserved for the Heidelberg Materials cement factory in Brevik and the waste-to-energy plant in Oslo. The goal is to reach 5 million tons of CO2 per year.	CO2 is transported from the capture plants by ship to a receiving terminal in western Norway for interim storage. It is then transported 100 km by pipeline for storage in a 2,600 meter deep reservoir under the seabed	The CO2 storage complex is called Aurora and is located 2600 meters deep in the sea. It is part of the EL001 license granted in January 2019.	Norway Government: 1.190.000.000 USD (2020) Equinor, Total and Shell: 440.000.000 USD (2020) EU-Commission, CEF-Programme: 4.000.000 Eur (2022)	Northern Lights is part of the Longship project by the Norwegian government. Its their ambition to develop a full-scale CCS value chain in Norway by 2024, and demonstrate the potential of this decarbonisation approach to Europe and the world.	**https://norlights.com/what-we-do/** **https://www.upstreamonline.com/energy-transition/norway-greenlights-1-2bn-funding-for-northern-lights-carbon-transport-and-storage-scheme/2-1-931379** **https://commission.europa.eu/news/eu-invests-over-eu-1-billion-energy-infrastructure-support-green-deal-2022-01-26_en**
Porthos	2024	The CO2 will be captured by various companies. The companies will feed their CO2 into a 30 km long joint pipeline that runs through the port area of Rotterdam. The CO2 will then be pressurized in a compressor station. An average of 2.5 million tons of CO2 will be stored per year	The CO2 is transported through an offshore pipeline to a former gas-platform in the North Sea, 22 km off the coast. From this platform, the CO2 is pumped into an empty gas field.	The empty gas fields are located in a closed reservoir of porous sandstone, more than 3 km under the North Sea. Porthos will store around 37 million tons of CO2	EU-Commision: 102.000.000 Eur (2020) In addition the Dutch government will provide 2.1 billion euros in subsidies for Porthos' four customers: Air Liquide, Air Products, ExxonMobil and Shell. The companies in question will capture the CO2 at their facilities in the Rotterdam port area.	Porthos is a partnership between the Port of Rotterdam Authority, Gasunie and EBN. the Port of Rotterdam Authority will be focusing on the local situation and market, Gasunie can offer extensive experience with gas infrastructure and transport, and EBN will be sharing its expertise in the area of deeper soil layers and offshore infrastructure.	**https://www.porthosco2.nl/en/project/** **https://www.portofrotterdam.com/en/news-and-press-releases/102-million-euros-funding-horizon-porthos-carbon-storage-project** **https://www.porthosco2.nl/en/dutch-government-supports-porthos-customers-with-sde-subsidy-reservation/**

SSC Ravena Hub	2024	The CO2 comes from an Eni natural gas processing plant near Ravenna. 25,000 tons of carbon dioxide per year are discharged into a depleted offshore gas field. In 2027, 4 million tons of carbon dioxide per year will be stored: 1 million tons will come from plants owned by Eni and the remaining 3 million tons will be reserved for third-party industrial emitters. Potential CO2 sources are from the steel, chemicals, ceramics, cement, waste to energyindustry	The CO2 will be captured from industrial chimneys and piped to the future pumping station in Casal Borsetti. From there, the CO_2 will be pressurized and transported via pipelines to offshore platforms, where it will be injected into depleted reservoirs via existing wells.	Storage takes place in depleted offshore gas reservoirs in the Adriatic Sea off the coast of Ravenna, 2500 meter below the seabed. The total storage capacity is estimated at 500 million tons	E.U.: 37.370.000 Eur (2018)	The hub utilizes innovative proprietary solvent mixtures with ionic liquids, offering flexibility in handling CO2-containing gases, solvent stability, effective separation using both chemical and physical properties of CO2, and low toxicity. Eni employs simulation algorithms to study CO2-rock interactions, optimizing storage solutions based on reservoir geomechanical and geochemical properties	**https://ccushub.ogci.com/focus_hubs/ravenna/** **https://www.eni.com/en-IT/operations/storage-reuse-co2.html** **https://www.eni.com/ravenna-ccs/en-IT/project/ravenna-hub.html** **https://www.portseurope.com/ravenna-port-hub-signs-for-european-funding-of-e37-million/**
Leilac-2 Project	2023	Together with the Australian technology company Calix and a European consortium, HeidelbergCement will build a demonstration plant that will be integrated into HeidelbergCement's cement plant in Hanover. The potential capture capacity is designed for 20% of total CO_2 emissions, which corresponds to around 100,000 tons of CO_2 per year.	No transportation	No storage	E.U. Horizon 2020 programme: 16.000.000 Eur (2020) Project-Partners: 6.000.000 Eur HeidelbergCement: 3.000.000 Eur	There are currently no plans to actually store or use the CO_2 from Leilac-2, but an analysis will take place to gain a better understanding of potential uses and safe geological storage options. Also, in consideration of minimizing the use of fossil energy for CO_2 capture, the use of alternative fuels and electrical energy will also be examined.	**https://www.heidelbergmaterials.com/de/pi-23-03-2022** **https://bioenergyinternational.com/hanover-cement-plant-selected-for-leilac-2-carbon-capture-demo-project/**
DMX Demonstration in Dunkirk	2022	IFPEN and Axens are carrying out a project to demonstrate an innovative process for capturing CO2 from industrial activities. It is part of a wider study looking at the development of the future European Dunkirk-North Sea capture and storage cluster.The “3D” project (for DMX™ Demonstration in Dunkirk) is part of Horizon 2020, the European Union’s research and innovation program. The plant will be able to capture 4400 tons of CO2 a year from steelmaking gases by 2021. This is post-cumbustion CO2 capture from retrofitted steel industry plants.	No transportation	No storage	The project has a 19.3-million-euro budget over 4 years, including 14.8 million euros in European Union subsidies.	The DMX™ process, uses a solvent that reduces the energy consumption for capture by nearly 35% compared to the reference process. Additionally, using the heat produced on site will cut capture costs in half. Prepare the implementation of a first industrial unit at the ArcelorMittal site in Dunkirk, which could be operational starting in 2025. It should be able to capture more than 125 metric tons of CO2 an hour, i.e. more than one million metric tons of CO2 a year. In addition the CO2 extracted from the DMX™ process is extremely pure (99.7%)	**https://automotive.arcelormittal.com/news_and_stories/news/2019DMXproject** **https://www.geos.ed.ac.uk/sccs/project-info/2625**

Preem CCS	2025	In 2020, the test facility captured CO_2 from the flue gases from Preem's hydrogen gas plant at the Lysekil refinery. Carbon capture in the hydrogen production plant, which is based on steam methane reforming (SMR), was tested at steam methane reforming (SMR)	No transportation	No storage	Norwegian CLIMIT-Demo program via Gassnova Swedish Energy Agency Partners: (Preem, Aker Carbon Capture, SINTEF Energy Research, Chalmers University of Technology, and Equinor).	Sweden's largest carbon capture and storage plant. The Preem CCS project was a collaboration between Preem, Aker Solutions, Chalmers University of Technology, Equinor and the Norwegian research institute SINTEF. Key findings of the project activities are: - In-depth investigation of energy efficiency opportunities along the CCS chain, including the use of residual heat at the Lysekil refinery site to satisfy the energy requirements for solvent regeneration - Evaluation of the technical feasibility and cost evaluation of the CCS chain including CO2 capture and transportation by ship to storage facilities off the Norwegian west coast - Investigation of relevant legal and regulatory aspects related to trans-border CO2 transport and storage and national emissions reduction commitments in Norway and Sweden	**https://www.sintef.no/en/latest-news/2020/new-plaunch-of-swedens-largest-carbon-capture-and-storage-plantage/** **https://www.preem.se/globalassets/om-preem/hallbarhet/d5.1-preemccs-synthesis-of-main-project-findings-final.pdf** **https://research.chalmers.se/en/publication/528685**