Green transition and decarbonization: the role of CCUS projects*

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Abstract

Carbon Capture Utilization and Storage (CCUS) technologies are critical for achieving decarbonization and carbon neutrality, yet implementing effective projects remains complex and costly. Using the IEA's CCUS projects database (1990-2023), we study the factors explaining why certain countries attract more projects, why CCUS projects are more concentrated in specific industries and how organizational choices affect their implementation and scale. We find that the recent surge in CCUS initiatives has occurred particularly in oil & gas, agrochemicals, and materials sectors, and that different policy frameworks in the EU and North America may have lead to different deployment in these regions. Focusing on corporate strategies, we observe that even the largest companies collaborate within project hub, leveraging combined expertise and competences across sectors, and that project deployment and capture capacity vary by organizational structure, location, and scope of the value chain. Finally, a preliminary assessment of the potential to reduce GHG emissions by 2030 shows that the current number and scale of projects fall short of climate targets, highlighting the need for stronger public support and more efficient capture technologies.

Keywords: CO_2 capture, CO_2 utilization, CO_2 transportation and storage, green transition, energy policy, decarbonization policy

JEL Codes: O32, Q16, Q4, Q42, Q55

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1 Introduction

Carbon Capture, Usage, and Storage (CCUS) refers to a set of heterogeneous technologies designed to capture carbon dioxide emissions from large-scale industrial sources such as power and chemical plants and heavy industry sector, where fossil fuels or biomass serve as primary feedstock. Some of the CCUS technologies have been deployed for several decades, mostly in natural gas processing and enhanced oil recovery (EOR); once captured, the CO_2 is compressed and transported via pipelines or ships, to storage sites in geological formations like depleted oil and gas reservoirs or saline aquifers, or for industrial uses. Recently, however, new applications such as DACC (Direct Air Carbon Capture and Storage) or BECCS (Bio-Energy Carbon Capture and Storage) feature as more modern developments in the field of CCUS. Hence, CCUS is increasingly recognized as pivotal in promoting the green transition, especially within hard-to-abate industries, although its progress, in terms of operational initiatives, has been slow, due to high costs and technological barriers (Mahjour & Faroughi, 2023[17]).

The CCUS landscape is technologically and logistically complex: deployment strategies differ across countries and across industries, as the choice of technologies and project types depends not only on the institutional and policy context but also on sectoral specialization. However, the current literature is still specialized, focused on technological evaluations or confined to project- or country-level case studies that do not allow an understanding of this multi-layered subject from the economic point of view. This paper aims to fill this gap by providing an exploratory analysis of the current state of the CCUS sector, its evolution over time, industrial specialization and organizational issues and the policy frameworks that support it. By relating the geographical and sectoral distribution of worldwide CCUS projects to different policy frameworks we also aim to derive the factors that contributed to the current pattern.

We leverage the International Energy Agency's (IEA) 2023 CCUS project database to investigate: i) why certain countries attract more projects, ii) why activity is concentrated in specific industries, and iii) how organizational choices affect implementation and scale. From the existing literature, we draw technological knowledge and anecdotal evidence about the governance and structure of projects that motivate our research questions and we derive a conceptual framework that relates the research questions, the data, the levels of analysis and the results. Then, we describe the policy framework, differentiating the US vs. the European agendas, as their implementation as well as project deployment are different in the two regions. Associating the geographical, technological and organizational patterns of CCUS projects to the policy instruments can provide a helpful insight into the strategies that have so far been more effective.

We delve into a comprehensive analysis of the geographic distribution of worldwide CCUS projects by status of advancement, timing of implementation, and relationship between technology and fate of captured carbon (i.e., usage). Next, we shift to the industry-level perspective to identify the sectors most engaged in CCUS projects and how they interact. This analysis allows a better understanding of the CCUS value chain, highlighting how industrial clusters and public policies contribute to the scalability of these projects across countries. Finally, we focus on organizational models, in particular on project hubs, i.e., a governance construct that, in this field, has contributed to scaling technological efforts and investments, and compare the performance of different project types.

Our findings offer new insights into the ongoing efforts to scale CCUS implementation and the challenges that have to be addressed to align policy and industrial actions with global decarbonization objectives. Our paper also aims to serve as a basis for further research in the CCUS field by highlighting key points to consider when seeking a wider, and well informed, diffusion of these technologies, namely clearer policy frameworks for quicker deployment, exploitation of inter-industry relationships to promote technological positive spillovers and structured hubs for cost containment.

The paper unfolds as follows. Section 2 outlines the literature and our main research questions. Section 3 describes the environmental policies in the CCUS sector. Section 4 describes the data, the methodology and the conceptual framework. Section 5 presents the results. Finally, in Section 6 we discuss the results and in Section 7 we conclude.

2 Literature review and research questions

The primary objective of CCUS, when applied to industrial plants, is to reduce emissions generated by industrial processes. However, the net effect is not always positive due to the GHG emissions produced while these technologies are used (see, for example Ravikumar et al., 2020 [21]). Our survey reports evidence of these pros and cons. Figure 1 illustrates the CCUS value chain.

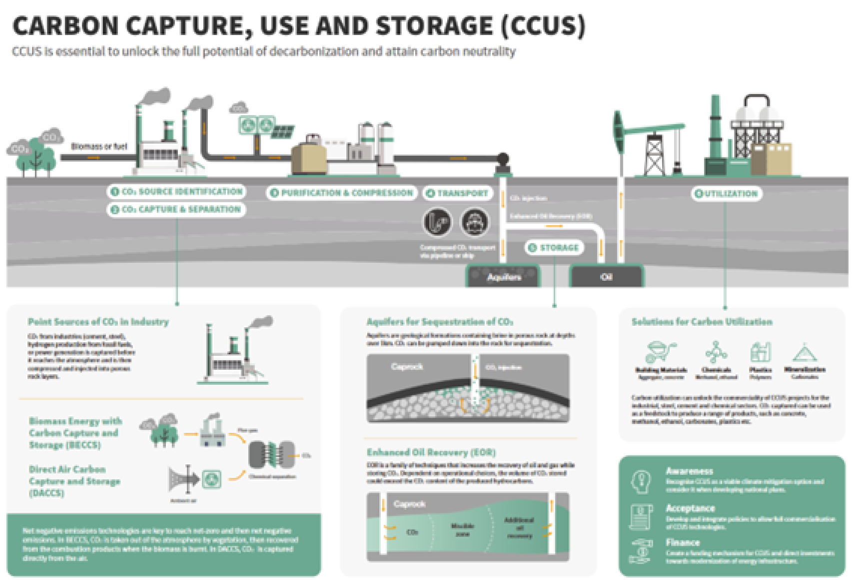

Figure 1: CCUS value chain. Source: UNECE CCUS report (2021)

The literature on CCUS – carbon capture, utilization, and storage – is primarily focused on its technological features and environmental potential, rather than analyzing its economic implications[1]. Our survey has identified three main areas of interest of the current literature: first, technical studies on the different methods of capture, storage and use

[1]A recent study by Barchi and Rondi (2024)[4] studies the determinants of patent activity in CCUS technologies and the impact of CCUS patents on firms' financial performance in the stock market. For a reference literature that studies the financial consequences of the climate transition risk see for example Bolton and Kacperczyk (2021)[6], Xepapadeas (2021)[33], Bauer et al. (2022)[5], Bolton et al., (2023)[7].

associated with the CCUS system, their supply chains and environmental implications (see Hepburn et al., 2019[12]); second, feasibility and techno-economic analyses and risk assessments (see Pettinau et al. 2013[19]) based on case studies of CCUS facilities (see Leeson et al., 2017[16], Taghizadeh-Hesary et al., 2024[28], Rui et al., 2025[24]); third, policy-oriented studies describing the different frameworks designed to incentivize the development of CCUS technologies and projects (see Åhman et al., 2018[2]). However, a comprehensive and detailed analysis of the geographical diffusion, industrial deployment and organization of CCUS projects, is still missing. With this study, we aim to fill this gap.

Many technical and feasibility studies of CCUS facilities stress the importance of project location as well as size (see Mahjour & Faroughi , 2023[17] for a survey). Optimal site selection is influenced by the presence of raw materials and of industrial specialization in the area, as technological and logistic barriers require larger resources to allow projects to exploit economies of scale (Wang et al., 2021[30]). Hence, as noted by Singh & Haines (2014)[25] these projects should be strategically located both to serve the local region and to attract international funding. However, the location of CCUS projects is also affected by the local community's perception of risk and requires strategies to mitigate potential public opposition (Pianta et al., 2021)[20]. In particular, opposition increases when facilities are situated near residential areas and when deployment costs are very high. The topic of public perception of CCUS projects is the subject of various studies. Vodopic et al. (2022)[29], based on a survey in Croatia, finds that the "Not-in-my-backyard" ($NIMBY$) phenomenon is observed in 13% of the sample. The evidence is similar in a study on Poland by Langhelle et al., 2024[15]. Such risk-averse attitude might be motivated by the lack of information about the complexity of the technology and of the project, which does not allow the public opinion to form an informed judgment, either positive or negative (Arning et al., 2019[3]). Consequently, projects that have institutional backing, such as financial commitments from government bodies and and informed public acceptance are more likely to succeed.

The effective deployment of CCUS also requires coordinated international policy efforts, which were inadequately provided at the beginning of the 2000s (Reiner, 2016[22]), but started to increase in 2015, after the COP21 agreement in Paris, when many countries established national plans for CCUS deployment[2]. National and supranational strategies typically include subsidies for R&D, project coordination, and financing, along with regulation and carbon taxation to incentivize long-term emissions abatement solutions such as CCUS (Rey and Madiès, 2021[23]). In this context, a combination of direct subsidies and carbon tax measures may be effective in reducing both costs and greenhouse gas emissions. This dual approach may drive the localization of CCUS projects as well as their innovative effort more effectively than either policy alone (Duan et al., 2013[9]). Diffusion of CCUS is thus likely to be dependent on policy choice, since project costs can be significantly decreased thanks to the right mix of incentives (Fan et al., 2022[10]). The case studies available often highlight the enabling role of the local policy for project location and success. For instance, Wettestad et al. (2024)[32] compare the model of Norway's first Mongstad CCUS project with its successor, Longship, finding that path dependency and policy learning largely explain the progress of CCUS technology in Norway. Inderberg & Wettestad (2015)[13] compare policy outcomes in the UK and Germany, concluding that greater sectoral development results from more favorable structural capacities, supported by technological specialization and political endorsement. However, most studies are conducted at the national level, highlighting the need for the supranational perspective that is appropriate to the case of CCUS technologies. Our analysis of project data helps throw some light on the relationship between policy contexts and sector development at the regional level. This leads us to our first research question:

1. What factors influence the current geographical diffusion, development and the fate of carbon of CCUS projects?

CCUS technologies are complex and diverse, and their applications potentially extends

[2]See for example the NextGeneration EU plan that is currently funding the NODES project SPOKE 2 on Green Technologies and Sustainable Industry in the field of scientific research.

to many industries[3]. The specialized engineering literature has shown that different types of CCUS techniques require different standards for their application, leading to different costs according to the firms' sector of activity (Nath et al., 2024[18]). Along with established pre- and post-combustion capture techniques, new alternative capture technologies like direct air capture and storage (DACCS) or bio-energy capture and storage (BECCS) are becoming more efficient. CCUS is traditionally applied in Oil & Gas, Cement and Chemicals for reasons related to the use these firms make of the captured CO_2. In fact, a side benefit of CCUS is the potential use of captured CO_2 as a raw material for producing intermediate or even consumer goods (i.e., CCU). For example, captured CO_2 can be utilized in the production of e-fuels (such as sustainable aviation fuels, e-naphtha, and e-methanol), building materials (like cement and concrete), and chemical products (including fertilizers and food-grade CO_2). Projects that leverage mature technologies or have secured revenue streams through the utilization of captured CO_2 are more likely to be convenient (Abdulla et al., 2020[1]). Anyway, despite potential applications for captured CO_2, CCUS requires additional energy, making it economical and sustainable only when the benefits from CO_2 reduction outweigh the associated costs (Gibbins & Chalmers, 2008[11]). This balance depends, among other factors, on the sector of application. For example, Ravikumar et al. (2020)[21] find that production of methanol using captured CO_2 has net environmental benefits compared to conventional production processes. Their analysis also highlights the environmental opportunity cost of using Renewable Energy (RE) for e-methanol production instead of using it directly in the grid. Indeed they find that the CO_2 saved by supplying RE to the grid surpasses the benefits of using renewable hydrogen in methanol production in a CCUS framework.

The complexity of these projects asks for coordination skills and involves different capabilities, which may imply the collaboration among firms from different industries. Our second

[3]The portfolio of CCUS technologies is quite rich. A simplified list by technological domain comprises: i) pre- and post-combustion capture, oxyfuel, Bio-Energy Capture and Storage (BECCUS) and Direct Air Capture (DACC) within Capture technologies; ii) aquifers for sequestrations of CO_2, Enhanced Oil Recovery (EOR) within Storage technologies; and iii) three main areas as far as carbon usage is concerned: Mineralization (e.g., incorporating CO_2 into concrete); Chemicals and Biologicals.

research question thus studies the interplay between sectoral characteristics and technological feasibility.

2. How does the deployment of CCUS projects vary across industrial sectors? Why certain sectors appear better suited to specific CCUS technologies?

CCUS technologies are often integrated into systems designed for efficient CO_2 capture, though projects are typically costly and rely on economies of scale. The scope of these economies, however, may vary depending on the intended use of the captured carbon (i.e., its destination and application) and the complexity of the facility. As a result, there are multiple organizational forms assumed by companies that collaborate to coordinate projects and their supply chain (Yao et al., 2018[34]). In general, we distinguish between stand-alone projects and projects that are part of a hub. Within the stand-alone projects, companies have adopted several organizational models such as partnerships, joint ventures (JVs), and R&D collaborations (IEA, 2023)[4]. Project hubs are partnerships between firms or firm clusters, that allow participants to pool resources, share risks, and integrate specialized expertise at the various steps of the CCUS value chain[5]. They bring together one or multiple projects under a coordinated framework, enabling the sharing of essential infrastructure like CO_2 pipelines and storage sites, thus reducing costs and enhancing operational efficiency (Song et al., 2023[26]). To leverage economies of scale and resource pooling, energy generation and processing of raw materials are often concentrated in strategic geographical areas, generating agglomeration economies. The dimension of a project hub can vary depending on the type of sub-projects included and their features such as fate of carbon, project type[6] or the industry in which the sub-projects are deployed. These hubs typically involve both public and private partners, who collaborate to ensure smooth implementation and overcome logistical challenges. As far as they promote shared facilities (e.g., shared capture or storage sites,

[4] https://www.iea.org/reports/ccus-policies-and-business-models-building-a-commercial-market

[5] Source: the CCUS Hub https://ccushub.ogci.com/policies-business-models/business-models/

[6] I.e., full-chain, capture, usage, transport, storage. See Appendix A for a detailed specification.

and common infrastructure for transport), hubs might generate two main advantages for participants: cost-sharing (Wang, 2024[31]) and stable operation (Storrs et al., 2023[27]). In contrast, stand-alone projects, which often operate as a full-chain initiative where a single entity manages the entire process might be less cost-efficient (Julio et al., 2024[14]). Finally, Mahjour & Faroughi (2023)[17] stress the importance of well-structured cooperative strategies that incorporate international collaborations for the success of CCUS projects. Our third research question studies organizational models of CCUS and how they affect project implementation and results.

3. How organizational choices - hubs vs stand-alone projects - affect implementation and scale? Are CCUS hubs more efficient in sequestering emissions?

3 Environmental policies in the CCUS sector

The survey of the literature has emphasized how relevant public financing is in the support of these advanced technologies and the deployment of CCUS projects. Therefore in this section, we focus on environmental policies in the CCUS sector, differentiating the policy frameworks in Europe and in North America, as their different agendas and instruments may affect the development of CCUS projects also at the regional level. Furthermore, the more advanced state of regulatory settings and subsidizing systems may serve as a benchmark for other countries trying to engage in the CCUS domain. Since the 1990s, Carbon Capture, Utilization, and Storage (CCUS) technologies have been recognized as crucial to achieving global decarbonization goals, particularly in hard-to-abate sectors such as cement, steel, and chemical production. Before 2020, projects were small-scaled and policy support was limited, particularly in Europe, where implementation of new CCUS technologies was slow also due to high costs of deployment, technological immaturity. The early development of CCUS was heavily fragmented, efforts dispersed across sectors and technologies, but largely concentrated within oil and gas, where enhanced oil recovery (EOR) provided an immediate economic return. In recent years, though, there has been an acceleration driven by more structured policy interventions and by increasing availability of financing mechanisms. As the pace and scale of CCUS development vary significantly both between Europe and the U.S. and before and after 2020, in this section we provide an overview of their policy instruments and interventions which sets the scene for an informed analysis of the actual project planning and realization in the two macro-regions.

3.1 EU policy framework

Prior to 2020, EU policies for CCUS were focused on small-scale pilot projects. Initiatives like the NER300 program, launched in the early 2010s, were aimed to support CCUS and renewable energy projects but delivered limited results. Out of €2.1 billion allocated, only one significant CCUS project was developed, and 67% of funds were not used, signaling the inadequacy of the early funding models. The same happened also with other instruments: in Appendix Table 8, we report the estimated budget for all calls published in the last three years of Horizon 2020 (2018-2020), in the first four years of Horizon Europe (2021-2024), and for the two CEF programs (2014-2020, and 2021-2027). Only 3.1% of the CEF 2014-2020 budget was allocated for the development of cross-border CO_2 networks (EU Commission). These early policy frameworks were insufficient to incentivize large-scale projects that could move beyond the research and pilot phases. Many of the announced projects struggled to progress through the critical Front-End Engineering Design (FEED) phase due to bureaucratic delays and fragmented support structures. A marked shift in the financing of CCUS projects occurred after 2020, with more substantial public commitments and policy reforms aimed at scaling up large projects. In the EU, the establishment of the Innovation Fund, backed by revenues from the Emissions Trading System (ETS), created a dedicated stream of financial support for large-scale industrial decarbonization projects. Through the monetization of 530 ETS allowances, it will bring more than €30 billion in investments in innovative low-carbon technologies and processes in energy-intensive industries. The budget allocated to CCUS projects is in Appendix Table 7. Although many challenges persist – such as slow permitting processes and complex alignment of policies across member states – the EU policy framework in the Twenties appears designed to overcome these hurdles[7].

By 2030, the EU aims at matching the CCUS deployment rates in the U.S., which are driven by a stronger regulatory framework and more generous financial support for large-scale CCUS hubs.

3.2 US policy framework

In contrast to Europe, the U.S. has consistently supported CCUS through targeted tax incentives and significant public investment. The U.S. had a dedicated financial mechanism in place well before 2020 with the Section 45Q tax credit[8], introduced in 2008 and later enhanced in 2018. This tax credit provided direct incentives for companies to capture and store CO_2, particularly in sectors like oil and gas where Enhanced Oil Recovery (EOR) made CCUS more economically viable. The U.S. also benefited from an early focus on large-scale CCUS projects, particularly in the oil and gas industry. Many of these projects were operational before 2020, allowing the U.S. to maintain a leadership position in global CCUS deployment. By 2023, the U.S. had 25 operational CCUS hubs compared to far fewer in the EU. Furthermore, key legislative changes, such as the enhancement of the Section 45Q tax credit in 2018 and, more recently, the Inflation Reduction Act of 2022, have significantly improved the financial viability of CCUS projects. The 45Q tax credit, which increased from \$20/tCO_2 in 2008 to \$85/tCO_2 for CCUS in 2022, has enabled many projects to move forward without incurring in financial stringency. In addition, the Infrastructure Investment and Jobs Act (IIJA) of 2021 allocated \$21 billion for CCUS projects, with a particular focus on large-scale carbon capture plants and transport and storage infrastructure. Despite

[7]However, the race to enhance investment in CCUS has also been criticized on the grounds that these technologies are too risky, expensive and of uncertain realization. Over-reliance on CCUS in terms of financing might in fact hinder the development of alternative technologies, such as low-carbon (green) hydrogen and natural climate solutions. See `https://ieefa.org/articles/eu-bets-unproven-technology-high-risk-carbon-capture-plan`.

[8]Appendix Figure 14 summarizes the main S45Q changes occurred from 2018 to 2022.

challenges like building permitting delays, consistent policies and financial incentives have helped the U.S. maintain a leading role in CCUS deployment. By 2030, the U.S. is expected to have a significant share of worldwide operational CCUS projects, mostly driven by both federal and state-level incentives.

4 Data and Methodology

The purpose of our study is to describe the CCUS domain and to determine what factors contribute to its current development worldwide. As a methodological approach, we delve into the complex CCUS landscape to unearth the antecedents of its heterogeneity by analyzing the characteristics of projects. We start from their geographical diffusion and status of advancement, and then turn to technological and industrial applications, fate of captured carbon, expected and actual capture efficiency, extension of their value chain and companies involved.

4.1 Data and description of the sample

The primary source of data is the IEA's 2023 CCUS Projects Database. The International Energy Agency collects and updates this database as part of its efforts to track advances in the CCUS industry worldwide. It covers all CO_2 capture, transport, storage, and utilisation projects with an announced capacity of more than 0,1 $MtCO_2$ per year (1000 tCO_2 per year for Direct Air Capture facilities due to market and technological infancy) that have been commissioned since the 1970s. It includes projects with a clear objective to reduce carbon emissions[9]. The database reports all key information to profile a CCUS project, such as project name, country, type and status, companies involved, progress time roadmap, announced carbon capture capacity, project technological type and the fate of captured

[9]Hence, the database excludes projects that capture CO_2 for utilisation purposes that bring low climate benefits, e.g. food and beverages, or which are part of conventional industrial process (e.g. internal use for urea production).

carbon.[10] "Status" classifies projects as "planned", "under construction", or "operational". The database keeps also track of projects that are "suspended" or "decommissioned". Up to March 2023, the database covers information for 572 worldwide projects at an industrial scale level, i.e. with a carbon capture potential greater than 0.1 $MtCO_2$/year[11]. Of these 572 projects, 431 are planned, 75 under construction, 58 operational and 8 are suspended or decommissioned. We expand our analysis by looking into the set of firms involved in CCUS projects. Each firm cited in the "partners" list of the projects was matched and identified in the Orbis database by Bureau van Dijk and firm-level information (e.g., NACE sector classification) was retrieved therein. All in all, 585 companies that have at least one participation in a CCUS project were identified and considered in this study.

4.2 Conceptual framework

In Figure 2 we present the conceptual framework behind our empirical analysis, linking the research questions, the data, the levels of analysis and our findings. We start by analyzing projects by region, operational status and fate of carbon. We then focus on firms that participate to CCUS projects, collecting information about their primary industry. Based on this evidence, we derive which industries are more involved in the realization of the projects and to what extent they interact with other industries in order to develop CCUS technologies into projects and, ultimately, operational plants and networks. As a third step, we study the structure of projects, sorting project-hubs from stand-alone projects and investigate whether the organizational model affects their effectiveness in terms of carbon capture capacity, comparing different organizations. Each step of the analysis is also viewed in relation with the policy framework.

[10]Description of each variable in the database is in Appendix Table 3.
[11]The IEA database does not cover projects below that threshold.

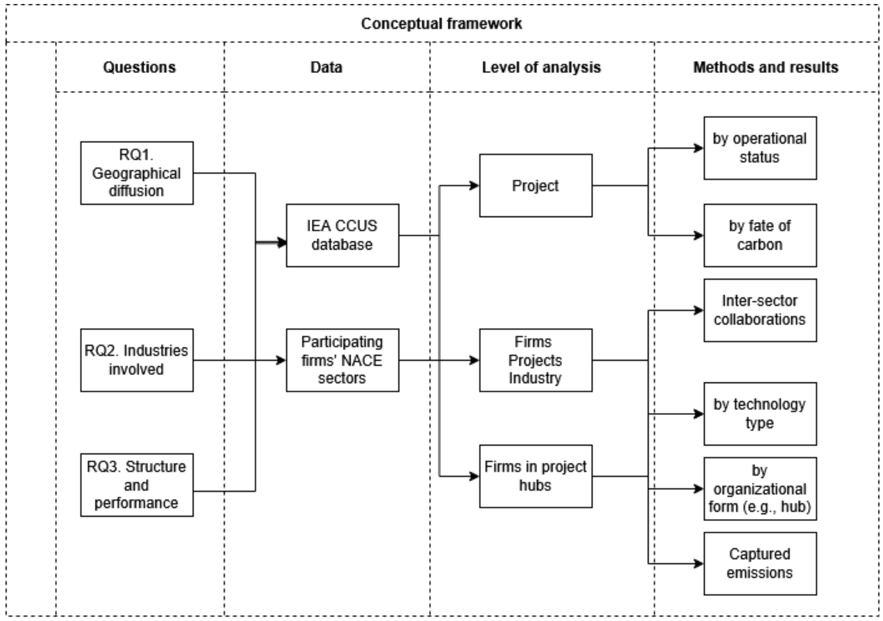

Figure 2: Conceptual framework

5 Results

5.1 Where are CCUS projects and where does captured CO_2 end?

5.1.1 Geographical diffusion and operational status of projects

This section offers a thorough analysis of projects' geographic distribution and varieties, shedding light on the advancement of CCUS technology deployment. Figure 3 describes the cumulated number of project by status over time,[12] and reveals that the progression gained momentum around 2015 — the year of the pivotal COP 21 Conference in Paris[13].

Between 2018 and 2022, the number of announced projects increased tenfold, but that of operational projects did not rise correspondingly. According to their estimated timelines, these projects should reach the operational status after 2023, whereas, based on the information in the IEA dataset, the average time for a project to become operational since its

[12]Since the latest available update of the IEA's database is set to March 2023, the new projects announced cannot be observed thereafter. From 2023 onward, the graph shows a simulated trend based on project status evolution over time, assuming no other projects are announced.

[13]Notably, patent activity in CCUS technologies also increased significantly after this conference (Barchi and Rondi, 2025).

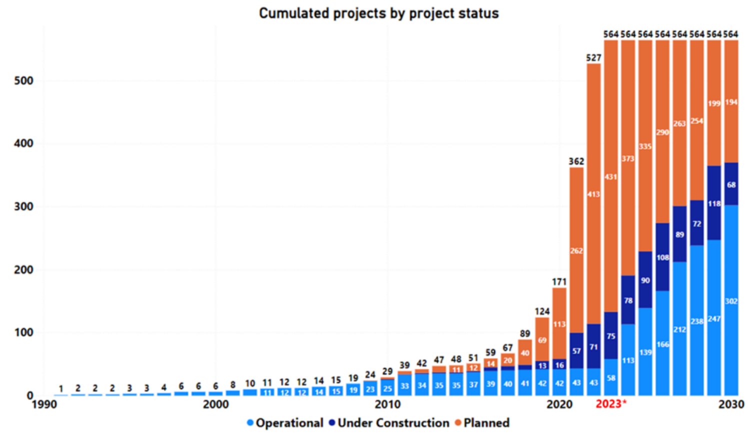

Figure 3: Cumulated curve of projects by status from 1990 to 2030. Source: Our elaborations of IEA's CCUS 2023 Database.

announcement is 6.4 years.

The breakdown of CCUS projects across the top 15 countries, in Table 1, shows a significant concentration in Western nations (83%), particularly in North America (United States and Canada), although the information for many countries might be incomplete. So it appears that only 44 out of 564 CCUS projects worldwide, are planned for deployment in China, Indonesia, the Russian Federation, and the United Arab Emirates. Due to limited data availability on CCUS initiatives in non-OECD economies, our empirical analysis focuses primarily on North American and European CCUS ecosystems.

N°	Country	Planned	Under construction	Operational	Total
1	United States	125	40	20	185
2	United Kingdom	63	2	0	65
3	Canada	52	3	7	62
4	Australia	25	3	1	29
5	Norway	22	4	2	28
6	Netherlands	19	3	1	23
7	People's Republic of China	10	5	6	21
8	Germany	18	/	/	18
9	France	17	/	/	17
10	Belgium	12	/	1	13
11	Denmark	12	/	/	12
12	Indonesia	10	/	/	10
13	Sweden	8	/	/	8
14	Russian Federation	7	/	/	7
15	United Arab Emirates	5	/	1	6
Top 15 countries by total number of CCUS projects					**504 (89%)**
Total CCUS projects examined					**567**

Table 1: Top 15 countries by total number of CCUS projects. Source: Our elaborations of IEA's CCUS 2023 Database.

In Figure 4 data are organized by continent and project status. North America has the highest share of projects under construction or operational, while in Europe, the number of operational or in-progress projects is lower, but the number of planned projects (where the UK leads with a share of 30%) is larger. Finally, the decarbonization effort in Oceania is concentrated in Australia, which has quite few ongoing projects.

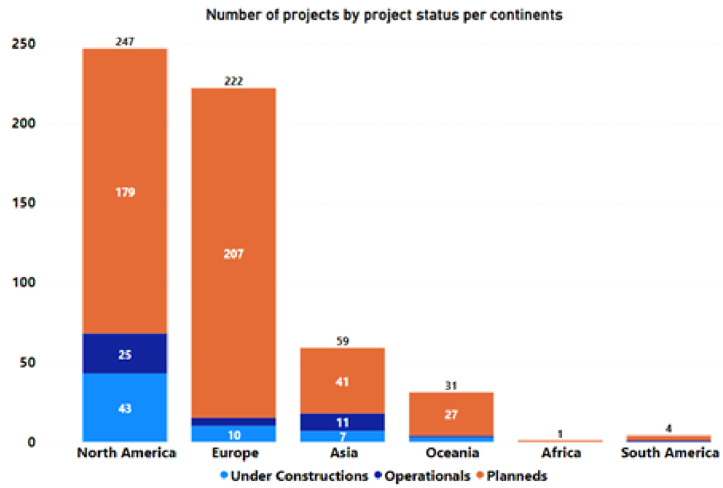

Figure 4: Number of CCUS projects by region and status.

Figure 5 details the progression of cumulative projects by development status in North America and Europe.

In 2023, North America features as the technological and industrial leader in the CCUS sector. This leadership can be attributed to larger R&D investments and higher capacity in industrial scalability, as the U.S. have started to invest in CCUS facilities prior to the 1990s, initially focusing on enhanced oil recovery (EOR) technologies. In contrast, the EU has a higher number of planned projects but significantly fewer operational facilities. Based on the announced inception dates, the EU is expected to match the U.S. by 2030 in terms of operational projects. However, achieving this target would require an increase from 7 operational projects in 2023 to nearly 150 within seven years—an optimistic target. Notably, in 2021, the EU reported twice as many announced projects as North America and yet, by 2023, only 5 facilities became operational, compared to 25 in North America.

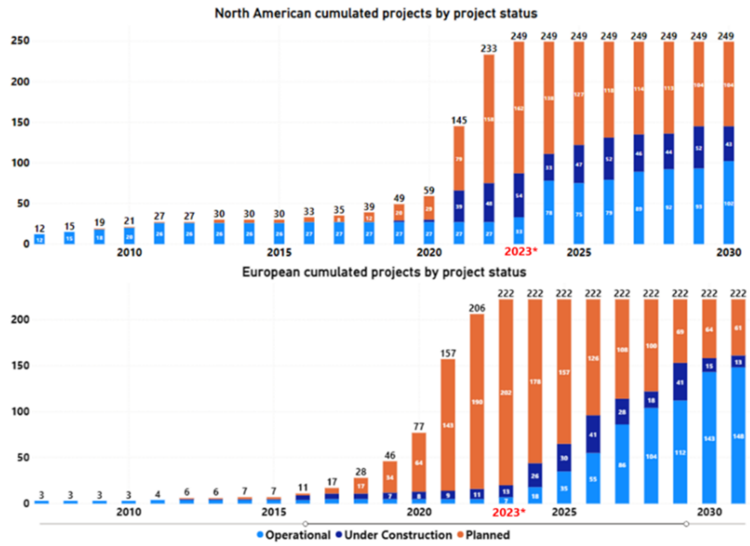

Figure 5: North American and European CCUS projects by status. Source: Our elaborations of IEA's CCUS 2023 Database.

5.1.2 What is the fate of captured carbon emissions?

CCUS projects can be classified based on the ultimate use of captured CO_2: dedicated storage, enhanced oil recovery (EOR), mixed-use, or carbon utilization (CCU). Figure 6 shows that the majority of projects (78%) are dedicated to underground storage, highlighting that geological storage remains the predominant approach. North America and the EU report similar numbers of geological storage projects, but their engagement in EOR differs significantly. North America, with an established oil industry, has extensive experience in EOR and currently leads with 44 projects—23 operational in the U.S. and 21 in Canada. By contrast, the EU, where oil extraction is more scarce, has only four EOR projects in the planning stage. In Asia, the introduction of CCUS technologies is more recent, and China and Indonesia are the major players, with 21 and 10 EOR projects, respectively[14].

As for carbon capture utilization (CCU), the EU leads in planned projects, with 33 specifically aimed at employing CO_2 in downstream chemical processes, such as producing carbon-neutral e-fuels and construction materials. In the steel industry, the Steelanol project stands out as a notable operational initiative that converts CO_2 into ethanol for chemical

[14]In China, the IEA database lists 6 operational projects and 5 under construction, all dedicated to EOR.

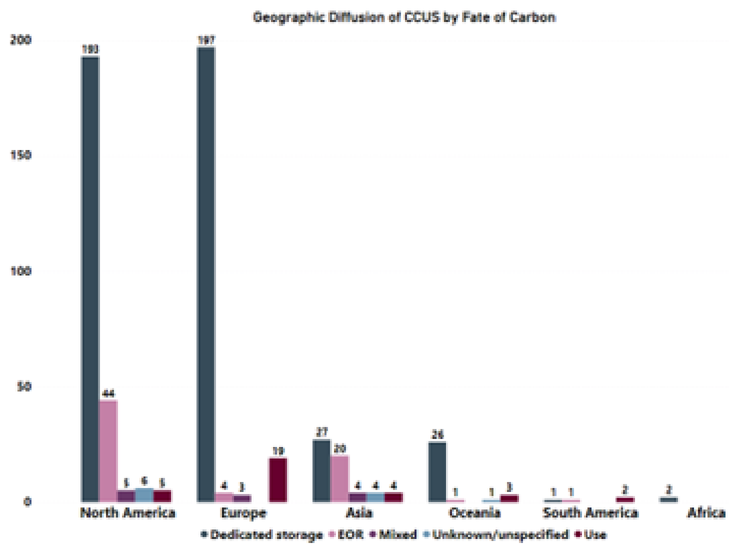

Figure 6: CCUS projects by region and fate of carbon. Source: Our elaborations of IEA's CCUS 2023 Database.

production. To date, despite these advancements, the market for captured CO_2 is still thin, hindered by infrastructural problems and financial constraints.

Table 2 shows how projects in different "sectors"[15] are distributed by technology and fate of carbon.[16]

Sector	Technology	Storage	EOR	Usage
Energy	Hydrogen/ammonia	64	3	1
	Power and heat	61	9	6
	Biofuels	52	5	1
	Natural gas processing	31	16	0
	Other fuel transformation	24	10	2
CC infrastructure	CO2 storage	47	1	0
	CO2 transport	39	7	0
	CO2 T&S	66	3	0
Materials	Cement	18	0	6
	Iron and steel	3	1	2
DACC	Direct Air Capture	19	2	11
Other	Other industry	20	10	4
TOT		**444**	**67**	**33**

Table 2: Distribution of IEA projects by sector, technology and fate of carbon (Storage, EOR, Usage)

[15]T&S Infrastructure, Materials Industry, and Energy Industry clusters are composed as follows. Energy Industry: Hydrogen/ammonia, Power and heat, Biofuels, Natural gas processing, Fuel transformation; CC Infrastructure (T&S): CO_2 T&S, CO_2 Transport, CO_2 Storage. Materials Industry: Cement, Iron and steel.

[16]We exclude CCUS projects that, according to IEA, are characterized by a mixed fate of carbon.

The energy sector accounts for more than 50% of CCUS projects, with applications ranging from hydrogen, ammonia, biofuels, to natural gas production. Currently, 98% of hydrogen is produced via high-emission processes ("brown" hydrogen), while only 0.6% is derived from CCUS-supported methods ("blue" hydrogen), and less than 0.1% from water electrolysis powered by renewable electricity (IEA, 2024). Biofuel production is also CO_2-intensive, which has driven biofuel CCUS projects to comprise the largest share of projects under construction.[17] Transport and storage (T&S) infrastructure projects make up for 34% of all initiatives, developing onshore and offshore storage sites, CO_2 pipelines, and transport networks. This infrastructure is the backbone of the CCUS value chain, enabling a secure transport of captured CO_2 to storage sites.

The remaining 15% of projects fall into three subcategories: materials (iron, steel, and cement), direct air carbon capture (DACC) and other sectors. Interestingly, the cement and iron/steel industries, responsible for 8% and 7% of global CO_2 emissions, respectively, have few CCUS projects (18 in cement, 2 in iron/steel), despite their carbon-intensive nature. This limited engagement likely reflects the high costs and complexities of CC technologies, which deter investment in these industries (Cozzi et al., 2023[8]).

Direct Air Carbon Capture (DACC) is an emerging technology designed to extract CO_2 directly from the atmosphere at any location. It differs from other carbon capture techniques that are applied at the source of carbon emissions, such as steel plants. For this reason, DACC is viewed as a distinct, nascent industry. Currently, DACC is in an early stage of development, within industrial plants, mainly in the US and in Canada, with an annual capture capacity of around 1,000 tons of CO_2. Although DACC is still regarded as costlier and technologically more uncertain than standard CCS methods, recent advancements in capture capacity have improved its outlook. These advancements have contributed to a reduction in the cost per ton of CO_2 captured, bringing DACC closer to the price levels seen

[17] A key example is the U.S.-based Midwest Carbon hub, designed to capture 12 $MtCO_2$ annually from ethanol facilities and transport it via a 2,000-mile pipeline for underground storage—a large-scale model integrating transport and storage infrastructure within CCUS hubs.

in the European Union's Emissions Trading System (ETS)[18].

Turning to applications of captured carbon, we find that most projects concern storage facilities (81.6%), then EOR (12.3%) and, finally, just 6.1% are dedicated to utilization. Hence, projects engaged in innovative CO_2 utilization are, despite some progress, still quite few. For example, Cozzi et al. (2023[8]) have estimated that, by 2030, only 10 million tons of CO_2 per year could be captured for innovative uses, such as CO_2-based synthetic fuels, chemicals, cement and concrete.

5.2 Industrial concentration of CCUS projects

5.2.1 Which sectors and companies are involved in CCUS projects?

The CCUS system is shaped by a heterogeneous range of industries, in which oil and gas, energy, high-tech and manufacturing companies play a pivotal role in driving its development. To understand the industrial orientation of CCUS projects, we identified the companies involved in these projects and the industries they belong to. Firms' commitment to CCUS projects can be assessed by the number of projects they have invested in and by how closely their core competencies align with the technologies and operations required by CCUS diffusion. Figure 7 shows the number of companies by NACE section (the Statistical Classification of Economic Activities in the European Community) and level of commitment as measured by the number of CCUS projects in which they are involved.

It appears that most of the firms committed to CCUS projects are in manufacturing, as 64% of CCUS projects showcase at least one manufacturing company, typically producing chemical products, coke and refined petroleum, machinery and equipment and other non-metallic mineral products. Many are early adopters of innovations aimed at decarbonizing their operations (mainly chemical producers)[19], while others are at the forefront of CCUS

[18]See: The Economist, "Can carbon removal become a trillion-dollar business?" May, 21, 2023

[19]Chemical producers often play a dual role, being involved in projects either as CC technology developers or because they are large chemical producers striving to reduce their environmental impact. For example, Aker Carbon Capture AS, with 13 CCUS projects, stands out as a leader in developing the technologies needed to capture and reuse CO_2. Carbon Clean Solutions Ltd and Sunfire GmbH provide innovative

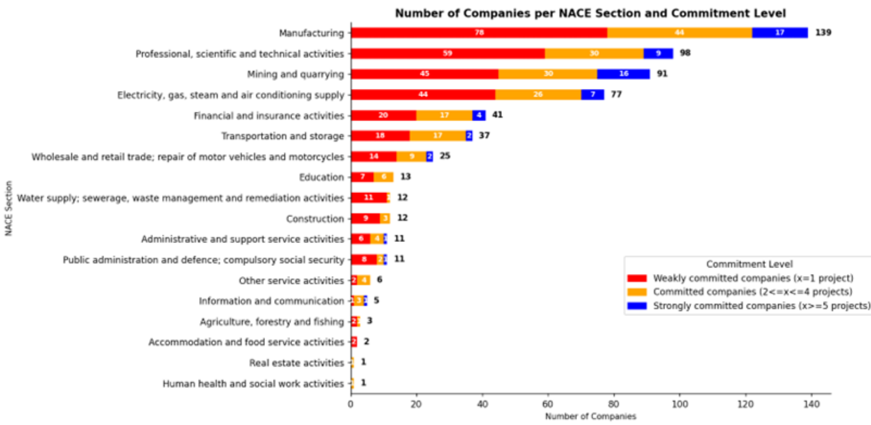

Figure 7: Number of companies by NACE Section and level of commitment to CCUS projects.

technology. In high CO_2 emitting industries - oil and gas and coke and refined petroleum products - companies such as ExxonMobil Asia Pacific Pte. Ltd., with 22 projects, and BP Plc and Chevron Corporation (11 and 10 projects, respectively) lead the industry's efforts to implement CCUS technologies while Shell Plc, Equinor Asa, Total Energies SE, Eni S.P.A., Denbury Inc, ADNOC Drilling Company P.J.S.C, ESSO, and Wintershall Dea AG (Mining and quarrying) take part in more than 100 CCUS projects worldwide, often collaborating with each other in the same project.

Companies in the carbon-intensive cement and concrete industry are also quite involved and often become partners with construction companies within joint-ventures or consortia to secure sustainable applications in the market.[20] In iron and steel, ArcelorMittal SA, JX Nippon Mining & Metals Corporation, and Thyssenkrupp AG are the major players in CCUS technology while, in the machinery and equipment sector, Air Liquide is involved in 31 CCUS projects worldwide. With its extensive experience in CO_2 management, from

solutions for the reduction of CO_2 emissions. Large chemical manufacturers such as Ineos Industries Limited (9 projects), and BASF SE (4) are also installing CC plants to reduce emissions from their energy-intensive productions. Petronas Chemicals Group, Yara Sluiskil B.V., and Lotte Chemical Corporation are also taking steps toward decarbonization. Within this same sector, bioethanol producers like Green Plains Inc., Conestoga Energy Partners LLC, Cardinal Ethanol, LLC, and Aemetis, Inc. together contribute to 14 CCUS projects.

[20] Heidelberg Materials AG is most active in this field, with 13 ongoing CCUS projects. Likewise, Holcim AG, after merging with Lafarge in 2015, is involved in 12 CCUS projects, while Lhoist, Cemex S.A.B. de C.V., and CarbonCure Technologies Inc., the latter known for its expertise in low-CO_2 concrete production, are also prominent in their effort to push the industry toward sustainability.

capture to purification, liquefaction, and storage, Air Liquide applies its technologies across multiple regions, including Europe and North America, where its solutions help reducing emissions in heavy industries such as steel and cement. The geographical and sectoral scope, and the size of companies involved in CCUS projects suggests that only few firms, mainly multinational enterprises, can supply the large-scale capital requirements and the specialized knowledge implied by carbon capture technologies.

Many companies in Professional, Scientific, and Technical Activities sectors, such as engineering and consultancy, and research laboratories contribute to the development, optimization and integration with existing plants of new CCUS technologies[21] while those in the Scientific research and development sector are at the forefront of CCUS innovation[22]. Also many universities are engaged in CCUS projects, playing a key role in bridging academia research and market applications, while technology companies transfer innovative CCUS solutions to the market by raising their Technological Readiness Level (TRL). Finally, we find that consulting and financial companies are also involved in such large-scale CCUS projects, to provide advice on financial, administrative, legal and regulatory issues, especially during pre-FEED (Front End Engineering Design) and FEED stages.

5.2.2 Do companies in different industries cooperate within CCUS projects?

We now turn to analyse to what extent companies of different sectors coordinate their effort to deploy a CCUS project. To assess the intensity of these inter-industry relationships, we constructed a matrix of 'co-occurrences' (Figure 8). A co-occurrence between two NACE sectors is identified when companies from each sector participate in the same project. Our

[21] Carbon Engineering Inc., with 12 CCUS projects, and Climeworks and Global Thermostat Operations LLC are specialized in DACC technology while Oxy Low Carbon Ventures, LLC, 8 Rivers Capital, LLC, and ION Clean Energy, INC. play a vital role in advancing CC solutions through their R&D activities, particularly within the energy industry.

[22] For example, Carbfix HF has 6 projects that focus on the permanent storage of CO_2 by transforming it into minerals underground, contributing to long-term carbon sequestration solutions while Schlumberger Carbon Services, also in 6 projects, leverages its expertise in subsurface technologies to enhance CO_2 management and storage.

purpose is to find which industries are more likely to allow CCUS projects to exploit inter-industry economies of scope and synergies, thus favouring companies involved in the project. Only sectors with at least five occurrences are reported.

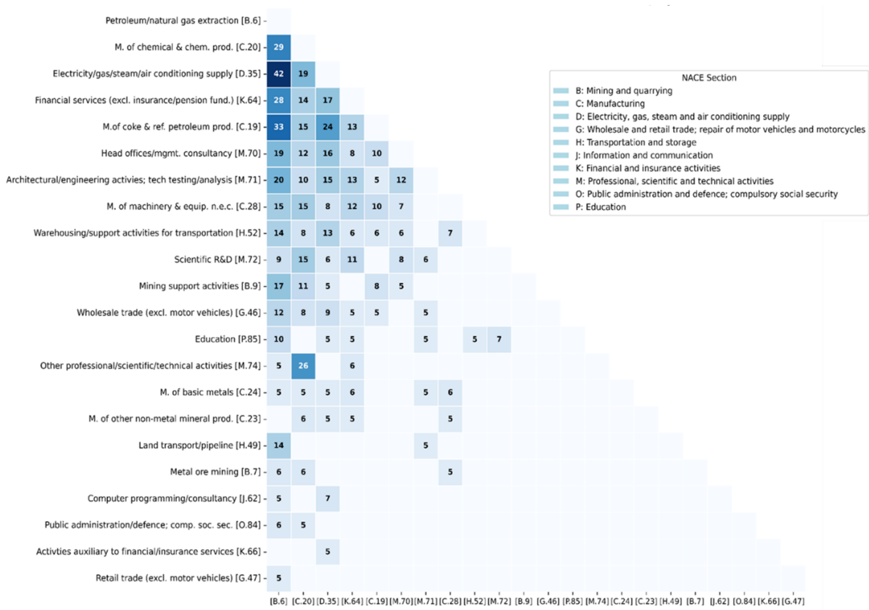

Figure 8: Inter-industry co-occurence matrix in CCUS projects by NACE sectors.

We find that collaborations are more likely among carbon-intensive industries, where companies in oil and gas extraction cooperate with companies in industries such as electricity and gas supply, chemicals and refined petroleum production. Indeed, the electric power industry plays a crucial role in the CCUS value chain to which it may supply the energy required for industrial decarbonization. This suggests that companies adopting CCUS technologies to reduce CO_2 emissions have a prior relevant expertise to integrate CCUS within their existing value chains. Equally significant is the participation of scientific research and engineering companies, which provide the technical foundations necessary for the development and deployment of CCUS technologies. Their partnerships with heavy industries, such as machinery manufacturing and chemicals, highlight the importance of technological innovation and specialized expertise in addressing the challenges of industrial decarbonization. The co-occurrence matrix also reveals the intense participation of financial services companies to projects in the energy and chemical sectors, providing the expertise to raise the large capital endowments needed to carry on and realize CCUS projects. Collaboration between industry and finance is therefore critical to overcome economic barriers to sustainability.

To complement our analysis of inter-industry collaborations, Figure 9 illustrates the industrial diversity of companies within CCUS projects by sector/technology and by region (continent). In CCUS projects for power and heat generation, natural gas processing, fuel transformation, material (cement, iron and steel) diversification appears relatively low. In contrast, projects that require advanced technological innovation and new market infrastructure — such as direct air capture (DACC), hydrogen and ammonia production, and CO_2 transport and storage — tend to rely on a broader range of industries. Finally, turning to diversity by region (Figure 9), we find that European CCUS projects typically benefit from more extensive cross-industry collaborations, whereas diversification appears lower within North American projects, possibly as a result of a preference for vertical integration.

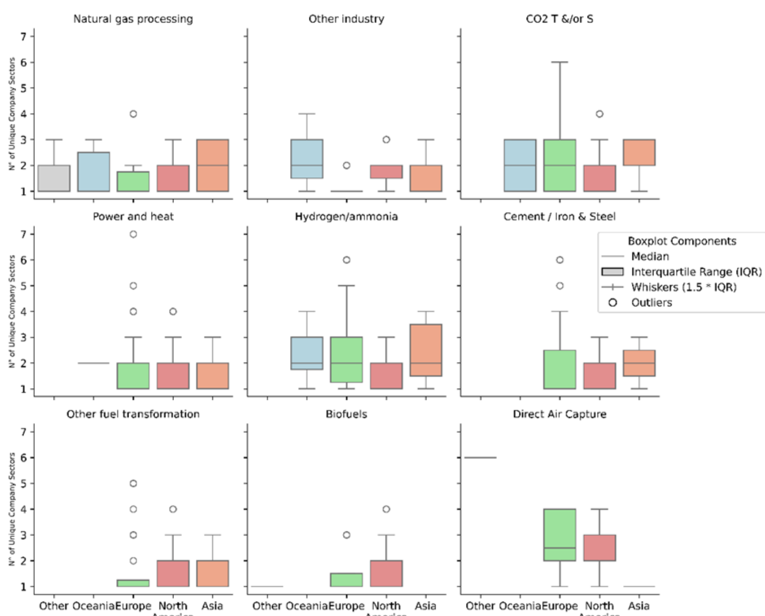

Figure 9: Diversity of company NACE sectors within projects by region and CCUS technology

5.3 Organizational choices and capture capacity: The role of hubs

To address the research question about the organizational structure and performance of CCUS projects, we start by presenting some estimations of their CO_2 sequestration capacity for projects that are or will become operational up to 2030, based on estimates of the actual and future amounts of carbon captures in the IEA database.[23] We then focus on the different organization models projects can adopt, and end up by comparing their capture performance.

5.3.1 The estimated trend of cumulative CO_2 capture capacity

Figure 10 reports the cumulative CO_2 captured by CC operational projects up to 2030, assuming a high vs. low capture capacity scenario.[24] Should all planned projects become operational as announced, and the self-declared projections realized, they would reach a capture capacity of 250–300 $MtCO_2$ per year by 2030, implying an increase in the scale of the CCUS industry by 600%. Although this estimate does not appear very realistic, we have to consider that, before 2020, CCUS (excluding the EOR component), was primarily in a stage of research and development and performed within pilot-scale projects to validate technological feasibility and readiness. Very few CCUS initiatives exceeded a capture capacity of 0.1 $MtCO_2$ annually, and Operational Capture Projects (OCP) that had started before 2020 were just 34. In future years many more projects should become operational.

Turning to Figure 11, we find that the estimated capture capacity varies with the different capture technologies used by the (carbon-intensive) industries that implement them - biofuels, other fuels, iron and steel, H2/ammonia, DACC, Cement, Liquid Natural Gas (LNG), Power and Heat and others. Once again, we find that Power&Heat, Hydrogen/Ammonia and LNG, associated with the energy industry, are at the top of the list of capture capacity. Notably, the horizontal dotted lines highlight two different innovation phases, i.e., from

[23]For consistency, we use information only for the 256 projects that, in the IEA database, actually operate carbon capture (CC)

[24]The latest ascertain capture data is at 2023. From then on, the cumulative curve is drawn based on the amounts self-declared by projects developers, assuming no new projects will be set up after 2023.

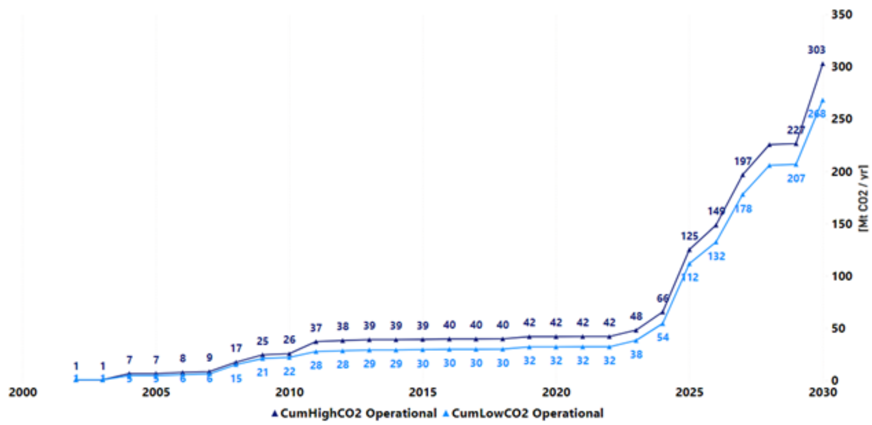

Figure 10: Cumulated captured $MtCO_2$/yr for operational CC projects (high vs low capacity scenarios). Source: Our elaborations on IEA's 2023 CCUS Projects Database.

1990 to 2020, product innovation was characterized predominantly by R&D investments and pilot scale projects and, from 2023 onward a period in which the technological progress has started to generate incremental/process innovation with major investment in mid-/large-scale projects.

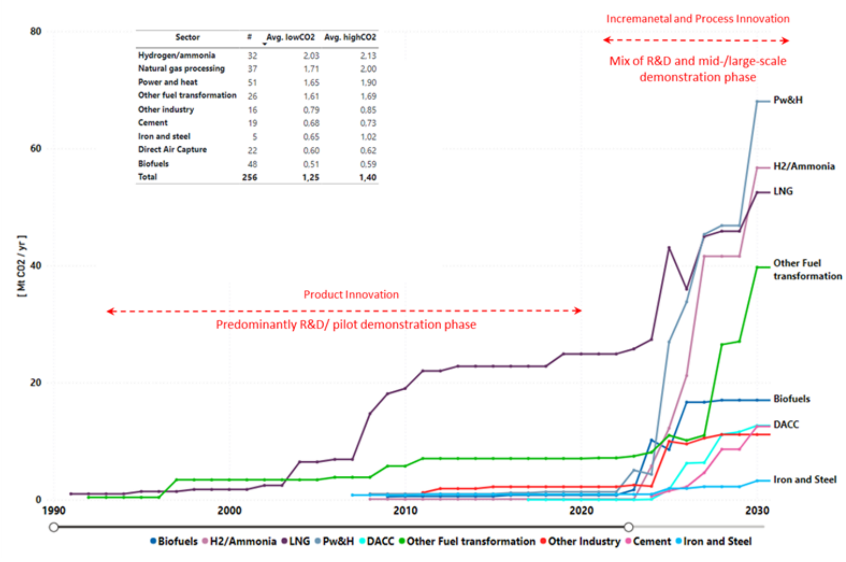

Figure 11: Cumulated captured $MtCO_2$/yr for operational CC projects (low capacity scenario) by technology. Source: Our elaborations on IEA's 2023 CCUS Projects Database.

5.3.2 Organizational models and performance

We now address the organizational structure of CCUS projects, in particular focusing on the the so-called *project-hub* model (The CCUS Hub, 2022)[25], and then relate different models to estimated carbon captured (in $MtCO_2$ per year).

Project hubs are viewed as crucial to scale up CCUS initiatives in that they allow the integration of capture, transport, and storage infrastructures across multiple industrial sites (Yao et al., 2018)[34]. Our analysis reveals that, on average, 57% of CCUS projects are implemented within a hub structure, and that 158 currently operate worldwide. There are different models of hubs, depending on the length and scope of the value chain they involve. “Cradle-to-Grave” hubs cover the entire CCUS chain, i.e., capture, transport, and storage; “Half Value Chain” hubs engage in at least two these stages (e.g., capture and transport, capture and storage, or transport and storage); while “Single-Project” hubs are limited to a single stage of the value chain, though equally involving more companies (IEA, 2023)[26]

Figure 12 shows project hubs by region and by the length of the value chain. Typically, project hubs are more diffused in countries with advanced CCUS technology and infrastructure, because they imply a more sophisticated coordination of the different activities. We find that while North America has the greatest concentration of Single-Project hubs, in Europe the distribution is more balanced, with a relatively higher share of the more complex Cradle-to-Grave hubs (with respect to the US).

The analysis by region also shows that in large and rich of natural resources nations like the United States, Canada, and China, full-chain CCUS projects outside a hub structure are more common than in Europe. Indeed, because North America has a well-established oil and gas industry as well as favorable mix of financial resources and technological capabilities, large-scale CCUS projects can develop independently or through joint ventures rather than

[25]link: `https://ccushub.ogci.com/policies-business-models/business-models/`

[26]IEA (2023), CCUS Policies and Business Models: Building a Commercial Market, IEA, Paris https://www.iea.org/reports/ccus-policies-and-business-models-building-a-commercial-market, Licence: CC BY 4.0

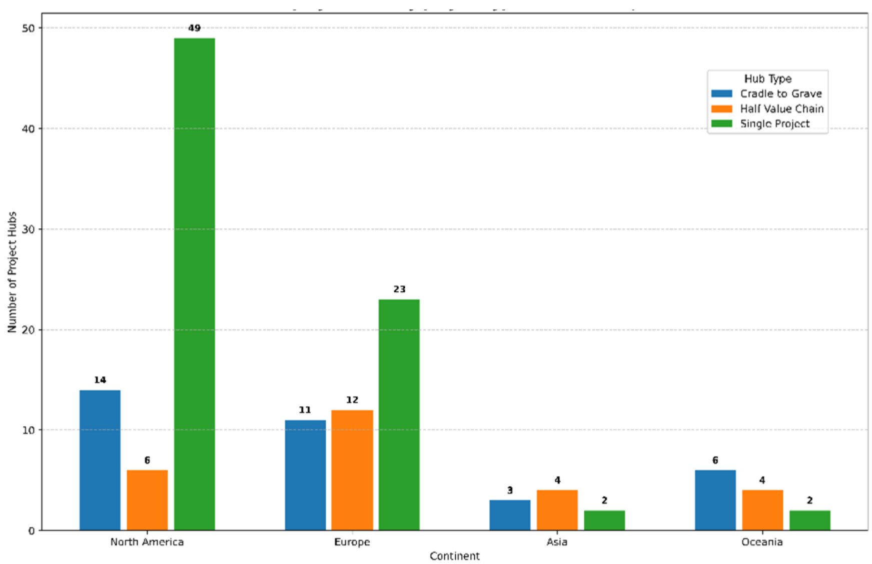

Figure 12: Distribution of project hubs by region and scope of the value chain.

within hubs. In contrast, in Europe, the smaller domestic market scale, and the need to develop innovative CCUS technologies (vis-à-vis the established applications related to the energy industry, like EOR) may incentivize collaboration within hubs.

Finally, we turn to our main question, i.e., which project organization seems to be more effective in terms of capture capacity. Figure 13 compares this performance of initiatives inside and outside hubs. On the whole, projects inside hubs seem to perform better. We find that hub-based projects, where collaborative infrastructure enables shared capital investment and larger economies of scale, exhibit higher efficiency when employed in either the transport and/or the storage of captured CO_2 while projects focusing exclusively on the utilization of CO_2 tend to operate outside of hubs and, not surprisingly, have the lowest GHG capture capacity. Finally, in full-chain initiatives as well as in projects solely focused on carbon capture the performance in terms of capture capacity is more similar, which suggests that existing capture technologies are sufficiently optimized and well-integrated into company-specific processes, even without the support of hub infrastructure.

Overall, the figure underscores how project-hubs, particularly those incorporating transport, storage, and full-chain operations, capitalize on shared resources to improve capture

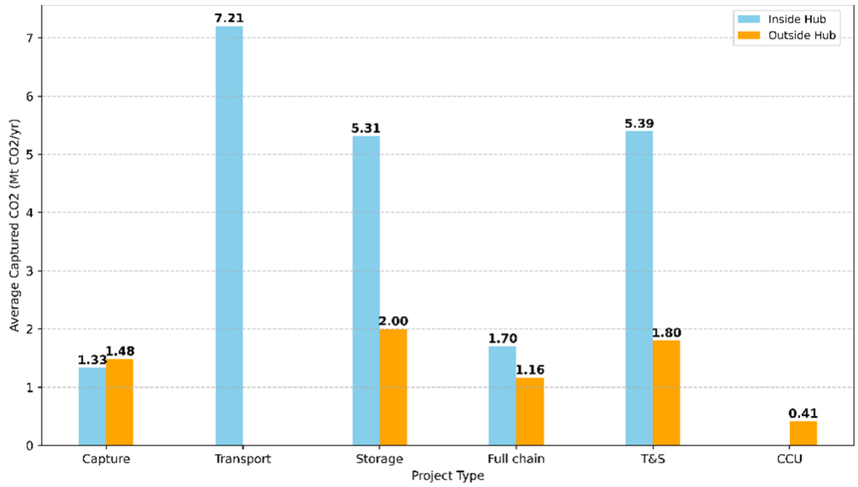

Figure 13: Announced GHG emissions captured by projects inside and outside a CCUS hub.

efficiency, emphasizing the critical role of coordinated infrastructure in enhancing large-scale CCUS effectiveness.

6 Discussion

The results presented in the previous section allow us to draw new insight into the factors contributing to the heterogeneous geographical and technological diffusion of CCUS projects, and to derive some policy implications.

Our first research question addresses the geographical diffusion of CCUS projects. We find that the worldwide diffusion of CCUS projects mirrors the substantial heterogeneity, across regions and sectors, in terms of policy frameworks and industrial specialization. For example, our results show that dedicated storage is the most prevalent application, suggesting that CCUS diffusion still depends on pre-existing expertise in geological exploration, pipeline construction, and underground drilling for permanent storage. Countries without this specialized knowledge do not develop the CCUS network infrastructure that is key to the energy and petrochemical sectors, which are, currently, the primary market for CCUS. So, Southern EU countries appear far less engaged in CCUS activities than Northern EU nations, which host many mining operations. However, we also find that being a leading oil producer alone is not sufficient to spur decarbonization efforts. Nations such as Iran, the United Arab Emirates, Saudi Arabia, Qatar, Mexico, Brazil, Venezuela, the Russian Federation, China, and Indonesia—despite their dominance in the oil industry—have no significant CCUS initiatives, thus suggesting that, in some of these countries, CO_2 emissions may be viewed as a necessary evil to maintain affordable energy and support economic growth.

A second factor is the regional environmental policy. We find that the policy framework is crucial in shaping the geographic distribution of CCUS projects. Countries like the United States and Canada, which established clear and sustained support policies — particularly via instruments like the 45Q tax credit — fostered the deployment of many projects. In contrast, the EU, despite a surge in the announcement of new projects after 2020, is still lagging behind in terms of project implementation due to delays in the commitment of financial resources and in the release of building permits.

All in all, this analysis suggests that certain regions attract more CCUS projects partly due to their pre-existing industrial structure, natural resources and technological specialization, and partly due to the quality of policy interventions and instruments.

Next, we turned to inquire why CCUS activity is concentrated in specific industries and we focused on cross-sectoral relationships of companies involved in these projects. Our results show that carbon-intensity is a major industry-specific factor behind the development of CCUS projects, as testified by their concentration in the energy and chemical sectors, where the technical expertise and capital intensity is the second key driver for large oil, gas, and biofuel producers. Our mapping of inter-sectoral firm relationships reveals intense multi-sector collaborations. This evidence suggests that the integration of diverse expertise is a further crucial factor not only from the technological point of view but also because it allows to exploit scale and scope economies. The current concentration of inter-industry relationships in carbon-intensive industries, however, confirms that the applications of captured CO_2 in other activities is still limited. The empirical insight from our second research question contributes to the literature a detailed overview of industrial participation in CCUS projects beyond anecdotal or technological case-studies. It also suggests that policies aiming to foster CCUS must target sectors and companies less engaged in CCUS not only through subsidies, but also by promoting inter-industry partnerships.

The third research question examines whether organizational choices affect the implementation and scale of CCUS technologies. On this matter, we highlight the role of project hubs that, by integrating the transport and storage infrastructures, appear more likely to benefit from economies of scale and to access public funding. We find that more than half of all capture-dedicated projects are developed within hubs, and that these settings are especially effective when they establish a broader value chain, embedding capture, transport and storage. In fact, the announced carbon capture capacity of projects within hubs appear to be larger than that of projects outside hubs. Interestingly, regional differences persist also with regard to organizational choices. So, while North American projects tend to be more vertically integrated and to rely on existing industrial infrastructure, European projects increasingly adopt the hub model to coordinate participants and expertise across national borders. Moreover, in Europe, CCUS projects in newer technological domains like DACC or hydrogen production are more often part of hubs, hinting at a broader, more collaborative industrial base. This suggests that hubs are not only a functional organizational choice and more effective in CO_2 capture, but also a strategic response to institutional complexity and technological diversity.

Overall, our results provide three original contributions to the literature. First, our comprehensive mapping of the global CCUS sector highlights how policy and industrial characteristics jointly shape project outcomes, and the importance of matching financial support with sector-specific and regional strategies. Second, we confirm that, in Western economies, carbon-intensive industries drive the deployment of CCUS technologies and projects, and we also find that companies from different sectors join in collaborative projects to exploit their technological capabilities. Third, we find that collaborative organizational forms such as project hubs seem to offer a valuable construct to inspire both policy design and business strategy. In fact they appear to provide higher carbon capture capacity, while at the same time allowing firms to access complex infrastructures, exchange technological know-how and diversify decarbonization risk.

7 Conclusion

This paper studies the evolution of the Carbon Capture, Use & Storage (CCUS) projects from 1990, based on the IEA database, which we have completed with hand-collected qualitative information. An interesting feature of the CCUS system is its encompassing very diverse technologies, some mature (like EOR), others at the frontiers of research (like DACC). While CCUS has been gaining momentum since 2020, only 10% of the projects are currently operational while many more of the announced projects are still stuck in their FEED phase.

Our analysis show that the geographical distribution and the technological specificity of CCUS projects worldwide result from the intertwined action of industrial specialization and carbon intensity, different environmental policies and size of the potential market. The different combination of these factors, in turn, affects the internal organization of projects, whether stand-alone or through a hub of projects. We thus find a high share of projects in both North America and in Northern Europe, where the concentration of natural resources and carbon-intensive industries related to energy production is high. Not surprisingly, most projects are dedicated to the storage of captured CO_2, while the others either use it for EOR (for oil and gas companies) or as a feed in cement, iron and steel and chemical plants. To date, capture and utilization projects are lagging behind capture, storage and transport, but enjoy higher public acceptance due to their supposed contribution to a circular economy. When we analyse the industrial origin of companies involved in CCUS projects, we find a prominence of chemical, oil and gas, iron and steel, cement, mining and machinery, most of them engaging in CCUS to decarbonize their production process. But we also find that many companies in different industries cooperate within CCUS projects in partnerships that range from electric power to engineering and financial service companies. This evidence leads to our last set of results on organizational choices, which highlight the growing diffusion of project hubs, with different levels of integration of the CCUS process. Although the hub structure can be viewed as particularly fitting cross-border European projects, because it allows them to scale up and exploit economies of scope at a regional (instead of national) level, it is also diffused in North America. However, America and Europe still differ because the former has relatively more single-project hubs while the latter has longer value chains. When we turn to the complex issue of which organizational structure is more effective in terms of capture capacity, our tentative evaluation, based on available data, is that project hubs tend to perform better.

Data availability is, unfortunately, a major limitation of this research, as complete and comparable information on financial investment, public subsidies, capture capacity - hence, expected performance - is not available on a consistent basis. Moreover, the majority of projects being at a preliminary stage, some of our evaluations had to be based on their own announced data and forecasts, seriously impairing the possibility to perform a robust statistical analysis. In our future research, we can focus on a specific CCUS technology and collect detailed project data also by means of surveys and personal interviews. With the caveats just mentioned, our study allows a deeper understanding of the dynamics shaping the CCUS system and its alignment with global decarbonization goals. Our findings underscore the need for coordinated actions among governments, companies, and research institutions to overcome barriers to scaling up capture capacity and to optimize the integration of CCUS technologies into climate strategies. This analysis serves not only as an academic contribution but also as a practical resource for policymakers and industry stakeholders aiming to accelerate the green transition.

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A The structure of the IEA's 2023 Projects Database

Appendix Table 3 reports the structure of the IEA's 2023 CCUS Projects Database and data characterization (available at `https://www.iea.org/data-and-statistics/data-product/ccus-projects-database`).

Column name	Value	Notes
Project name	/	
Country	/	
Partners columns	Partners.1 to Partners.12	For each project is specified main key players who are developing the project itself, including technology providers, contractors for Front-End Engineering Study (FEED), Equipment Procurement and Construction (EPC), consultancy and financial firms, transport or shipping companies, etc.
Project type	Full chain	Projects where CO2 is transported from one capture facility to one injection site, typically involving a single operator
	Capture	Capture-only project (the project does not include any transport and storage development but can be developed as part of a CCUS hub)
	Transport	CO2 transport-only project, which may include CO2 shipping, pipelines, terminals with liquefaction stations/buffer storage, etc.
	Storage	CO2 storage-only project (no mention of connecting infrastructure), including both dedicated storage and CO2 EOR
	T&S	CO2 transport and storage project which includes both transport and storage development
	CCU	A project that captures CO2 for use (excluding internal use such as urea production) with significant climate benefits and a clearly identified source for the captured CO2
Announcement	Year	Project announcement date (normally coinciding with MoU or JV between different companies)
FID	Year	Final Investment Decision
Operation	Year	Operation date
Decommissioning	Year	Suspension/decommissioning date
Project Status	Planned	Project at concept or FEED stage
	Under construction	FID has been announced and construction is ongoing or imminent
	Operational	Project has been commissioned and it is running
	Suspended	Project operation has been suspended for more than six months
	Decommissioned	Project operation is permanently stopped
CC capacity (low)	[MtCO2/yr]	Announced GHG emissions captured (lower bound)
CC capacity (high)	[MtCO2/yr]	Announced GHG emissions captured (upper bound)

Table 3: IEA's 2023 CCUS Database structure and specifications. *Source: IEA's CCUS 2023 Database.*

B Extended Data on companies and projects by different NACE Divisions

Manufacturing NACE divisions	**Number of companies**	**Number of projects**	**Total companies' participations**
Manufacture of chemicals and chemical products	57	117	129
Manufacture of coke and refined petroleum products	24	79	89
Manufacture of machinery and equipment n.e.c.	7	45	45
Manufacture of other non-metallic mineral products	14	42	36
Manufacture of basic metals	10	19	20
Manufacture of food products	3	11	11
Manufacture of electrical equipment	4	9	9
Manufacture of fabricated metal products, except machinery and equipment	4	5	5
Manufacture of computer, electronic and optical products	4	5	5
Manufacture of motor vehicles, trailers and semi-trailers	2	3	4
Manufacture of paper and paper products	2	2	2
Manufacture of basic pharmaceutical products and pharmaceutical preparations	2	2	2
Manufacture of tobacco products	1	2	2
Repair and installation of machinery and equipment	1	2	2
Manufacture of other transport equipment	2	2	2
Other manufacturing	1	1	1
Manufacture of furniture	1	1	1
Total	**139**	**347**	**365**
Mining and quarrying NACE divisions	**Number of companies**	**Number of projects**	**Total companies' participations**
Extraction of crude petroleum and natural gas	60	180	234
Mining support service activities	19	54	54
Other mining and quarrying	6	9	9
Mining of metal ores	2	8	8
Mining of coal and lignite	4	4	4
Total	**91**	**255**	**309**
Electricity, gas, steam and air conditioning supply NACE divisions	**Number of companies**	**Number of projects**	**Total companies' participations**
Electricity, gas, steam and air conditioning supply	77	126	155
Total	**77**	**126**	**155**
Transportation and storage NACE divisions	**Number of companies**	**Number of projects**	**Total companies' participations**
Land transport and transport via pipelines	16	34	36
Warehousing and support activities for transportation	15	27	34
Water transport	4	5	6
Air transport	2	2	2
Total	**37**	**68**	**78**
Professional, Scientific, and Technical Activities NACE divisions	**Number of companies**	**Number of projects**	**Total companies' participations**
Architectural and engineering activities; technical testing and analysis	34	62	74
Activities of head offices; management consultancy activities	26	50	54
Other professional, scientific and technical activities	17	43	53
Scientific research and development	20	33	52
Advertising and market research	1	1	1
Total	**98**	**18**	9 234

Table 4: Extended Data on companies and projects by different NACE Divisions

C US, Canada and EU CCUS Policies – facts and figures

In this Appendix section, we report the tables resuming our calculations on the financial commitment within various US (Appendix Table 5[27] and Figure 14[28]) and European (Appendix Table 7 and 8[29]) policies.

Infrastructure Investment and Jobs Act (2022–2026) [mln$]								
Category	**Sections**	**2022**	**2023**	**2024**	**2025**	**2026**	**Total**	**%**
USE	Sec. 40302. Carbon Utilization Program	41	65.25	66.562	67.941	69.388	310.141	1.5%
	Sec. 40303. Carbon Capture Technology Program (FEEDs)	20	20				100	
Carbon Capture	Sec. 40304. Carbon Capture Demonstration and Pilot Programs							16.9%
	(a) Carbon Capture Large-Scale Pilot Projects	387	200	200		150	937	
	(b) Carbon Capture Demonstration Projects Program	937	500	500	500	100	2537	
Storage	Sec. 40305. Carbon Storage Validation and Testing	500	500	500	500	500	2500	12.1%
	Sec. 40306. Secure Geologic Storage Permitting	11	11	11	11	11	55	
CO_2 Transport	CIFIA Program	600					3000	14.4%
	CIFIA Program Administrative Costs	9	9	9	9	9	45	
H_2 Hubs	Sec. 40314. Additional Clean Hydrogen Programs	1600	1600	1600	1600	1600	8000	37.9%
DACC	Sec. 40308. Carbon Removal (DACC)	700	700	700	700	700	3500	17.1%
	Sec. 41005. Direct Air Capture Technologies Prize Competitions							
	(a) Precommercial	15					15	
	(b) Commercial	100					100	
TOTAL		**4920**	**4205.25**	**4206.562**	**4257.941**	**3509.388**	**21099.14**	**100.0%**

Table 5: CCUS investment amount from the Infrastructure Investment and Jobs Act (IIJA). FYs: 2022-2026. Mln$. *Source: own data elaboration of U.S. Government Publishing Office's 117th Congress Public Law 58 (IIJA)*

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Equipment Placed in Service after 2/8/2018 and before 1/1/2023	Equipment Placed in Service after 12/31/2022 and Construction Beginning Prior to 1/1/2033
Credit Amount (per Metric Ton of CO_2)	
Geologically Sequestered CO_2	
\$40.89 per Metric Ton of CO_2 in 2023. Increasing ratably to \$50 by 2026, then inflation-adjusted.	Base credit of \$17 per Metric Ton of CO_2 (\$36 for DAC), increased to \$85 (\$180 for DAC) for facilities that pay prevailing wages during the construction phase and during the first 12 years of operation and meet registered apprenticeship requirements. Amounts adjusted for inflation after 2026.
Geologically Sequestered CO_2 with EOR	
\$27.61 in 2023. Increasing ratably to \$35 by 2026, then inflation-adjusted.	Base credit of \$12 (\$26 for DAC), increased to \$60 (\$130) for facilities that pay prevailing wages during the construction phase and during the first 12 years of operation and meet registered apprenticeship requirements. Amounts adjusted for inflation after 2026.
Other Qualified Use of CO_2	
\$27.61in 2023. Increasing ratably to \$35 by 2026, then inflation-adjusted.	Base credit of \$12 (\$26 for DAC), increased to \$60 (\$130) for facilities that pay prevailing wages during the construction phase and during the first 12 years of operation and meet registered apprenticeship requirements. Amounts adjusted for inflation after 2026.
Claim Period	
12-year period once facility is placed in service.	12-year period once facility is placed in service, reduced to 5-year period if transferred.
Annual Capture Requirements	
Power plants: Capture at least 500,000 metric tons. *Facilities that emit no more than 500,000 metric tons per year:* Capture at least 25,000 metric tons. *DAC and other capture facilities:* Capture at least 100,000 metric tons.	*Power plants:* Capture at least 18,750 metric tons and a capture design capacity not less than 75 percent of baseline emissions. *DAC facilities:* capture at least 1,000 metric tons. *Other capture facilities:* capture at least 12,500 metric tons.
Eligibility to Claim Credit	
Entity who owns the capture equipment and physically or contractually ensures the disposal, utilization, or use as a tertiary injectant of the CO_2.	Entity who owns the capture equipment and physically or contractually ensures the disposal, utilization, or use as a tertiary injectant of the CO_2. Certain tax-exempt entities can claim the tax credit through "direct pay" and other entities are allowed a one-time transfer to another entity.

Source: CRS analysis of IRC Section 45Q, 26 U.S.C. §45Q.

Notes: After 2017, the credit can be claimed for all carbon oxides, not just CO_2. Equipment placed in service prior to February 8, 2018, is no longer eligible for the 45Q tax credit.

Figure 14: Key Elements of the Section 45Q Tax Credit. *Source: Federation of American Scientists' The Section 45Q Tax Credit for Carbon Sequestration*

Table 6: EU's CCUS investment programs from 2012 to date are funded by EU ETS allowances monetarization. *Source: own data elaboration from European Commission's Climate Action documents and articles.*

Program name	Main goal	Call for proposals	Project type	Allowances sold (mn)	[bn€]	Projects funded
NER 300 program	Testing and demonstration of CCS (Carbon Capture and Storage) methods and renewable energy technologies	1° call: 2012	/	200	1.1	20 RE
		2° call: 2014	/	100	1	18 RE, 1 CCS
Innovation Fund	Innovative low-carbon technologies and processes in energy-intensive industries, including products that can substitute carbon-intensive ones: CCU projects, CCS facilities, innovative renewable energy generation, hydrogen hub and fuell cells, energy storage.	1° call: 2021	small-scale**	not specified	0,1	Grant: 4/32 CCUS PDA***: 1/10 CCUS
			large-scale**	not specified	1,1	Grant: 4/7 CCUS PDA: 2/15 CCUS
		2° call: 2022	small-scale**	not specified	0,062	Grant: 0/16 CCUS PDA***: 0/16 CCUS
			large-scale**	not specified	1,8	Grant: 7/16 CCUS PDA: 2/15 CCUS
		3° call: 2023	small-scale**	not specified	0,1	72 applications (process ongoing)
			large-scale**	not specified	3	239 applications (process ongoing)
		future calls: 2024-2030	Unknown	Around 500	25-30****	Unknown
TOTAL FUNDING IN CCUS PROJECTS THROUGH ETS ALLOWANCES MONETIZATION (2012-2023)						**€6.3 billion**

Table 7: Notes: * Renewable Energies; ** small-scale: capital expenditures €2,5 – €7,5 million / large-scale: capital expenditures €7,5 million; *** PDA: Project Development Assistance by the European Investment Bank (EIB); **** The Innovation Fund's total funding depends on the carbon price, and it may amount to about €40 billion from 2020 to 2030, calculated by using a carbon price of €75/tCO2. NER300 Program (2012-2014) signed grants. Innovation Fund (2021-2023) signed grants.

Table 8: EU investments in CCUS R&D projects from 2012 to date are funded by CEF – Energy, Horizon 2020 and Horizon Europe programs. *Source: own data elaboration from European Commission's documents.*

Program Name	Calls & Tenders	Period	[bn€]	%
Connecting European Facilities (CEF) - Energy	Projects of Common Interest (PCIs), electric, gas, smart grid, and CO_2 networks. Here, only cross-border CO_2 networks (pipeline and transport hubs) investment are reported only	**2014-2020** (total budget)	**0.144 €** 4.70 €	**3.10%**
		2021-2027 (total budget)	**not found** 5.84 €	**CEF 2014-2020**
Horizon 2020	**Secure, clean and efficient energy. Tot. Budget**	**2018-2020**	**2.302 €**	
	- LC-SC3-NZE-1-2018: Advanced CO_2 capture technologies	2018	0.001 €	
	- CE-SC3-NZE-2-2018: Conversion of captured CO_2	2018	0.004 €	
	- LC-SC3-NZE-3-2018: Strategic planning for CCUS development	2018	0.003 €	
	- LC-SC3-NZE-4-2019: Integrated solutions for flexible operation of fossil fuel power plants through power-to-X-to-power and/or energy storage	2019	0.001 €	
	- LC-SC3-NZE-5-2019-2020: Low carbon industrial production using CCUS	2019-2020	0.012 €	
	- LC-SC3-NZE-6-2020: Geological Storage Pilots	2020	0.010 €	
	- LC-SC3-NZE-5-2020: Low carbon industrial production using CCUS	2020	0.015 €	
	Horizon 2020 total budget	**2018-2021**	**2.302 €**	
	Horizon 2020 CCUS R&I total budget	**2018-2020**	**0.046 €**	**2%**
Horizon Europe	**Climate, Energy and Mobility. Tot. Budget.**	**2021-2022**	**3.603 €**	
	- HORIZON-CL5-2021-D3-02-12: Integration of CCUS in hubs and clusters, including knowledge sharing activities	2021	0.002 €	
	- HORIZON-CL5-2021-D3-02-13: Cost reduction of CO_2 capture	2021	0.030 €	
	- HORIZON-CL5-2021-D3-02-14: Support to the activities of the European Geological Services	2021	0.020 €	
	- HORIZON-CL5-2022-D3-01-15: Decarbonising industry with CCUS	2021	0.058 €	
	Horizon EU CCUS R&I total budget	**2021-2022**	**0.110 €**	**3.05%**
	Climate, Energy and Mobility. Tot. Budget	**2023-2024**	**2.777 €**	
	- HORIZON-CL5-2023-D3-01-17: Development of CO_2 transport and storage demo projects	2023	0.040 €	
	- HORIZON-CL5-2023-D3-02-01: Development of near zero-emission biomass heat and/or CHP including carbon capture	2023	0.008 €	
	- HORIZON-CL5-2024-D3-02-11: CCU for the production of fuels	2024	0.015 €	
	- HORIZON-CL5-2024-D3-02-12: DACCS and BECCS for CO_2 removal/negative emissions	2024	0.015 €	
	Horizon EU CCUS R&I total budget	**2023-2024**	**0.078 €**	**2.81%**

D List of companies highly involved in CCUS projects

Table 9 reports the first 40 companies in terms of the number of projects. For each company, we also report the corresponding BvD sector surveyed in the Orbis - Bureau van Dijk database. In total, there are 628 companies involved in at least one CCUS project, of which 42 show more than 7 CCUS projects.

N	Companies	BvD Sector	Company's projects
1	Summit Carbon Solutions Llc	Business Services	34
2	Shell Plc	Mining & Quarrying	33
3	L'Air Liquide	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	31
4	Equinor Asa	Public utility services	26
5	Totalenergies Se	Mining & Quarrying	24
6	Exxonmobil Asia Pacific Ltd	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	22
7	Eni S.P.A	Mining & Quarrying	18
8	Mitsubishi Corporation	Wholesale	17
9	Holcim Group Support Ltd	Business Services	16
10	Aker Carbon Capture As	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	13
11	Denbury Inc	Mining & Quarrying	13
12	Heidelberg Materials Ag	Leather, stone, clay and glass products	13
13	Carbon Engineering Inc	Business Services	12
14	Bp Plc	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	11
15	Chevron Corp	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	10
16	Wintershall Dea Ag	Mining & Quarrying	10
17	1Pointfive Llc	Business Services	9
18	Ebn B.V.	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	9
19	Fluxys	Public utility services	9
20	Ineos Industries Limited	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	9
21	Port of Rotterdam	Public utility services	9
22	8 Rivers Capital Llc	Industrial, electrical and electronic machinery manufacturing	8
23	Adm Hamburg Ag	Food & Tobacco Industry	8
24	Adnoc Drilling Company P.J.S.C.	Mining & Quarrying	8
25	Gasunie Transport Services B.V.	Public utility services	8
26	Green Plains Inc.	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	8
27	Linde Inc.	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	8
28	Neptune Company	Industrial, electric and elecotronic machinery manufacturing	8
29	Occidental Petroleum Corporation	Mining & Quarrying	8
30	Oxy Low Carbon Ventures, Llc	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	8
31	Santos Ltd	Mining & Quarrying	8
32	Sse Thermal Energy Operations Limited	R&DTechnological	7
33	Arcelomittal Sa	Metallurgy & Metal products	7
34	Borealis Exploration Limited	R&DTechnological	7
35	Cf Industries Holdings, Inc.	Chemicals, pharmaceuticals, petroleum, rubber products and plastics	7
36	Climeworks iceland Ehf.	Biotechnology & Life sciences	7
37	Mitsui & Co Ltd	Wholesale	7
38	Rwe Aktiengesellschaft	Public utility services	7
39	Sk E&S Australia Pty Ltd	Banking, isnurance and financial services	7
40	Storegga Holding As	Real Estate Services	7

Table 9: Most Involved companies in terms of number of projects. *Source: own data elaboration on IEA's 2023 CCUS Projects Database.*