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Overview of the institutional background of Carbon Capture, Utilization and Storage (CCU/S) Technologies in the European Union

Krisztina Kádár – Zsófia Kószó

Nowadays, global climate change is an outstandingly important issue. In order to minimize its negative consequences, carbon dioxide (CO_2) emissions and their atmospheric concentration must be reduced. Despite the ambient CO_2 concentration being unprecedently high, it is a challenge to reduce it because the emissions are very diverse and there is no one-size-fits-all solution for them. The multifaceted problem thus requires multifaceted solutions, such as Carbon Capture, Utilization and Storage (CCU/S) technologies besides the other decarbonization tools. However, due to being an emerging technology, the appropriate regulatory and political background is still in its infancy, but these technologies are gaining more and more attention. The purpose of this review is to discuss the current institutional background of CCU/S technologies in the European Union (EU). By examining the critical points for CCU/S technologies to be deployed widespread, it can be seen that the EU considers these solutions to be of strategic value due to their future importance and relevance in climate change mitigation.

Keywords: carbon dioxide, carbon capture, carbon utilization, carbon storage, CCUS technologies in the EU

1. Introduction

For the sake of our future, global climate change has been getting increasing attention in the past decades and in our present as well. Although, without greenhouse gases and their effect, life could not exist on Earth, anthropogenic greenhouse gas emissions, including carbon dioxide, have upset the balance of nature (Alsarhan et al. 2021).

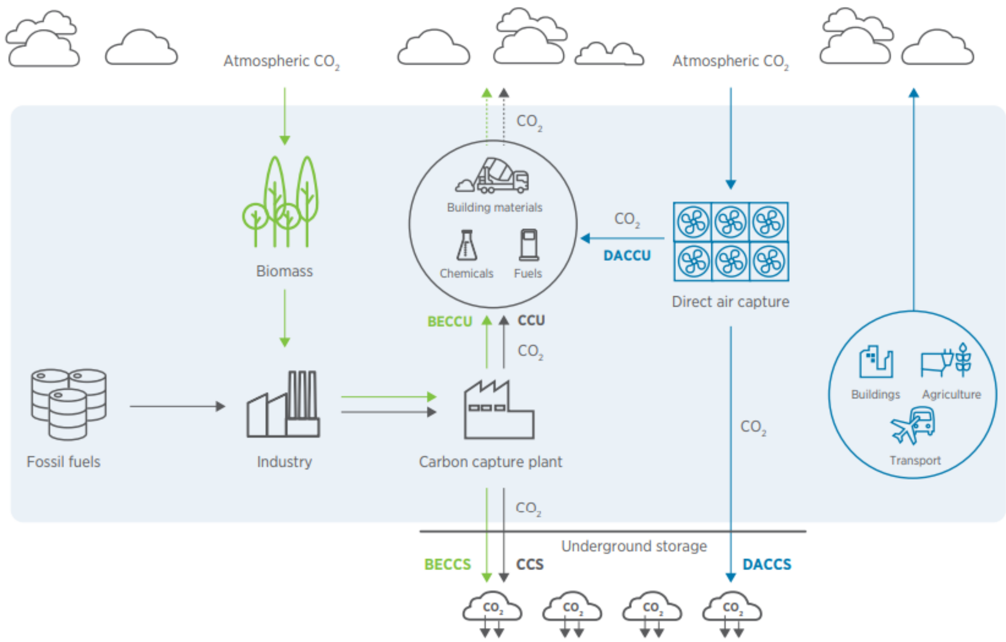
The reduction and management of the unprecedently high level of CO_2 concentration (~420 parts per million) (NOAA 2023) and emissions are essential, and it is more expedient to consider CO_2 as a resource and not as waste (Anwar et al. 2020, Dibenedetto et al. 2014). To mitigate climate change and to achieve the set climate goals, it is necessary to switch from the conventional fossil-based economy to more predictable, cheap and low-carbon, even zero carbon energy systems. The EU manages this issue with high importance and addresses it in its policy. As there is no one-size-fits-all solution to do so, a wide range of different technologies are needed (Cuéllar-Franca–Azapagic 2015, Rezaei et al. 2023).

CCU/S technologies can mean such solution in mitigating climate change. CCU/S refers to technologies in the field of Carbon Capture and Utilization (CCU), and Carbon Capture and Storage (CCS). There is a wide variety of carbon capture and separation solutions (MAN Energy Solutions 2022, Maniarasu et al. 2023, Kenarsari et al. 2013) that aim to capture CO_2 directly from the ambient air (direct air capture, DAC) (Bouaboula et al. 2024, Sun et al. 2023) or the flue gas of emission points

(Astuti et al. 2024, Cuéllar-Franca–Azapagic 2015). Cabon capture and storage technologies include the separation of CO_2 produced by large-scale industrial and energy sector plants, and also the transport and the long-term storage of CO_2 (CCUS Set-Plan 2022). Carbon capture and utilization, or CCU, is the process by which captured CO_2 is used in industrial processes or to produce products and raw materials as they consider carbon dioxide as a resource and not as waste (Baena-Moreno et al. 2019). CCU technologies are used in the production of everyday CO_2-based products such as building materials, synthetic fuels, chemicals, plastics (Butnar et al. 2020). CCU thus replaces carbon-intensive products already on the market, reducing dependence on fossil resources and promoting the transition to the Circular Carbon Economy (CCE).

CCE, which is based on the circular economy model, would achieve sustainable economic growth with the help of carbon dioxide (Figure 1), and can also play a fundamental role in achieving climate stabilization (Alsarhan et al. 2021). With its 4R (Reduce, Reuse, Recycle, Remove) model, in addition to reduction, reuse and recycling, it pays attention to a fourth component, the removal of CO_2 as well (Kokal 2020).

Figure 1. The Circular Carbon Economy



Source: Lyons et al. (2021)
Note: /BECCS=Bioenergy with Carbon Capture and Storage; BECCU= Bioenergy with Carbon Capture and Utilization; DACCS=Direct Air Capture with Carbon Storage; DACCU= Direct Air Capture with Carbon Utilization/

CCU/S technologies may serve as the only solution to reduce emissions in key sectors where other alternatives, such as electrification, are extremely expensive or impractical (IEA 2020b). According to the International Energy Agency (IEA), CCU/S technologies can contribute to the aggregated CO_2 emission reductions in the energy sector by 15% by 2070, and they play a key role in the following four ways: (1) they can manage emissions from existing power generation/industrial plants by retrofitting them with the technology applications; (2) they are able to support the low-carbon blue hydrogen production; (3) they can serve as a solution for hard-to-decarbonize industries (i.e. steel, cement, fertilizer production) and also for aviation and maritime transport (i.e. with the productions of synthetic fuels); and (4) by the removal of CO_2 from the atmosphere they can help to achieve the circular (carbon) economy.

The purpose of the present paper is to overview the institutional background of carbon capture and storage, and carbon capture and utilization technologies in the European Union. During this overview, starting from the basics, the most important areas will be discussed, which helps to better understand the topic. In our work, we aim to discuss the most defining points in the field of CCU/S in order for their deployment to map the present situation of CCU/S technologies and their relevance in the future. In this study, some frameworks and reports are overviewed that can influence the spread of the use of carbon capture, utilization and storage (CCU/S) technologies, and the role attributed to CCU/S in the decarbonization scenarios is also examined. In addition, we take a look at completed and operational pilot projects in the field of CCS and CCU separately, but also those that cover the entire value chain, including transportation, as well as provide insight into future infrastructure development plans that enable the transport and storage of CO_2. We also list the main organizations and networks that, among other things, help spread the application of CCU/S technologies. Last but not least, we present some support options that provide financial assistance for the implementation of CCU/S projects.

2. CCU/S-relevant background in the EU

In connection with the mitigation of climate change, many frameworks and reports have been prepared at the international level. The contents of these define basic directions and goals for both the near and the distant future. The documents below are all directly or indirectly related to the solutions provided by CCU/S technologies, with the help of which the set targets can be reached.

2.1. European Green Deal

The European Green Deal is a set of policy measures made public in December 2019 and designed to make the EU's economy sustainable: to reduce the net GHG emissions by 55% by 2030 based on the year 1990, and to achieve climate neutrality by 2050 being the first climate neutral continent in the world (European Commission, 2019). Its aim is to turn environmental challenges into opportunities in all policy areas, to ensure that the green transition is fair and that all economic actors are involved and not left behind.

The political activity generated by the European Green Deal and the legally binding targets related to achieving carbon neutrality by 2050 have raised the interest of both political decision-makers and industrial stakeholders in carbon capture and storage, and carbon capture and utilization (Popielak et al., 2024). CCS and CCU can significantly support the achievement of EU objectives, providing a path for sectors that heavily rely on energy-intensive industries, and help preserve jobs in core sectors of the EU economy (IEA, 2020a). In the meantime, the creation of additional sectors along the CCU/S value chain can be realized, which can contribute to the preservation of industrial competitiveness. The EU is also working with global partners to facilitate the development of an international carbon market, a key tool for creating economic incentives for climate action.

2.2. Intergovernmental Panel on Climate Change: Sixth Assessment Report

The Intergovernmental Panel on Climate Change (IPCC) evaluates the latest climate change related scientific findings and recommends solutions to address the arising issues (IPCC 2024). They provide regular assessments, and their objective is to promote governments by providing them information on a scientific basis, so they can receive help in developing climate policies. With these reports, the organization wants to draw the attention of the world's decision-makers to the extent of global changes caused by society.

Three Working Groups are operating under the IPCC. In 2022, Working Group III., which deals with the mitigation of climate change, reported in the Sixth Assessment Report (IPCC AR6 WG3) (IPCC, 2022). According to their report, the Nationally Determined Contributions (NDCs) of the countries signing the Paris Agreement do not contribute sufficiently to the achievement of the goals set in the Agreement, as being inadequate, too broad and insufficient. In order to achieve the goal of limiting global warming to 1.5°C, it is necessary to reduce emissions in all sectors, including and highlighting the energy sector and the industry, where significant transformation is needed. Some of the existing measures taken in many countries are proving to be very effective. However, IPCC proposes to expand and apply them fairly on a wider scale. These measures and steps taken by the countries are the building blocks of achieving significant emission reduction.Renewable Energy Directive: Revisions.

2.3. Renewable Energy Directive: Revisions

Since the introduction of the Renewable Energy Directive (RED) (2009/28/EC) in 2009, renewable energy sources have become more and more widespread: in 2023, the share of renewable energies in the energy consumption of the EU has increased to 24.5% (European Commission n.d.b). It set the EU target: 20% renewables by 2020 and national binding targets.

The directive's ambitions and measures have been revised a few times. A revision was made and entered into force in 2018 (2018/2001/EU) (European Commission n.d.b). The RED II set a comprehensive European target for the share of renewable energy: 32% by 2030, and rules had also been formed to remove potential barriers, encourage investment and reduce the costs of technologies. In addition, the realization of the broad involvement of the actors gained attention, citizens and businesses were provided with the opportunity to participate in the transition to clean energy.

In 2021, the European Commission proposed another revision (COM/2021/557 final) to accelerate the deployment of using renewable energy sources in the EU (European Commission, n.d.b). The RED III (EU/2023/2413) entered into force in November 2023 and has set a new overall renewable energy target: at least 42.5% by 2030 with an additional 2.5% top up aiming for 45%. The new directive speeds up the licensing procedures for new renewable energy power plants (i.e. solar panels, wind turbines) (Európai Parlament 2024).".

In regards of the CCU/S relevance, there are some significant numbers that could affect the possibilities for CCU/S technologies. In the transportation sector, member states can chose either to reduce the greenhouse gas emission intensity in the transportation by 14.5% until 2030 from the use of renewables, or to realize a share of renewable energies to be at least 29% by 2030 in the final energy consumption (Council of the European Union 2023). In addition, advanced biofuels and renewable fuels of non-biological origin (RFNBOs) sub-target is set of 5.5% in the share of renewable energies in the transport sector; within which target, the RFNBOs in this share are required to reach 1%. Moreover, in the industrial sector, there are set targets: by 2030 42% of the hydrogen used should come from RFNBOs, and by 2035 60% should. Besides these, in order to boost the fuel transition in maritime transport, the share of RFNBOs in the total amount of energy supplied to the maritime transport sector is required to be at least 1.2 % from 2030 (European Parliament–Council of the European Union 2023).

These specific expectations also promote the creation of a market for CCU products within the industry (mainly in the petrochemical and refining sector), as it is required for the transport industrial actors to fulfil the targets, i.e. to purchase CCU products (Farkas-Csamangó et al. 2023, Thielges et al. 2022).

2.4. EU Emissions Trading System: Revision

The EU Emissions Trading System (ETS), set up in 2005, is the world's first and largest carbon dioxide market, i.e. international emissions trading system, covering approximately 45% of the EU's greenhouse gas emissions (European Commission 2016). The Emissions Trading System is a key tool of the EU's climate change policy to cost-effectively reduce greenhouse gas emissions. The latest revision of the EU ETS Directive (2003/87/EU), adopted in 2018, sets the total amount of emission allowances for the period 2021–2030, in line with the EU's previous emissions reduction target (Erbach 2022). The committee's proposal for the amendment consists of five main elements (Erbach 2022): a reduction of emissions cap and setting more ambitious linear emission reduction targets for greenhouse gas emissions; a revision of the rules for free allocation of allowances and the stability reserve of the market; extending the ETS to maritime transport; establishing a separate new ETS for buildings and road transport; and increasing the Innovation and Modernisation Funds and new rules on the usage of ETS revenues.

According to the Commission's proposal, in order to align with the increased GHG emission reduction targets in the European climate law, it is necessary to reduce emissions from the sectors covered by EU ETS by 62% by 2030 (including the extension to maritime transport) compared to the 2005 level (European Council 2023). In order to achieve the set goal, the proposal increases the annual linear reduction factor by 4.3% per year in 2024–2027, and 4.4% in 2028–2030. The proposal would also extend the EU ETS to CO_2 emissions from maritime transport, with particular regard to large vessels over 5,000 gross tonnages, which would be gradually introduced between 2025 and 2027.

The Council and the European Parliament agreed that, from 2027, a new, separate emissions trading system (ETS II) will be created, which will include the distribution of fossil energy used for heating buildings and fuel for road transport and additional sectors. Regulated organizations, i.e. fuel distributors will supply fuels to the sectors. Under ETS II, all allowances would be auctioned, and none would be provided for free. For this reason, it is likely that the price of road transport and heating fuels will rise, therefore the resulting indirect social effects will be dealt with by the legislative proposal on the Social Climate Fund.

Fluctuations in the CO_2 price within the EU ETS impact the cost-effectiveness of CCS and CCU technologies, contributing to market uncertainty (Lamberts-Van Assche et al. 2022). The level of CO_2 prices in the EU ETS is influenced by various factors, including commodity prices, policy shifts, and geopolitical events. To enhance the EU ETS's effectiveness, policymakers should consider promoting environmental research networks, international cooperation, and organizational innovation (Mandaroux et al. 2023). Moreover, the examination of technology, current regulations, and case studies underscores the importance of implementing CCU/S systems in Waste-to-Energy (WtE) contexts to reduce CO_2 emissions (Bertone et al. 2024). This initiative aligns with the ambitious goal of achieving carbon neutrality in waste management in the EU. The EU ETS Directive 2023/959 outlines a plan to incorporate WtE incinerators into the EU ETS by 2028. This move could significantly drive the adoption of CCU/S in WtE incineration plants, as it mandates WtE facilities to financially account for their fossil CO_2 emissions.

2.5. REPowerEU Plan

In May 2022, the European Commission presented the REPowerEU plan, the overall goal of which is reducing Europe's dependence on the Russian fossil fuels, preferably before 2030 (Dinu 2023, European Commission 2022g). The plan also outlined the measures that can be used to respond to the sharply rising European energy prices, as well as preparing gas reserves for winter. It accelerates the transition to clean energy and focuses on providing help for the EU in saving energy, producing clean energy and diversifying the energy supplies.

In 2022 the Council and the European Parliament reached a political agreement on financing the REPowerEU Plan (European Commission 2022h). Even though the details of REPowerEU are not entirely clear, there is a strong motivation to change the energy system faster than previously planned. In the current situation, it can be expected that the public will accept the accelerated change to a greater extent, considering the technologies that were previously considered negative and the costs associated with them.

It is a subject of question what effect the REPowerEU Plan will have on the field of CCU/S (Farkas-Csamangó et al. 2023). Reducing the use of fossil resources may also affect the extent to which CCU/S technologies will be needed and applied. Although, in spite of the climate policy goals, among traditional energy sources an increase in the performance of coal power plants can be expected in the short term. In addition, although to a much lesser extent, natural gas and crude oil will still be part of the energy system in 2030 and 2050 – in this case, CCU/S can also play a role. In addition, Carbon Dioxide Reduction (CDR), which is part of most emission scenarios, will also rely heavily on CCS technologies. Besides, CCU will be important to achieve the target levels of e-gases and e-fuels. Moreover, REPowerEU also pays particular attention to the flourishing of the hydrogen industry (Uhde 2022). While doing so, in addition to hydrogen, products produced from it, i.e. ammonia, methanol, e-kerosene, or e-gasoline, play an important role. It also has an indirect effect on carbon dioxide: in addition to hydrogen, the production of e-fuels requires access to critical raw materials such as CO_2 from sustainable sources.

2.6. Industrial Carbon Management Communication

The European Union is committed to reach climate neutrality by 2050, in order to reach that the European Commission set out how to take advantage of CCU/S technologies (European Commission 2024b). It is stated that while currently making an effort to reduce emissions, we need technologies that can capture the CO_2 and utilize or store it as well. The Industrial Carbon Management Communication was adopted in 2024. It goes into details about how CCU/S technologies can serve as solutions contributing to 90% emission reduction by 2040 and to reaching climate neutrality by 2050.

The identified set of actions describe how to enable CCU/S technology deployment and the single market establishment for CO_2 in Europe with the necessary infrastructural developments. Preparatory work has already started on a regulatory package in regard to CO_2 transport and storage. Moreover, the volume of industrial carbon removals will be assessed by the Commission to meet the previously set goals, including the assessment of removal and storage processes to be accounted for under the EU ETS. In connection with the industrial uptake of sustainable carbon, establishing a clear accounting framework for CCU became a goal of the Commission.

In addition, for the establishment of the EU's CO_2 value chain, the Commission set out horizontal actions to create an enabling business environment. It is planned to happen in three fields of action: investment and funding; research, innovation and public awareness; and international cooperation.

2.7. Net-Zero Industry Act

On April 25, 2024, the European Parliament formally adopted the provisional agreement reached on the Net-Zero Industry Act (NZIA) (Global CCS Institute 2024). Being a key legislation in the field, it is anticipated to strengthen the EU's net-zero industry, making it more competitive and resilient, and also to contribute significantly to achieve climate neutrality by mid-century. The NZIA is designed to support the scaling up of a wide range of net-zero technologies, which are considered essential for Europe's decarbonization efforts, including Carbon Capture and Storage (CCS). Specifically, the act designates CO_2 capture, transport, and storage projects as net-zero strategic projects, which are eligible for several benefits, such as streamlined and efficient permitting procedures and priority status at the national level.

The Act facilitates the creation of net-zero strategic projects, which are crucial for strengthening the resilience, strategic autonomy, and competitiveness of the EU's net-zero industry (European Commission n.d.c). These projects receive additional advantages, including 'priority status' at the national level, expedited permitting processes, dedicated support through the Net-Zero Europe Platform (including financial guidance), and urgent treatment in judicial and dispute resolution procedures, in accordance with both national and EU regulations

3. CCS and CCU in Decarbonization Scenarios in the EU

The EU examines the feasibility of the objectives through different decarbonization scenarios, depending on the solutions used. As a possible method, CCU/S technologies were also considered in some scenarios, their role and the importance of their application are evaluated as follows.

Currently, many models are used to analyze future scenarios of decarbonization at national, regional and global levels (Butnar et al. 2020). The most prominent of these are the Integrated Assessment Models (IAMs), which corroborate the IPCC assessment reports.

An important finding made during the investigation of the role of CCU technologies in the decarbonization of Europe is that, in addition to the rich portfolio of CCS technologies (Dalla Longa et al. 2020), there is no mention of CCU in global IAMs (Butnar et al. 2020). The broader literature also highlights the issue that CCU technologies are missing from global IAMs. Nevertheless, in 2018 CCU was listed as a key technology in the EU's "Clean Planet for All" report (European Commission 2018). PRIMES (EU-scale Energy System Model) scenarios compatible with 1.5°C and 2°C temperature targets suggest that by 2050, 47-80 Mt of CO_2 will be sequestered as products, and an additional 154-372 Mt of CO_2 will be used during the production of synthetic fuels. In order to ensure carbon neutrality in these scenarios, only CO_2 can be used for synthetic fuels and products that does not come from the flue gas produced by the combustion of fossil fuels. The level of CO_2 utilization in this study is approximately 50% of the total CO_2 captured.

The central role that could be played by the CCU/S in the realization of climate ambitions was confirmed by the "Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios" in 2020, which presents the role of CCU/S on the road to carbon neutrality (Butnar et al. 2020). The document emphasizes that the application of these technologies is essential to achieve net zero carbon dioxide emissions by 2050.

According to the 1.5°C scenarios, the median carbon dioxide sequestered by CCS will be between 230-430 Mt CO_2/year in 2030, which may increase to 930-1,200 Mt CO_2/year by 2050 (CCUS Set-Plan 2022). CCS for carbon dioxide removal is a topic that has undergone a more detailed review compared to previous assessments. According to the models that use Bioenergy with CCS (Bio-Energy Carbon Capture and Storage, BECCS) and CCS with direct CO_2 capture from the air (Direct Air Carbon Capture and Storage DACCS), the role of these technological solutions has significantly increased in the mitigation of climate change and to meet the previously determined target levels. In the modelled 1.5°C scenarios, which also consider carbon sequestration, the global cumulative CO_2 removal between 2020 and 2100 is 30-780 Gt CO_2 for BECCS and 0-310 Gt CO_2 for DACCS. The values for the 2°C scenario are 170-650 Gt CO_2 (BECCS) and 0-250 Gt CO_2 (DACCS). It can be seen that the modelled CO_2 removal values range within wide limits, which is due to the consideration of different costs, the availability of technologies and the assumptions regarding the limiting factors.

Assuming that all planned activities are implemented in the upcoming period, the target figures required for the 2°C scenario by 2030 can still be reached, however, it would be still far from the values of the 1.5°C scenario (CCUS Set-Plan 2022). It is more than unlikely that all the planned projects will be realized. Following the path of the current scenario, we will not be able to achieve the 2050 objectives. For this reason, it is essential that (as many as possible) commercial-scale projects start up by 2030, and following this, facilities with commercial-scale capacity spread more and more until 2050.

The contribution of CCU to the climate goals is still unclear, as the carbon footprint is not always quantified during modelling and scenario creation (CCUS Set-Plan 2022, Farkas-Csamangó et al. 2023). However, it is indisputable that CCU technologies could contribute to emission reductions by avoiding new emissions by using existing ones, and in certain use cases CO_2 can be permanently stored (incorporated into the final product). According to estimates, by 2050, the amount of CO_2 used by CCU technology may reach up to 7 gigatons, which can be used to produce materials such as various fuels and chemicals.

In the document entitled "Stepping up Europe’s 2030 climate ambition, Investing in a climate-neutral future for the benefit of our people", the European Commission also noted the critical importance of the industrial-scale installation of CCU/S systems, which should achieve significant results in this decade (European Commission 2020). It also shows the importance of the upscaling of CCU/S technologies, identifying the key factors hindering their development, and creating economic conditions and a favorable political framework related to them.

4. CCU/S pilot projects in Europe

Although CCU/S technologies are relatively new, there are already laboratory developments, demonstration projects, or even industrial-scale facilities in Europe. In this section, we have collected the projects that are of the greatest importance – without any claim to completeness. To emphasize, in this section we are presenting ideas from Europe and not only the European Union, as the United Kingdom (UK) left the EU in 2020, but several projects were launched there while they were a Member State of the EU, so in our point of view, it is justified to take a look at the UK as well.

There are several databases available to track the CCU/S pilot projects. One of them is the database of the Global CCS Institute, which focuses on CCS projects mainly in the United States of America (USA) (Global CCS Institute n.d.). Another one is the database of CO_2 Value Europe which focuses on CCU project in the EU, without aiming the claim to completeness (CO_2 Value Europe 2024). The IEA CCU/S Database is the most comprehensive one covering projects since the 1970s (with capacity of more than 100,000 t/year, or for DAC facilities 1,000 t/year) on the whole CCU/S value chain: carbon capture, transport, storage and utilization (IEA 2024).

4.1. Carbon Capture and Storage Projects

The Global CCS Institute's 2023 report lists 41 projects currently in operation (most of them are operating in the United States, Canada and China), of which only four are located on the European continent: two in Norway, one in Hungary, and one in Iceland (Global CCS Institute 2023a). The Norwegian Equinor Sleipner project and the Hungarian MOL Szank Field project began operating in the 1990s, the other Norwegian project, Equinor Snohvit, launched in the second half of the 2000s, while the Icelandic project started in the early 2020s. Their activities are different, since while the Icelandic and Norwegian projects store carbon dioxide geologically, in Hungary it is used for Enhanced Oil Recovery (EOR).

According to the report published in 2023, a total of 155 CCS projects in various stages of readiness (early development, advanced development, in construction, operational) are under development in Europe (Global CCS Institute 2023a). There was a rise of 63% in projects of different development stages and operation since the previous report in 2022 (Global CCS Institute 2023b).

For many projects, improvements and progress are made in the advanced development stage, such as the following two (Global CCS Institute 2023a):

- (i) The Exergi KVV8 facility in Stockholm may be the largest biomass-based combined heat and electricity power plant in Europe. The BECCS project to be used in the facility can remove up to 0.8 Mt of CO_2 per year.
- And (ii), the proposed BECCS project for the UK's largest power station, Drax Power Station in Yorkshire, is making steady progress and could reach 8 Mt/year CO_2 capacity. Drax has announced a partnership with Mitsubishi Heavy Industries to capture the plant's carbon emissions (IEA 2021).

Also, in the early development stage, such as the ENI Ravenna Hub project will be one of the first CCS projects in the Mediterranean region. The project will initially carry out its decarbonization activities in Ravenna, Northern Italy, and later offer other players in the region the opportunity to manage their emissions.

4.2. Carbon Capture and Utilization Projects

Based on the CO_2 Value Europe database, there are a total of 103 completed and 145 ongoing CCU projects in Europe (CO_2 Value Europe 2024). These projects are extremely diverse in terms of the technology used, its maturity or technology readiness level (TRL 3-9) and the type of product produced.

Among the technologies at TRL 9 maturity level, there are two completed and three ongoing projects in Europe (Table 1) (CO_2 Value Europe 2024).

Table 1. Completed and ongoing TRL 9 CCU projects in Europe, 2024

Project name	**Country**	**Timeframe**	**Status**	**CCU information**	**Products**
Biocat 3	Denmark	2017-2020	completed	catalytic and biological conversion	fuels: methane
VABHYOGAZ 3	France	2016-2020	completed	chemical conversion	chemicals: bicarbonate
Carbon2Product Austria (C2PAT)	Austria	2020-2030	ongoing	chemical conversion	fuels and chemicals: hydrocarbons, olefins, captured CO_2
COLUMBUS	Belgium	2020-2025	ongoing	biological conversion	fuels: methane
Project AIR	Sweden	from 2019	ongoing	thermal conversion	chemicals, fuels: methanol

Source: own construction based on CO_2 Value Europe (2024)

A large number of TRL 8 CCU projects can also be found in Europe (5 completed and 34 ongoing projects), some examples are the following:

- BioPower2Gas: The completed project in Germany operated at three different locations between 2013 and 2016. All three units used the same technology, biological conversion in order to produce methane.
- CO_2ncrEAT: The mineralization project in Belgium, which uses CO_2 to produce building materials, aims to reduce emissions from the construction industry. The project started in the spring of 2022.
- George Olah Plant: One of the longest-operating projects is the George Olah Plant in Iceland, which has started in 2009. In the plant, methanol is produced by chemical conversion.
- LIPOR: One of Portugal's special CCU projects started in February 2021. In contrast to the projects listed so far, LIPOR deals with the production of aviation fuel and special chemicals, as opposed to common CCU products (methane, methanol).

Commercialization of CCU technologies is at an early stage, but within the next five years several ongoing and announced projects could reach industrial scale (CCUS Set-Plan 2022).

4.3. Entire CCU/S Value Chain Projects

According to the IEA CCU/S Projects Database, there are 5 projects in Europe that cover the whole CCU/S value chain. There are 4 operational projects and 1 project is under construction (IEA 2023):

- Iceland: two projects will use DAC in order to store CO_2, the Climeworks Mammoth Project will start in 2024 and the Climeworks Orca project has already been operating since 2021.
- Norway: two projects are storing CO_2 in the natural gas processing/LNG sector, the project called Sleipner launched in 1996, and the Snohvit CO_2 capture and storage project started in 2008.
- Hungary: MOL Szank field CO_2 EOR project started using CO_2 in EOR in 1992 and it is operating in the natural gas processing/LNG sector.

5. International CO_2 Infrastructure: Transport and Storage

Due to the growing demand for CO_2 sequestration, the need for transport and storage infrastructure is increasing; in light of this, CO_2 storage has developed rapidly (Global CSS Institute 2021). Harbor Energy, Neptune Energy, MOL and Independent Oil and Gas are just some of the companies that have publicly expressed interest in using European assets for CO_2 storage.

CO_2 is mainly transported by pipeline, but other modes of transport, such as water, rail or road transport, are also becoming increasingly important (IOGP 2019). Many CCS projects planned in Europe aim to transport CO_2 from one country to another with the aim of storing CO_2. Cross-border CO_2 transport can promote regional cooperation and the development of infrastructural connections through regional projects. The same approach is used by the Norwegian Northern Lights project.

The Northern Lights project aims to create a European CO_2 transport and storage network based on water transport (Northern Lights n.d.). By importing Europe's carbon dioxide emissions, the project aims to achieve economies of scale and lower costs, while at the same time making a larger-scale contribution to the reduction of CO_2 emissions of the EU. In 2017, the CO_2 transportation part of the project received the status of a Project of Common Interest (PCI), which was renewed in 2022 in order to expand the geographical scope of the project in Belgium, France, Germany, Ireland, the Netherlands, Sweden and also for locations in the United Kingdom (Northern Lights 2022). Companies Equinor, Total and Shell are responsible for the transport and storage part of the project. The project is scheduled to start operations in 2024 and its extension to cross-border transport of CO_2 is expected to take place from 2026 by shipping the first biogenic CO_2 from Denmark to Norway (Northern Lights 2023).

The development of CO_2 transport infrastructure, the connection of industrial clusters and storage sites is essential in order to exploit economies of scale at regional, national and European levels. The transition from individual solutions to the creation of clusters is crucial for the development of efficient CO_2 networks.

6. CCU/S Clusters and Organizations in the EU

In the case of CCU/S technologies, bottom-up organizations and clusters are already emerging, but the spread of the technologies' application is also promoted by specialized organizations in the European Union.

6.1. Clusters

The concept of industrial clusters is well known in the field of economic development. An industrial cluster means the geographical concentration and cooperation of businesses, suppliers and associated institutions related to each other in a given area, and there can be many reasons for its formation (Global CCS Institute 2016).

The efficiency and cost-effectiveness of the future carbon dioxide transport infrastructure will be determined by whether it can capture emissions from clusters of industrial facilities (IOGP 2019). According to a report in 2018 by Endrava and Carbon Limits, emissions from European power plants, industrial facilities and waste treatment facilities were 2.4 Gt/CO_2, which is two-thirds of all European CO_2 emissions (around 3.8 Gt CO_2). Within these two-thirds, 89% of emissions come from facilities emitting more than 100 kt CO_2/year, which accounts for 32% of these facilities. This indicates that the decarbonization of larger installations will enable effective and timely progress in reducing the EU's overall CO_2 emissions.

In the case of CCS, it is an advantage that the geographical location of many emission-intensive facilities (either in industry or energy) is concentrated within a narrow area (Global CCS Institute 2016). Such clusters can be found, for example, around energy facilities and ports. This gives the opportunity to create a CO_2 capture and/or storage cluster by uniting CO_2 emitters located relatively close to each other and connecting to a large CO_2 storage through an extensive infrastructure. In this case, the size of the infrastructure is not measured for the individual user, but for the combined needs of the users.

Several existing CCS clusters can be identified within the European Union (Global CCS Institute 2016, Aker Carbon Capture 2022), for example:

- France - Le Havre cluster (COCATE);
- Scandinavian region - Skagerrak/Kattegat cluster; and
- Bulgaria - ANRAV CCUS cluster.

Joining clusters can also be beneficial for smaller companies, as they can take advantage of economies of scale typically found only in large companies, get quick access to information networks (formal and informal) and skilled labour force, enjoy proximity to suppliers and/or customers (Global CCS Institute 2016).

6.2. Organizations

In the European Union, a number of organizations have been established with the aim of helping the deployment and application of CCU/S technologies and their spread across the EU.

6.2.1. CCUS Zero Emission Network (ZEN)

The goal of the Zero Emissions Network is to accelerate the spread of CCU/S throughout Europe by building networks, and to contribute to the reduction of CO_2 emissions in industrial clusters and hubs by sharing knowledge and experience related to CCU/S (European Commission 2022h). Its duties include providing stakeholders with important information to make informed decisions about CCU/S, and development of concrete and feasible plans for the development of CCU/S value chains.

ZEN partners have extensive expertise and knowledge in the field of the CCU/S value chain, including land and water transportation, pipeline and energy industries, and CO_2 storage (SINTEF 2022). The two-and-a-half-year project started in September 2022, the opening event of which was held in Paris, where, in addition to the 14 partners, 60 members of the network were represented. CCUS ZEN is funded by EU Horizon Europe.

6.2.2. Zero Emissions Platform (ZEP)

ZEP is the EU's advisor on the deployment of the CCU and CCS (Zero Emissions Platform n.d.). In addition to consulting, its activities include writing studies and reports, as well as providing consultation opportunities. The organization's members include multinational companies such as BP, Shell, ExxonMobil or GE.

According to the organization, in order to promote a cluster-based approach to CCU/S, the emission sources of the region must be mapped, and a unified position must be developed between the member states and the industry in order to build a common user infrastructure. This could be done by Member States in a coordinated way with industry in order to better identify where there might be cluster opportunities for efficient carbon capture and transport and how to encourage early public financial support for CO_2 infrastructure.

6.2.3. CCUS Forum

The CCUS Forum is an annual event organized by the European Commission, which serves as a common platform for stakeholders (European Commission 2022a). The purpose of the Forum is to bring together representatives of EU institutions, EU and third countries, non-governmental organizations, business sector and academia to facilitate the spread of the deployment of CCU/S technologies (European Commission 2024a).

The first high-level CCUS Forum took place in 2021 (European Commission 2024a). The event attracted nearly 400 participants, demonstrating the growing interest in CCU/S and the need for ongoing dialogue between stakeholders. The first forum resulted in creating three working groups. The first working group deals with CO_2 infrastructure and addresses gaps in infrastructure development. The second group is designed to develop a CCU/S vision document that examines the role of CCU/S in the EU's energy decarbonization, while the third group works for the establishment of industrial partnerships and the greater involvement of industries in technological deployment.

The groups helped prepare the second plenary session of the Forum (European Commission 2024a). At the second meeting of the CCUS Forum held in 2022, Oslo, almost 300 in-person and up to 1400 online participants gathered. Four working groups were established on CCU/S strategy, public perception, CO_2 infrastructure and CCU/S industrial partnerships.

The third CCUS Forum (in Denmark, 2023) gathered more than 450 in-person and up to 1,400 online participants, and resulted in the establishment of four working groups on CO_2 infrastructure, CO_2 standards, public perception and CCU. According to the CCUS Forum, these numbers illustrate the interest in accelerating the deployment of CCU/S technologies in Europe. The fourth edition of the CCUS Forum is being organized, it will take place in France in 2024.

6.2.4. CCUS Hub

The purpose of the CCUS Hub is to accelerate industrial decarbonization by creating an infrastructure that is suitable for transporting and storing CO_2 from multiple sources in a safe and environmentally responsible way in the long-term (CCUS Hub 2024). The CCUS Hub aims to support policy makers, potential hub developers and emitters who are interested in establishing a CCUS hub by sharing knowledge and experience from the most advanced hubs. This platform was created by the organization called the Oil and Gas Climate Initiative (OGCI), which relies on the knowledge and support of numerous partner organizations.

The platform has three key tools (CCUS Hub 2024). CCUS Hub Search is an interactive map that identifies 279 potential CCUS hubs in 56 countries and matches clusters of CO_2 sources from emitting industries with potential storage sites. The tool serves as a starting point for policy makers, industrial emitters and potential hub developers. The Playbook was commissioned by OGCI, based on in-depth interviews conducted with transport and storage operators, hub developers, regulators and emitters in advanced hubs as part of the KickStarter initiative. Hubs in Action is a collection of profiles of CCUS hubs currently under development, including key information and descriptions of participants, storage capacity and type, and planned starting dates. Currently, OGCI member companies are actively involved in the development of almost 40 emerging hubs, and about 80 are under planning or construction.

7. Supporting System

The work of the organizations presented in the previous chapter is momentous for the spread of CCU/S technologies, however, the provision of financial support is still essential. With the help of grants, research projects can reach industrial scale, and their operation can become more efficient through further developments.

The EU offers several funding programs to finance European energy projects, including CCU/S (IOGP 2019, Farkas-Csamangó et al. 2023). These grants cover the entire range of technological development levels: from research carried out under Horizon 2020 and Horizon Europe to commercial-scale projects of the Innovation Fund. EU funding systems and innovation networks are vital to support the early adoption of CCU/S solutions.

7.1. Connecting Europe Facility and Trans-European Networks for Energy

The Connecting Europe Facility (CEF) is a funding initiative of the European Commission, which includes numerous calls for the development of cross-border CO2 infrastructure (Balakin, 2021, IOGP 2019).

The Trans-European Networks for Energy (TEN-E) policy is also indirectly related to the European support system (European Commission 2023c, Jenkins 2015). TEN-E is a policy that focuses on connecting the energy infrastructure of EU countries. As part of the regulation, eleven priority trans-European corridors and three priority areas have been identified, one of which is the "Cross-Border Carbon Dioxide Network". The EU helps countries in these key thematic areas to cooperate in order to develop better connected energy networks, and also provides financing for new energy infrastructure developments. In the program, CO_2 infrastructure projects can apply for the status of a project of common interest and then receive support within the framework of the CEF.

Among the three sectors of the CEF (energy, transport and digital sectors), EUR 5.84 billion from the budget of the energy sector will be allocated to the implementation of the TEN-E policy in the period 2021–2027 (European Commission n.d.a). Furthermore, the energy sector also focuses on the co-financing of cross-border renewable energy projects, the interoperability of networks and the better integration of the internal energy market (European Commission 2021a). In the listed areas, CEF has so far co-financed studies and works related to PCI in connections with CO2 emissions (European Commission 2022a).

7.2. European Innovation Fund

In November 2023, the European Commission announced the Innovation Fund’s 2023 call for propos als (European Commission 2023a). The announced incentives are worth a total of 4 billion euros. The 2022 call is expected to boost the use of industrial solutions to decarbonize Europe. Focusing on the priorities of the REPowerEU Plan, the call provides further support for reducing the EU's dependence on Russian fossil fuels.

Grants are divided to five topics:

- General decarbonization (large-scale): €1.7 billion available
- General decarbonization (medium-scale): €500 million available
- General decarbonization (small-scale): €200 million available
- Cleantech manufacturing: €1.4 billion available
- Pilot: €200 million available

The European Commission invests over €65 million to support the selected 17 small-scale innovation (European Commission 2023b). The selected projects are located in Italy, Spain, Croatia, France, Hungary, Latvia, Greece, the Netherlands, Sweden, Finland and Norway. By supporting the projects, it would help commercialize technologies in the market in energy-intensive industries, as well as contribute to the construction of infrastructure for hydrogen, renewable energy, carbon capture and storage, and the manufacturing of key components of energy storage and renewable energy sources.

7.3. Horizon Europe

Covering the seven-year period of 2021 through 2027, the European Union's research and innovation framework program, Horizon Europe, was launched in June 2021 with a budget of 95.5 billion euros (European Commission 2021b, Farkas-Csamangó et al. 2023). The funding program is more ambitious than the Horizon 2020 framework program. It provides 30% more resources to support European research excellence and breakthrough innovations, as well as to address the most important societal challenges and creating jobs. In addition, tackling climate change, it accelerates the competitiveness and growths of the EU, and aims to contribute to the Sustainable Development Goals of the United Nations.

In line with the REPowerEU Plan and the European Green Deal, the measures promote the transition to clean energy (European Commission 2022f). In order to support the green transition, Horizon Europe allocates at least 35% of its total budget to climate policy objectives.

In the frames of the second pillar of the funding program, called "Global Challenges and European Industrial Competitiveness", there is a budget of 53.5 billion euros, of which the "Climate, Energy and Mobility" cluster receives a total of 15.35 billion euros (NKFIH 2021). Horizon Europe Work Program 2023-2024 was adopted by the European Commission in 2022. It invests around 13.5 billion euros in research and innovation activities shaping the future of Europe (European Commission 2022b). A significant part of the financing budget is used for targeted measures that support making the society and the economy greener.

The four (A-D) Key Strategic Orientations for the period 2021-2024 of the Horizon Europe Strategic Plan define higher-level objectives in which research and innovation investments are expected to bring about change (European Commission 2022f). For our paper, the relevant key strategic directions could be as follows:

- B – Restoring Europe's ecosystems and biodiversity, and managing sustainably natural resources: Horizon Europe promotes knowledge creation, expands capacities and innovative technologies, and offers solutions to support ecosystems, ensure a clean and healthy environment and sustainable management of natural resources, contributing to climate change adaptation and achieving carbon neutrality. From the perspective of our work, "Clean and healthy air, water and soil" can be the most relevant of the three impact areas.
- C – Making Europe the first digitally enabled circular, climate-neutral and sustainable economy: Its goal is for the EU to become a provider of green solutions for the benefit of all, and to place Europe in a technological and industrial leading position during the green transition in order for the EU to become climate neutral by implementing the transition in all economic sectors. Among the four impact areas, the followings are relevant for our work:

- Promoting climate change mitigation and adaptation
- Reducing energy dependencies and promoting affordable and clean energy
- Contributing to the regenerative, circular and clean economy

Below, we collected a list from the calls of the "Climate, energy and mobility" cluster which aim to deploy the entire CCU/S value chain (including transport as well) or its separate elements (CC, CCU or CCS) (European Commission 2022c):

- HORIZON-CL5-2023-D3-01-17: Development of CO_2 transport and storage demo projects
- HORIZON-CL5-2024-D3-02-11: CCU for the production of fuels
- HORIZON-CL5-2024-D3-02-12: DACCS and BECCS for CO_2 removal/negative emissions

Moreover, further clusters, such as the "Digital, Industry and Space" cluster (European Commission 2022d) and the "Food, Bioeconomy, Natural Resources, Agriculture and Environment" cluster (European Commission 2022e) also mentions the parts of the CCU/S technologies in their calls.

In funding programs other than Horizon Europe (i.e. Interreg Danube Region Program 2021-2027 (Interreg Danube Region, n.d.), Interreg Central Europe Program 2021-2027 (Interreg Central Europe n.d.), Interreg Europe Program 2021-2027 (Interreg Europe, n.d.)) similar topics are also mentioned to support the low-carbon economy and green innovations, however, due to its volume, we highlighted the Horizon Europe Program.

It can be seen that the European financial support systems also have a place to promote efforts to develop and deploy different CCU/S methods. The financing of these kinds of projects clearly indicates the importance of these technological solutions and anticipates the trends of future technological developments.

8. Critical review of CCU/S technologies

There are numerous reviews that underscore several critical challenges associated with carbon capture, utilization, and storage technologies, i.e. high energy demands of current capture processes, infrastructure requirements for transport and storage, and associated costs (Chen et al. 2022, Gedam 2024, Nath et al. 2024, Prajapati et al. 2024, Tapia et al. 2018). The reviews recommend enhancing capture efficiency, advancing reliable storage site evaluations, improving monitoring technologies, exploring sustainable uses for captured CO_2, and promoting adoption through policy incentives. If coordinated global efforts are made, CCU/S could significantly contribute to achieving carbon-neutral energy systems on a worldwide scale.

Gedam (2024) reviews the role of CCU/S technologies in a low-carbon future, stating these points. First, economic and policy measures will be critical in facilitating the widespread commercial implementation of CCU/S technologies. Reducing energy penalties associated with capture and compression processes is essential for lowering costs. Incentives such as tax credits, carbon pricing mechanisms, and mandates are vital for encouraging CCU/S adoption, with a need for policies that support both the electricity sector and industrial applications.

Second, the costs of CCU/S vary widely depending on the source of CO_2 and its concentration in the flue gas. Direct air capture is currently the most expensive option but may still play a unique role in carbon removal strategies. The variability in costs is further influenced by the commercial availability of capture technologies and the logistics of CO_2 transport and storage, which depend on factors such as volume, distance, and storage conditions.

Third, international cooperation is vital for the broader adoption of CCU/S technologies. Clear regulatory frameworks regarding project permits, CO_2 storage management, monitoring requirements, and liability issues are essential to attract investment.

Fourth, although progress in CCU/S technology is promising, cost reduction remains a significant hurdle. While the costs associated with CCU/S are declining, they still exceed those of conventional energy production methods. Addressing this economic challenge is crucial to making CCU/S a more competitive and appealing option for industries aiming to lower their carbon emissions. Broad deployment of these technologies, supported by ongoing technological advancements and favourable policies, will be key to reducing greenhouse gas emissions and moving towards a low-carbon future.

And, finally, fifth, CCU/S technologies hold substantial potential for mitigating greenhouse gas emissions. However, further development, testing, and validation are necessary to lower costs, enhance performance, and confirm their effectiveness and reliability in practical applications. The review also emphasizes the importance of supportive policies, such as carbon pricing, investment subsidies, and tax incentives, to drive the adoption of CCU/S technologies.

9. Discussion, conclusions

The present study has aimed to discuss the institutional background that has effect on the spread and deployment of carbon capture, utilization and storage technologies. In order to do so, we have taken a look at the most relevant frameworks and reports in the European Union to map the EU's approach to these technologies. There are several ambitious goals for mitigating climate change set in the EU, however, the efficiency and effectiveness of the undertaken efforts may be the subject of debate.

As the given issue is multifaceted, there is no one-size-fits-all solution for it (Chen et al. 2022, Gedam 2024, Nath et al. 2024, Prajapati et al. 2024, Tapia et al. 2018). Besides the other decarbonization solutions, it can be stated after the revision of the EU's approach, that CCU/S technologies can play a key role, especially in the hard-to-abate sectors such as aviation, maritime shipping, and cement industry as they can help them maintain their competitiveness. It shows the importance of the upscaling of CCU/S technologies, and also the identification of the key factors hindering their development. Creating a supportive legal, policy and business environment is critical to the success of the spread of emerging technologies, including CCU/S as well (Farkas-Csamangó et al. 2023). As their application takes place in a rather complex, currently forming technological, economic and legal environment, research, development and innovation activities are of prime importance in the development and scalable implementation – it also appears in the examined frameworks and financial supporting systems. Forming CO_2 infrastructure, clusters, pilot projects are also significant in order to showcase the upscaling of these technologies, to accelerate technological development and to promote professional cooperation between stakeholders – professional events, for example workshops are needed to provide them a platform where they can share and change ideas.

Overall, our present study contributed to confirming the promising future role of carbon capture, utilization and storage technologies in the EU climate policy and in reducing carbon dioxide emissions, as several policy and regulatory changes, and endeavours occur in the European Union that include the CCU/S technologies. The topic of CCU/S technologies seems forward-looking; however, further steps are needed to be taken in practice, even the creation of a CCU/S Strategy on EU and national levels.

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