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Contents

Abstract

This report provides an overview of the current status, value chains and market positions of carbon capture utilisation and storage (CCUS) technologies in the EU as well as globally. In 2023, the CCUS industry experienced unprecedented growth globally, with all the projects under development summing up to more than 360 Mtpa of CO_2 captured. While there are commercially available technologies across all steps of the CCUS chain, work is needed regarding the interconnection of those different steps. The costs of CCUS technologies vary widely depending on the industry, technology, location, plant design and regulatory frameworks in place. According to the review presented here, capture costs lie in the 40-90 EUR/t range for hard-to-abate industries such as cement and the iron and steel sector, while transport costs are within 2-30 EUR/t and storage within 5-35 EUR/t. Taking together Member State and EU funding, the EU was the world leader in public RD&I funding of CCUS technologies in 2022. Within the EU, Germany was the leader, followed by France and Denmark. Global venture capital investment at early stage reached a peak in 2023, with the US attracting most venture capital investment. Lastly, this report shows that new business models are being adopted for the deployment of CCUS projects. While most CCS projects currently in operation follow the full value chain model, issues with this model have resulted more recently in increased traction for partial value chain models, e.g. capture as a service, transport and storage as a service and self-capture with 3rd party offtake.

Foreword on the Clean Energy Technology Observatory

The European Commission set up the Clean Energy Technology Observatory (CETO) in 2022 to help address the complexity and multi-faced character of the transition to a climate-neutral society in Europe. The EU's ambitious energy and climate policies create a necessity to tackle the related challenges in a comprehensive manner, recognizing the important role for advanced technologies and innovation in the process.

CETO is a joint initiative of the European Commission Joint Research Centre (JRC), who run the observatory, and Directorate Generals Research and Innovation (R&I) and Energy (ENER) on the policy side. Its overall objectives are to:

- monitor the EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal
- assess the competitiveness of the EU clean energy sector and its positioning in the global energy market
- build on existing Commission studies, relevant information & knowledge in Commission services and agencies, and the Low Carbon Energy Observatory (2015-2020)
- publish reports on the Strategic Energy Technology Plan (SET-Plan) SETIS online platform

CETO provides a repository of techno- and socio-economic data on the most relevant technologies and their integration in the energy system. It targets in particular the status and outlook for innovative solutions as well as the sustainable market uptake of both mature and inventive technologies. The project serves as primary source of data for the Commission's annual progress reports on competitiveness of clean energy technologies. It also supports the implementation of and development of EU research and innovation policy.

The observatory produces a series of annual reports addressing the following themes:

- Clean Energy Technology Status, Value Chains and Market: covering advanced biofuels, batteries, bioenergy, carbon capture utilisation and storage, concentrated solar power and heat, geothermal heat and power, heat pumps, hydropower & pumped hydropower storage, novel electricity and heat storage technologies, ocean energy, photovoltaics, renewable fuels of non-biological origin (other), renewable hydrogen, solar fuels (direct) and wind (offshore and onshore).
- Clean Energy Technology System Integration: building-related technologies, digital infrastructure for smart energy system, industrial and district heat & cold management, standalone systems, transmission and distribution technologies, smart cities and innovative energy carriers and supply for transport.
- Foresight Analysis for Future Clean Energy Technologies using Weak Signal Analysis
- Clean Energy Outlooks: Analysis and Critical Review
- System Modelling for Clean Energy Technology Scenarios
- Overall Strategic Analysis of Clean Energy Technology Sector

More details are available on the CETO web pages

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Executive summary

Policy context

Carbon capture, utilisation and storage (CCUS) has been acknowledged in the context of the European Energy Union as a fundamental research and development priority in achieving the 2050 climate objectives in a cost-effective way. In May 2024, the Council adopted the Net Zero Industry Act (NZIA), which not only lists CCUS technologies within the list of Strategic Net-Zero Technologies, but also sets an annual injection capacity target of at least 50 million tonnes of CO_2 by 2030 in storage sites located in the EU. In February 2024, the Commission published the Industrial Carbon Management (ICM) strategy, highlighting the role of CCUS in decarbonising the EU's hard-to-abate sectors and laying the groundwork for the measures to come.

Objectives

The aim of this report is to provide an overview of the status and trends of CCUS technologies and their value chains, along with their EU market position and global competitiveness.

Key findings

In 2023, the global CCUS industry saw unprecedented growth, with a 102% increase in project development over the previous year. As of 2023, there are 41 operational CCS facilities with a total capture capacity of about 49 Mt of CO_2 per year, while the capacity of projects in development is 361 Mtpa.

The technology readiness level (TRL) of CCUS technologies varies across steps of the value chain (capture, transport, utilisation and storage) and within sub-technology type. The review presented in this report reveals that while there are specific technologies commercially available (TRL 9) across all the steps of the chain, there is still development work needed when it comes to interconnecting all the steps of the chain, especially in industrial emission sources (much more development has been carried out in the power sector).

The cost of CCUS today is still difficult to assess. It varies based on sectors, technologies, and plant and system design factors. According to the literature review carried out here, the capture costs in hard-to-abate industries (iron and steel, chemicals and cement) lies between 40 and 90 EUR per tonne of CO_2 depending on the industry and CO_2 concentration. Carbon dioxide removal (CDR) technologies, on the other hand, offer costs of around 40-75 EUR/t in the case of Bioenergy with CCS, and of 300-500 EUR/t for Direct Air Capture. Transport and storage costs can also vary significantly depending on distance, volume, geographical location and storage conditions, and recent EU estimates are in the range of 2-15 EUR/t for pipelines, 12-30 EUR/t for shipping and 5-35 EUR/t for geological storage.

Regarding public RD&I funding, Canada and Japan are the top investors in the 2013-2022 period. However, the EU has spent more when taking Member State funding together with EU funding programmes. Since 2018, the European Climate, Infrastructure and Environment Executive Agency (CINEA) has built up a portfolio of 103 projects involving EUR 4.5 billion in EU contributions across the entire CCUS value chain. These are funded by three EU programmes: Connecting Europe Facility for Europe (CEF Energy), Horizon Europe (HE) and the Innovation Fund (IF). In addition, the Strategic Energy Technology Plan and Mission Innovation also support the development of CCUS value chains.

In 2022, Germany (EUR 45 million), France (EUR 44 million) and Denmark (EUR 30 million) were the leading Member States in annual RD&I funding within the EU, with Germany and France being the cumulative leaders within the 2013-2022 period.

The US has been the top investor in private RD&I since 2012. The EU ranks second, with a relatively stable level of funding for private RD&I. Within the EU, over the period of time analysed, Germany, France, the Netherlands, Italy and Spain are the top five countries with the largest private R&D investment in CCUS. The US companies attracted most venture capital (VC) investment, reinforcing its leading position in the CCUS industry from the very beginning, while EU companies managed to attract 18% of global VC investments. Over 40% of VC companies were founded after 2020, with a majority in the US and only a few in the UK and EU.

The US, EU and Japan filed the most patents for high-value inventions between 2010 and 2021. Among EU Member States, France had highest number (more than 35), followed by Germany and the Netherlands (25 and 14 respectively). From 2019 to 2021, L'air Liquide (FR) was the leading company in high-value inventions, both globally and in the EU. Linde (DE) ranks second in the EU and sixth in the world in the top 10 companies, based on the number of high-value inventions.

Regarding the value chain analysis, the CCUS industry is not yet operating at scale and does not have specialised supply chains yet. Various CO_2 capture technologies employ different solvents, sorbents, membranes, and cryogenic systems. One of the most mature technologies for capture is the amine solvent-based chemical absorption, which employs monoethanolamine (MEA). The captured CO_2 is dried using triethylene glycol and then liquefied for transportation. The transportation methods currently being evaluated primarily include pipelines and ships, as well as alternative means such as rail, truck and barge transport. All of these options are heavily dependent on steel. The bulk materials for storage are steel and cement, similar to those used for oil and gas wells. Steel and cement availability is unlikely to limit deployment. Due to CO_2 stream acidity, corrosion-resistant steel alloys are necessary. Chromium, mainly sourced from South Africa (56%), is the essential alloying element. Other elements, including nickel, silicon, copper, cobalt, manganese and tungsten, are considered strategic, while aluminum, phosphorus and vanadium are deemed critical for the EU economy according to the 2022 Critical Raw Materials list. China is the world's leading producer of several of these elements, producing 86% of the total output of tungsten, 79% of phosphorus, 76% of silicon, 62% of vanadium and 56% of aluminium.

The majority of CCS projects in operation were deployed following the full value chain model, according to which the CO_2 is captured from one facility and transported to an injection site, all owned and operated by a single entity. This model, although useful and simple for first-of-a-kind technologies, falls short when it comes to scalability and incentivising competition. Partial value chain models such as capture as a service, transport and storage as a service and self-capture with 3rd party offtake, have recently been gaining traction as a way to solve these issues. These models break the value chain into two or more parts. An example is CCUS hubs, which cluster local emitters and pair them with transport and storage developers, in an effort to mitigate risks and reduce costs by sharing the infrastructure. In the EU, the establishment of CCUS hubs is largely associated with industrial port cities, although not exclusively. The Porthos hub in the Port of Rotterdam will capture CO_2 from Air Liquide, Shell and ExxonMobil and store it in the North Sea. Other planned CCUS hubs in Europe include Longship in Norway, Coda Terminal in Iceland, and Pycasso and Dunkirk in France.

Analysis of CCUS's major strengths, weaknesses, opportunities and threats ('SWOT analysis')

Strengths	**Weaknesses**
• Included in all cost-effective climate change mitigation scenarios of the IEA and IPCC. • Growing political support. • Commercially available technologies across all steps of the chain. • Strong pipeline of projects under development all over the globe including in Europe.	• Perceived deployment risks that lead to lack of investor confidence. • Relatively expensive and lack of clear business case. • Limited operational experience of full-scale value chains. • Environmental concerns especially for some kinds of storage.
Opportunities	**Threats**
• One of the only effective emission reduction solutions for some industrial process emissions. • Cost reductions can be achieved through increased project capacity and mass manufacturing. • International and cross-border collaboration can accelerate the development of full-scale value chains.	• Government regulations and/or lack of investment. • Public concern/public acceptance. • Potential disruptions in the supply chain due to economic/geopolitical circumstances.

Source: JRC analysis

This document is structured as follows. Chapter 1 presents the scope and context of the work and provides an overview of the methods and data sources used in the study. Chapter 2 describes the readiness level and development trends of the different CCUS technologies. In Chapter 3, we take a look at the CCUS value chain, including environmental and socio-economic aspects, employment and EU production values for manufactured goods related to CCUS. Chapter 4 discusses the EU market position and global competitiveness. Lastly, Chapter 5 provides general conclusions

1 Introduction

1.1 Context and scope

Carbon capture, utilization and storage (CCUS) is a set of technologies acknowledged in the European Energy Union as a fundamental research and development priority to achieve 2050 climate objectives in a cost-effective way [1]. Later on, the European Green Deal included CCUS as one of the technologies necessary toward a transition to climate neutrality [2], and soon after, the communication on Sustainable Carbon Cycles highlighted that available solutions based on resilient natural ecosystems and industrial carbon capture and storage (CCS) should be deployed in an efficient and sustainable way to mitigate emissions [3]. In May 2024, the Council adopted the Net Zero Industry Act (NZIA) with the aim of enhancing European manufacturing capacity for net-zero technologies and their key components, addressing barriers to scaling up production in Europe. Within NZIA, technologies for CO_2 capture, transport, utilization and storage were included in the list of Strategic Net-Zero Technologies [4]. In addition, NZIA sets a CO_2 injection capacity target of 50 million tonnes per year (million tons per annum; Mtpa) across the EU. More recently, in February 2024, the European Commission highlighted the importance of capturing CO_2 for both utilization (CCU) and permanent storage (CCS) in order to meet the EU's climate targets. More specifically, the Industrial Carbon Management strategy (ICMS) [5] highlights that modelling results for the EU's climate target indicate that approximately 280 Mtpa of CO_2 would be captured by 2040 and 450 Mtpa by 2050. The ICMS highlighted the CO_2 transport infrastructure as a key enabler common to all decarbonisation pathways and underscored the importance of creating an EU-wide assessment of storage potential. In July of the same year, the Commission published revised Guidance Documents (GDs) supporting the implementation of Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive[1]). At the same time, several countries are working on their carbon management strategies (e.g. Austria, France, and Germany) or supporting schemes (e.g. Sweden, Denmark, the Netherlands). As a result of such political spotlight, the year 2024 has seen unprecedented advances for CCUS technologies (see Chapter 2).

Although originally targeted for the power sector, current trends indicate that CO_2 capture will play its biggest role within the industrial sector as well as a carbon dioxide removal (CDR) mechanism. Thus, this report mainly covers CO_2 capture from industrial point-sources as well as from bio-energy plants (referred as BECCS when combined with permanent CO_2 storage) and directly from the atmosphere (direct air capture; DAC). As a consequence of this broader spectrum of applications, and given the fact that a large fraction of CO_2 emissions in industrial plants does not arise from a combustion process, the traditional classification of capture technologies (pre-, post- and oxy-combustion) may not be representative and is not used here (see Chapter 2).

CO_2 utilisation processes deal with the transformation of the captured CO_2 into another product with commercial value. In this report only chemical transformations for the synthesis of fuels, chemicals and materials are included, i.e., leaving outside the scope the use of CO_2 for enhanced hydrocarbon recovery, for the food industry or as a supercritical solvent.

Regarding transport, this report concentrates on both shipping and pipelines and offers available data on alternative modes of transport, including rail, truck and barges.

Concerning storage, the focus is on both offshore and onshore aquifers as well as depleted hydrocarbon fields and alternative ways such as storage in basalts.

1.2 Methods and Data Sources

The present report provides an overview of the status (in terms of development, readiness, deployment and costs) of CCUS technologies, their value chains and the EU market position and global competitiveness (see Figure 1 for an overview of the content and the metrics used). For that, this work is based on a critical review of state-of-the-art data from various sources, mainly scientific literature, technical reports and outcomes from RD&I projects. A brief overview of the data sources and methods is given below, while a more extensive list of sources can be found in Appendix 1 and further methodological details are provided in each section.

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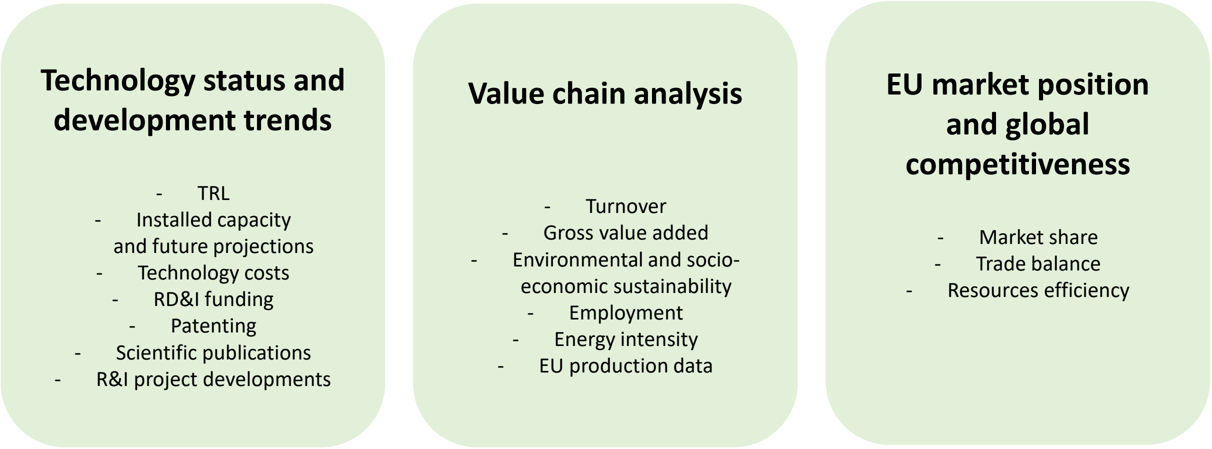
[1] https://climate.ec.europa.eu/eu-action/industrial-carbon-management/designing-and-implementing-industrial-carbon-management-projects_en#more-information

Figure 1. Overview of the content of the report.



Source: JRC

First, the review of the technology status is based on different relevant sources such as subject matter books and scientific articles published in peer-reviewed journals; the SETIS webpage and associated Strategic Energy Technology (SET) Plan actions; the Carbon Sequestration Leadership Forum (CSLF); technical reports from the International Energy Agency (IEA), the Global CCS Institute, the Carbon Capture Storage Association (CCS) and the Global Status of CCS series, among others. The technology readiness level (TRL) assessment follows the technology classification presented in [6], while TRL levels for CO_2 storage, transport and monitoring follow the technology classification given by [7] and [8]. In addition, to determine the TRL of a given sub-technology we assume that there should exist at least one project at the specific TRL assigned.

The technology costs are obtained from various reports and scientific articles and were converted to EUR 2019 utilizing exchange rates from the International Monetary Fund. Subsequently, costs were escalated from their base year to the reference year selected (2019) in order to establish a comparison across them. For that, the Chemical Engineering Plant Cost Index[2] (CEPCI) was used.

For the identification of the technology trends, needs and barriers, we have used the technology roadmaps and reports from various organisation and initiatives such as the International Energy Agency (IEA), Mission Innovation, the Zero Emissions Platform (ZEP), the SET Plan CCUS working group and CSLF, among others, which are properly cited where relevant.

The analysis of public RD&I funding is based on IEA data while that of private funding is based on an in-house methodology previously presented elsewhere [9], [10] . The data concerning patenting activities are sourced from the Joint Research Centre (JRC) based on the European Patent Office (EPO) PATSTAT database[3]. The analysis of scientific publication trends is carried out using data mapped using the JRC Tools for Innovation Monitoring (TIM)[4].

For the evaluation of EU-supported Research and Innovation, the main sources are CORDIS, Innovation Fund database, CINEA and internal databases for identifying the EU co-funded projects, while the project's relevance was determined based on their connection technologically to the SET Plan actions. It should be noted that many H2020 funded projects are still ongoing, and whether they have achieved their aims and targets might be inconclusive. Projects that do not consider the separation of CO_2 directly or its immediate reuse, such as for example specific catalyst development with chemical functionalisation, artificial photosynthesis and technologies aiming to advance CO_2 reduction have been excluded from the analysis. Technologies that are focusing on the molecular level are also excluded.

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[2] https://www.chemengonline.com/pci-home

[3] EPO - PATSTAT. Worldwide Patent Statistical Database

[4] TIM is a series of analytics tools that enables to support policy-making in the European Institutions in the field of innovation and technological development. It is available at: www.timanalytics.eu

Lastly, the analysis of value chain and markets is done using mainly data from Polaris Market Research, Pitchbook, COMEXT [5]and PRODCOM[6].

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[5] https://ec.europa.eu/eurostat/comext/newxtweb/

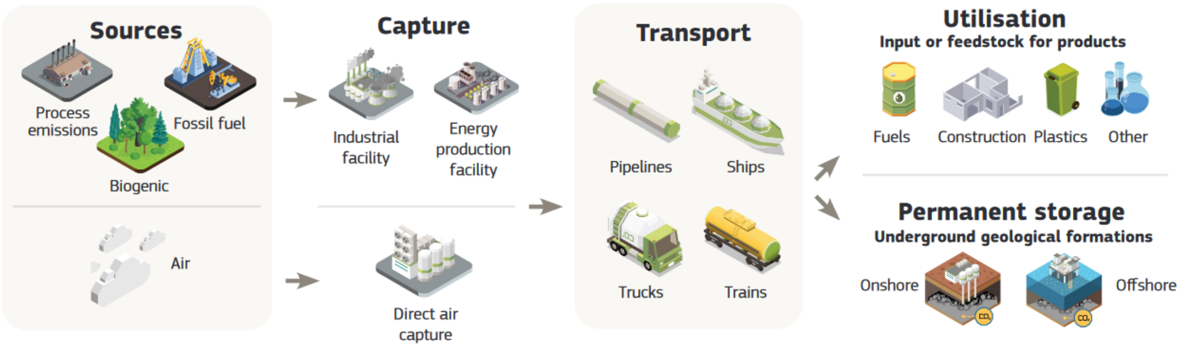
[6] PRODCOM provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries. https://ec.europa.eu/eurostat/web/prodcom

2 Technology status and development trends

The term CCUS actually comprises a chain of technologies, with each of the steps (capture, transport, utilization and/or storage) being independent from the other ones and containing several sub-technology choices. A schematic of the different steps involved in CCUS chains is shown in Figure 2 and briefly explained below:

- Capture involves the extraction of CO_2 emissions from various sources (process, fossil fuels or biogenic when referring to industrial and energy production facilities and air when referring to direct air capture).
- Transport involves the movement of captured CO_2 from the capture sites to the storage or utilisation locations. Typically, compression and liquefaction of the captured CO_2 are considered within the transportation step.
- The utilisation step (one of the two alternative last steps of the chain, see Figure 2) involves converting captured CO_2 into valuable products, for example using it as feedstock for fuels, chemicals or construction materials.
- The alternative last step of the chain is permanent storage in onshore and offshore underground geological formations.

Figure 2. Steps of the CCUS chain including examples of some technological options.



Source: European Commission [5]

Thus, in this report the technology status and development assessment is carried out in parallel for all the different technological options within each step of the chain. Table 1 summarises the main technologies and research fields identified for each of the steps of the CCUS value chain as defined in [11], [12]. In addition, CCUS include other research areas of a more trans-technological and cross-technological nature, some of which have been listed in Table 2.

Table 1. Technologies and research fields within each step of the CCUS chain.

Step in the CCUS chain	**Technologies and research fields**
Capture	Absorption
	Adsorption
	Membranes
	High-temperature looping cycles
	Oxy-combustion
	Direct separation
	Pre-combustion
	Hybrid
Utilisation	Direct CO_2 use without transformation
	Thermochemical conversion
	Electrochemical conversion
	Microbial conversion

	Mineralization
Storage	Injection in geological sites
	Definition and characterisation of the storage site*
	CO_2 migration and improved storage management procedures*
	Monitoring: CO_2 leakage, CO_2 long-term behaviour, safety, cost and risk reduction*
Transport	CO_2 compression and liquefaction**
	Ship
	Pipeline
	Safety aspects of transport*

*These research fields are not alternatives and are required regardless of the technological choice
** These sub-technologies are not strictly transport but for simplicity are here treated as such.

Source: JRC based on [11]

Table 2. Research areas of interest beyond the main technologies and sub-technologies listed in Table 1

Area
Materials and corrosion
Storage (natural analogues)
Ocean storage
CO_2 storage in other geological sites, e.g., reactive basaltic rocks.
Synergy with renewables such as geothermal energy, biomass, CSP, wind/H_2
Alternative modes of transport (by trains, trucks and barges).
Integration of the overall CO_2 value chain (capture, transport, utilisation, storage): CO_2 emissions along the chain, cost competitiveness of the overall chain and new business models.

Source: JRC

2.1 Technology readiness level (TRL)

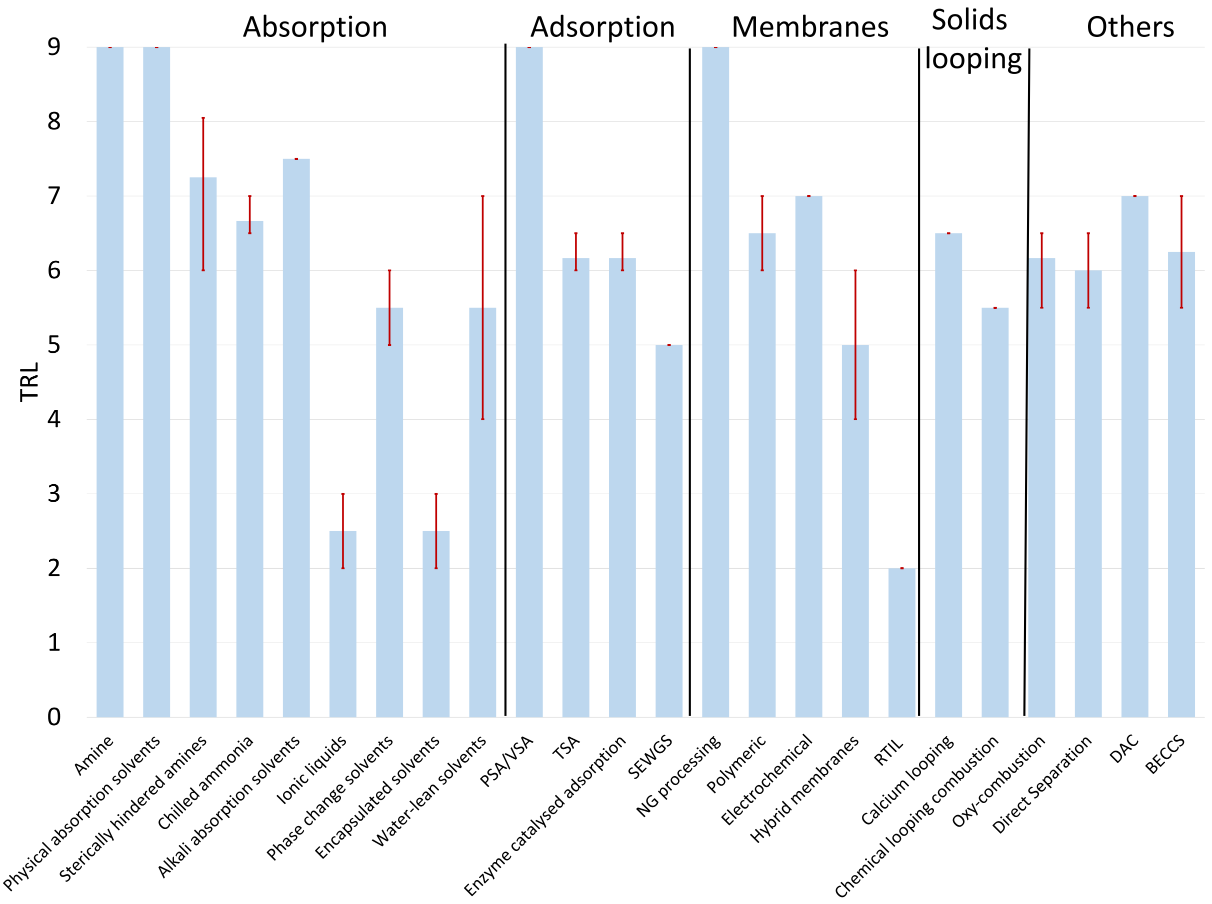
According to the Global CCS Institute [13], there are 41 commercial CCUS facilities operating worldwide (as of July 2023), out of which two are in operation within the EU, in Hungary and Croatia, in connection to enhanced hydrocarbon recovery (EHR). Three additional facilities operate in Europe, one in Iceland (in the field of DAC and storage) and two in Norway (in the field of capture from NG processing and storage). Nonetheless, and as depicted in Section 2.2, there are hundreds of projects under development across the different steps of the CCUS value chain, including research and development (R&D) of various technological choices. In the following subsections, the TRL of the main technologies within each of the CCUS steps are mapped.

2.1.1 CO_2 capture

First generation capture technologies correspond to (i) amine-based solvents, (ii) physical solvents, (iii) membranes for purification of natural gas processing and (iv) cryogenic air separation (air separation unit – ASU) to obtain pure oxygen. These technologies are currently commercially available (i.e., TRL 9), but R&D on necessary improvements is still ongoing. Second generation technologies include those in R&D phase that will be ready for demonstration at a later stage, while third generation technologies are at an early stage of development, even at a conceptual stage. Different demonstration timeframes have been suggested over the years. However, some technologies have not evolved in their TRL in the last 10 years, perhaps indicating some fundamental challenge to further development (e.g., functional material reactivity and/or stability, need of extreme operating conditions, limitations in gas-liquid/solid contact area, etc.).

The average TRL of different capture technologies across the main sources mapped [14], [15], [16], [17], [18], [19] are shown in Figure 3 (note that the plotted results are the average TRLs across the mapped literature and can therefore end up in non-exact TRL levels), including the minimum and maximum levels reported (red vertical lines), where it is seen that while several technologies lie on TRL 9, the average TRL across all capture technologies is 6.

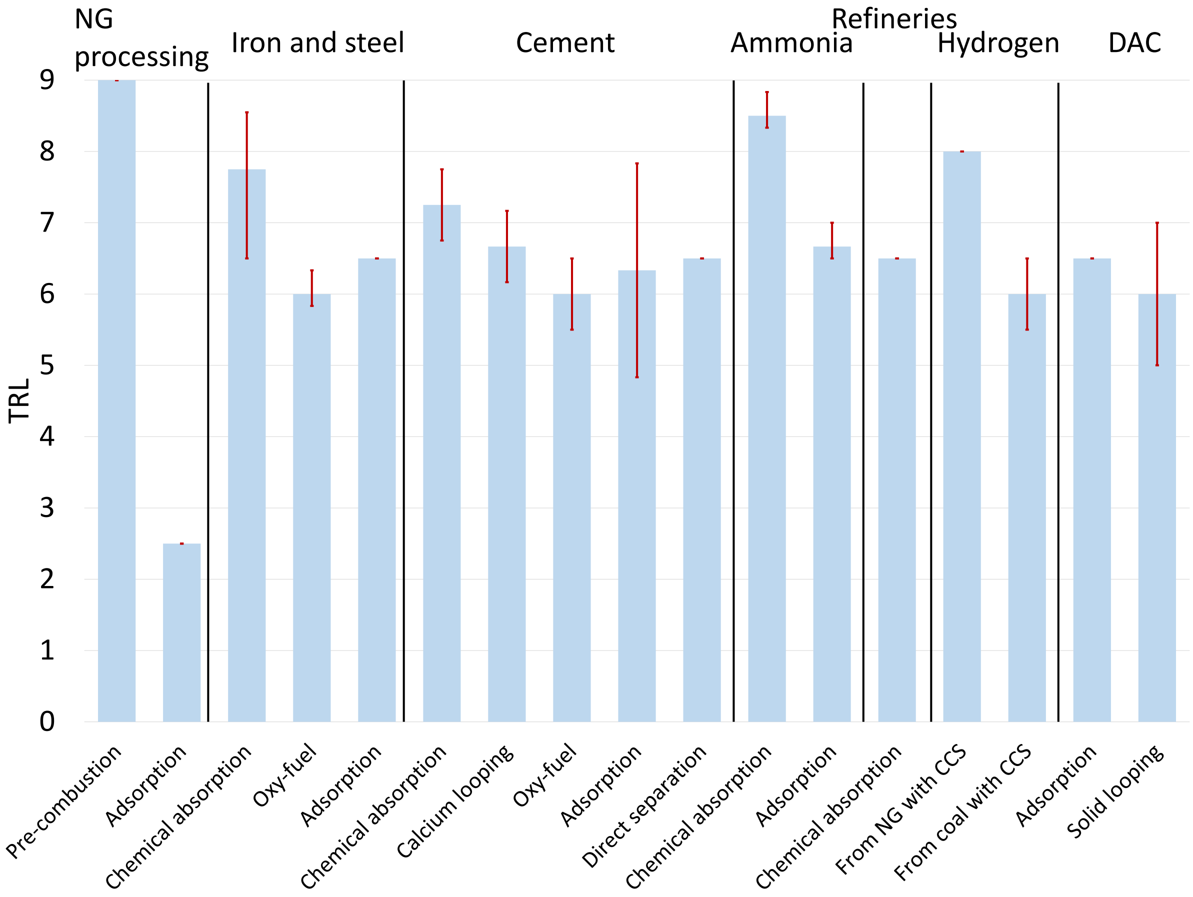
Figure 3. Average TRL of CO_2 capture technologies and sub-technologies (red vertical ranges represent maximum and minimum levels reported).



Source: JRC based on scientific literature, IEA, Global CCS Institute, IRENA.

The average TRL of different capture technologies across the main sources mapped are shown in Figure 4, including the minimum and maximum levels reported (red vertical lines), where it is seen that while several technologies lie on TRL 9, the average TRL across all capture technologies is 6. It is important to mention that the TRLs reported in Figure 3 refer to the standalone technologies, and not necessarily reflect the real readiness levels of the technologies when applied for CO_2 capture in industrial conditions. For that, Figure 4 depicts the mapped TRL when the technologies have been applied for CO_2 capture within specific industrial sectors. Figure 4 reveals that the number of technologies tested at industrial conditions is much lower than the number of technologies included in Figure 3, and that only natural gas (NG) processing has capture technologies at commercial scale (i.e., TRL 9), followed by ammonia and hydrogen production (with TRls of around 8).

Figure 4. Average TRL of CO_2 capture technologies when applied to different emission sources (red vertical ranges represent maximum and minimum levels reported). NG: Natural Gas. DAC: Direct Air Capture



Source: JRC based on scientific literature, IEA, Global CCS Institute, IRENA.

In addition to CO_2 capture from point sources, direct air capture (DAC) is one set of technologies that extract CO_2 directly from the atmosphere. Today, two technology approaches are being used to capture CO_2 from the air: liquid and solid systems. Liquid systems pass air through chemical solutions (e.g. a hydroxide solution), which removes the CO_2. The system reintegrates the chemicals back into the process by applying high-temperature heat while returning the rest of the air to the environment. Solid system technology makes use of solid sorbent filters that chemically bind with CO_2. When the filters are heated and placed under a vacuum, they release the concentrated CO_2, which is then captured for storage or use [20].

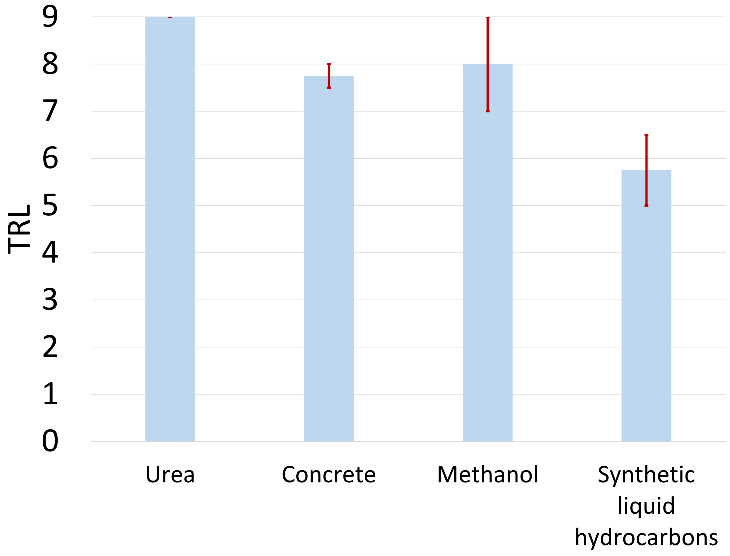
Bioenergy with carbon capture and storage (BECCS) is relatively well understood, but it has mostly struggled to move beyond demonstration projects. Efforts to combine the two technologies remain limited beyond pilot projects and small-scale BECCS projects at various kinds of facilities (e.g., waste-to-energy, ethanol, cement, electrical generation, etc.). In 2021, IRENA reported 28 BECCS/BECCU plants – comprising either commercial or pilot and demonstration projects [17]. In the USA, Archer Daniels Midland operates a commercial facility in Decatur, Illinois with CO_2 from ethanol fermentation process which can be considered to be at TRL 9. The British electrical power generation company Drax has converted a large coal-fired power plant in North Yorkshire to run on wood pellets, investigating and piloting the setup of a bio-CCS value chain. Toshiba is adding carbon capture and storage to its Mikawa biomass-fired power plant in Japan.

2.1.2 CO_2 utilisation

There is currently a global demand of CO_2 for synthesis of products. So far, CO_2 has been a by-product of industrial processes such as in H_2 production by steam reforming of NG or ethanol production by fermentation. The largest CO_2 consumer is the fertiliser industry, followed by oil and gas (EHR). From the wide range of possibilities for CO_2 use as a raw material, each one is at different levels of development, different scales and market prospects. Some technologies could be readily established in existing mature markets e.g. utilisation of CO_2 to boost urea production, whereas others are at prospective phases, or are at the pilot/demonstration phase, and need further development to reach commercial status.

According to [14], the term CCU is representative of a diverse array of technologies, most of which have their conceptual viability established in the pilot scale and the need to transform CO_2 into products that cannot yet be made available on the market due to the need for more research and/or modifications to the existing regulatory structure. Thus, it is typically assumed that mainly all CCU technologies have a TRL 6. However, there are possibilities to identify specific CO_2-based products on the TRL scale, with the main ones depicted in Figure 5. It can be seen that production of urea and methanol are within TRL 9, while mineralisation (e.g., into concrete) is reaching TRL8 and the production of synthetic liquid hydrocarbons follows behind at a TRL of 6.

Figure 5. Average TRL of selected CO_2 utilisation technologies (red vertical ranges represent maximum and minimum levels reported).



Source: JRC based on scientific literature, IEA, Global CCS Institute, IRENA.

2.1.3 CO_2 transport

The transportation of gasses and liquids via pipelines, trucks, ships or rail is technologically mature (i.e. TRL 9, see Figure 6). In fact, CO_2 is compressed and transported at significant scale through pipelines, primarily in the United States. In Europe, CO_2 pipelines are operating in the Netherlands, Norway, Hungary and Croatia. In Norway, an offshore 153-kilometre long CO_2 pipeline is operating for the Snøhvit CO_2 storage facility. An example of onshore pipeline is in Croatia where CO_2 from a natural gas processing plant is being transported in gaseous phase via 88 km long pipeline to the compression and liquefaction unit at the location of the EHR field [21]. Depending on the pressure and the temperature of the CO_2 its pipeline transport can be in both gaseous and liquid phases. The liquid phase is characterized by the high density of CO_2, which allows the transportation of larger capacities, while the gaseous phase, with its lower density, facilitates the transport of smaller quantities of CO_2. It is important to notice that there is considerable potential to reuse or repurpose existing oil and gas pipeline infrastructure for transport of CO_2 (although a number of technical considerations dictate the potential, see [18]).

For more than two decades CO_2 has been transported around Northwest Europe and the Mediterranean using relatively small liquefied CO_2 vessels serving the food and beverage industry, with a total capacity less than 0.5 Mtpa [22]. It is expected that the ships used for CO_2 transport in the future will most likely be similar to these ships but scaled to transport larger quantities at varying pressures. Currently, larger capacity-ships for CO_2 transport have been ordered in anticipation of the increased volumes of CO_2 to be transported with further development of the CCUS market. In addition to transporting CO_2, these type of ships could also be suitably adapted for the transportation of other cargo, such as LPG and ammonia, which offers a certain degree of assurance that the vessels will remain usable for transport even in the event of potential delays in the development of the CCUS market. Thus, the TRL for CO_2 shipping ranges between 6 and 9 according to the mapped references (see Figure 6).

CO_2 can be transported in small quantities over short distances using alternative modes of transport such as trains, trucks and barges. Although the average capacity that these modes can transport is not large, their role in total transportation could still be relevant in future scenarios. Alike ships, these alternative transport modes (mostly trucks) are already being widely used in Europe for the food and beverage industry. In the United States, nearly 10 Mtpa of liquid CO_2 is transported via trucks (mostly) and rails [23].

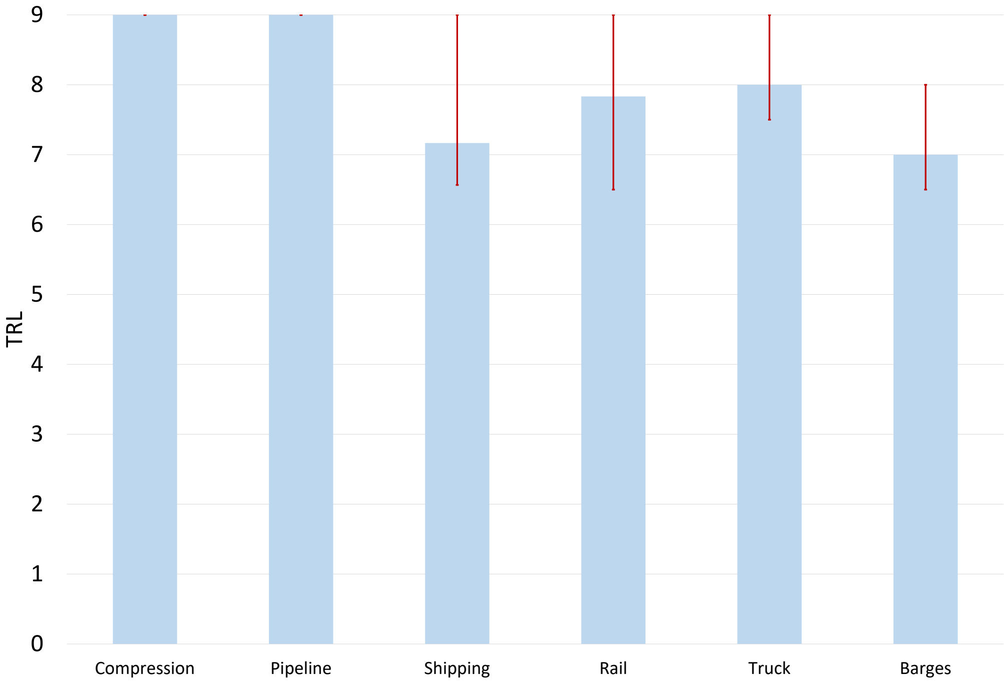
Although currently not playing a major role, the CO_2 transport via barges could be a relevant solution for emitters located closer to the European river/canal system. The design of the tug-barge combination and the offshore mooring system developed by the Carbon Collectors in the Netherlands received and Approval In Principle and plans to have first barge fleet for 0.5 -1.5 Mtpa project operational in 2027[7].

Some project developers, such as GO4ECOPLANET and ECO2CEE projects in Poland are planning to use rail transport for CO_2 as a potential temporary and transitional method of transporting CO_2 until further development of the CCUS market and the construction of pipelines.

The impact of scaling-up of these various transport modes on the already heavily used rail, road, and river transit routes (especially in Europe) is still unknown. However, they could be a potential solution for transporting CO_2 from smaller emitters to the main CO_2 transportation network, plus they could enable inland emitters and early adopters to advance their decarbonisation efforts and begin implementing projects sooner.

The compression technology, also included in Figure 6, is considered to be mature and its TRL is 9 [15].

Figure 6. Average TRL of selected CO_2 transport technologies (including compression). Red vertical ranges represent maximum and minimum levels reported.



Source: JRC based on scientific literature, IEA, Global CCS Institute, IRENA.

2.1.4 CO_2 storage

CO_2 storage resources and storage technologies are broadly divided based on the subsurface rock where the CO_2 is trapped: saline formations/aquifers, depleted oil and gas fields and unconventional resources such as igneous rocks (basalt and ultramafic rocks), coal seams and organic shales [24].

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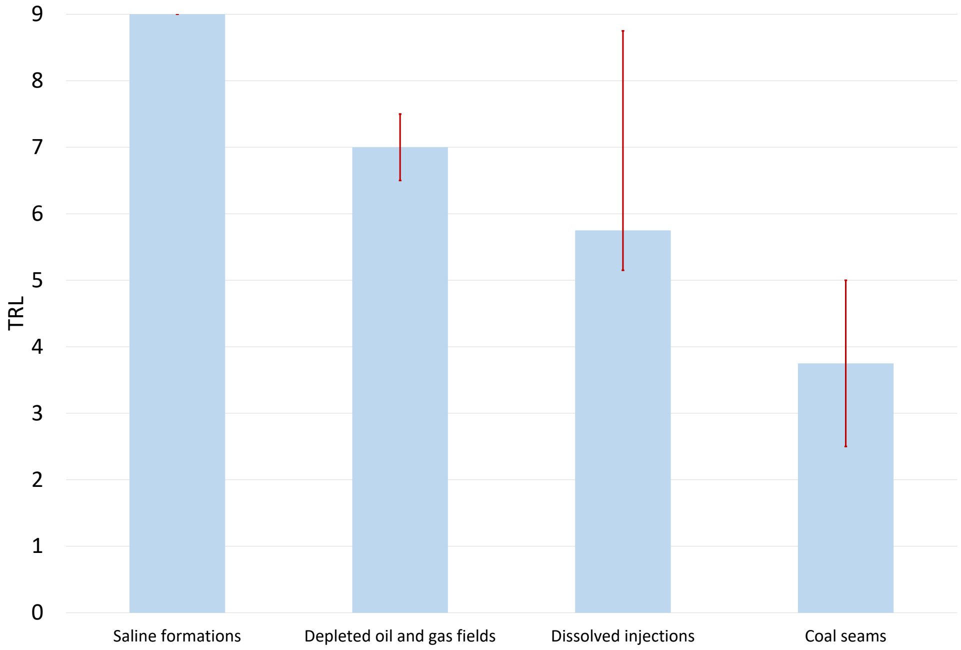
[7] https://carbontcollectors.nl/other/co2-barge-push-combination-receives-approval/

According to the mapped sources, geological CO_2 storage in saline formations has a TRL 9 as it has been occurring in the North Sea since 1996 when the Sleipner CCS project started operating. Since then, over 20 Mt of CO_2 have been injected for storage at that location and more sites became operational (e.g. Snøhvit in Norway, Gorgon in Australia, Quest in Canada, Illinois Industrial in the US).

Geological storage in depleted oil and gas fields is technically mature with the purpose of EHR (especially in the US), but dedicated storage has a lower TRL of 5-8 as it has only been applied in demonstration projects [25]. Nonetheless, the maturity of the technology is expected to ramp up fast as there are numerous storage projects currently being developed with the aim of storing CO_2 in depleted oil and gas field (e.g. ANRAV project in Bulgaria, Greensand and Bifrost projects in Denmark, Ravenna CCS project in Italy).

Lastly, among the unconventional options for the storage of CO_2 we highlight: mineral carbonation in basalt (e.g. Orca in Iceland and Wallula in the United States) and ultramafic rocks (TRL 2-6), storage in unmineable coal seams through Enhanced Coal Bed Methane (ECBM) production (TRL 3-5) and storage in organic shales which storage potential is still less explored [24]. An overview of the average TRL across the mapped sources is included in Figure 7.

Figure 7. Average TRL of selected CO_2 storage resources (red vertical ranges represent maximum and minimum levels reported).



Source: JRC based on scientific literature, IEA, Global CCS Institute, IRENA.

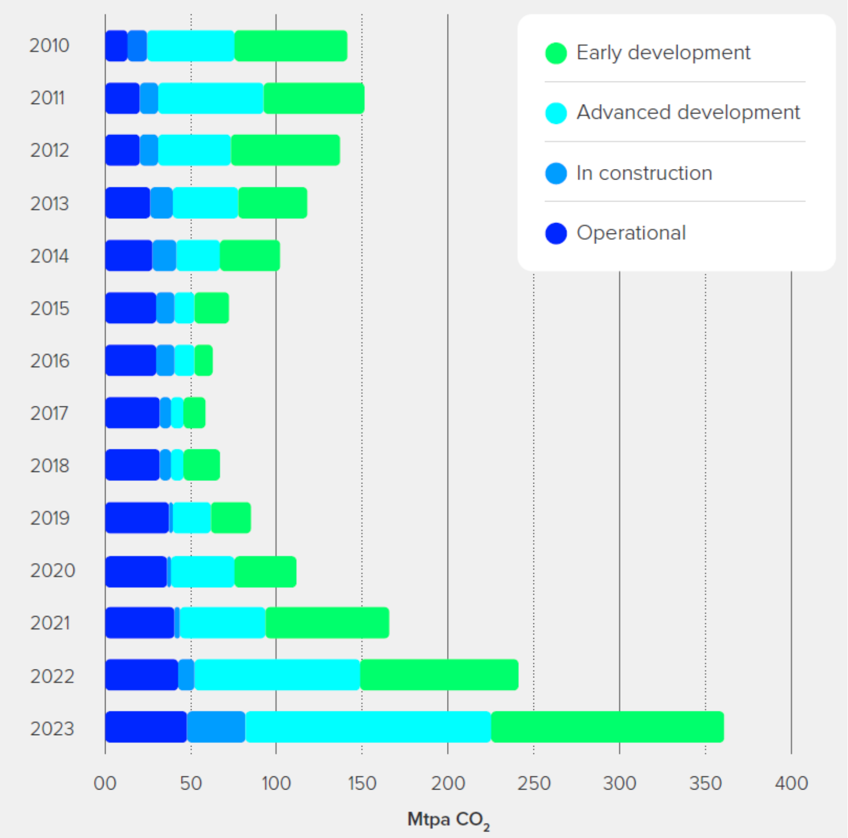
2.2 Installed Capacity and Production

2.2.1 Current situation

Globally, there are 41 operational CCS facilities with a total capture capacity of about 49 Mt of CO_2 per year [13]. The US and Canada lead the way globally with 51% of the market share. Other leading countries include Brazil (with the world's largest operating CCS facility), Australia and China, which in 2023 began operation of 5 new CCS facilities. Norway is the only country in continental Europe that has built large-scale capture and storage projects. Sleipner and Snohvit, built in 1996 and 2008 respectively add an average of 1.8 million tonnes per year of CO_2, representing 4% from the global market share [26]. It should be noted that due to the cost characteristics reviewed in Section 2.3, most of the existing CCS plants in operation are deployed in natural gas processing plants as well as ethanol and ammonia production. Direct Air Capture (DAC) has also received a lot of attention besides the typical CO_2 separation technologies. In Europe, the Swiss company Climeworks deployed their first commercial plant in 2017 and in May 2024 the largest commercial DACCS plant Mammoth started operation in Iceland following the launch of Orca in 2021.

As of September 2023, the total global capacity of commercial CCS projects across different phases (including not only operational but also projects in construction as well as projects in the planning phase, both in advanced and early development, see Figure 8) was 361 Mtpa of CO2 across 392 different projects, representing a 102% year-on-year increase [13]. These facilities and projects cover a wide range of industries and sectors including chemical and hydrogen production, iron and steel, natural gas processing, power generation, fertiliser and ethanol production. However, and as can be extracted from Figure 8, there is a lack of final investment decisions (FIDs) made across CCUS project pipeline.

Figure 8. Global pipeline of commercial CCS facilities from 2010 to September 2023 by capture capacity. Note that projects in early and advance development are still in the planning phase and are not necessarily to be realized.



Source: Global CCS Institute [13]

In Europe, promising projects in advanced phases of development are shifting focus towards CO_2 infrastructure such as the Northern Lights in Norway and PORTHOS and ARAMIS projects in the Netherlands. In addition, the European Commission published a list of Projects of Common Interest for cross-border carbon dioxide network (listed projects benefit from advantages such as priority status for granting procedures and improved and faster environmental assessment, among others) that included several CCS initiatives. Furthermore, some transmission system operators are developing plans for CO_2 transport networks that will cover the entire territories of individual Member States and potentially connect with the CO_2 transport networks of neighbouring countries (e.g. the OGE CO_2 transport network in Germany and the Fluxys CO2 transport network in Belgium). These plans incorporate individual CO_2 infrastructure projects with the aim of collecting and transporting CO_2 from large number of CO_2 emitters to the storage sites.

Regarding storage, the primary emphasis of the storage project's development is centred on the North Sea region. Nonetheless there are also promising storage initiatives underway in Italy, specifically Ravenna CCS hub, and in Greece, Prinos.

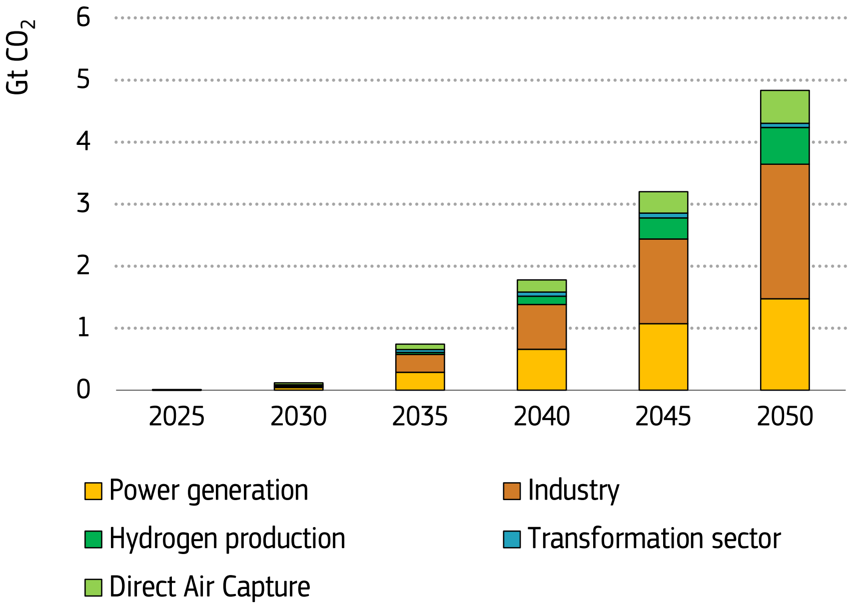
Besides transport and storage, capturing CO_2 from the production of hydrogen, ammonia and fertilizers is gathering a lot of attention in the last years, with up to 20 CCS facilities in the pipeline [13]. While CCS developments stagnated in power generation in the last decade, currently a total of 34 projects are linked to power and heat production plants (including bioenergy, i.e., BECCS).

Regarding CCU projects, the IEA estimates that around 230 Mt of CO_2 are used yearly worldwide, mainly in direct use pathways in the fertilizer and urea industries as well as for EHR (REFIEA). When it comes to CCU for the production of synthetic fuels, chemicals and building aggregates, the current pipeline shows that around 15 Mtpa could be captured for these uses globally by 2030 (IEA). However, only a handful of these projects are in operation today.

2.2.2 Projections

Despite the recent growth in CCUS projects across the globe, the latest IPCC assessment report pointed that the current rates of deployment are far below those in modelled pathways to limit global warming to 1.5 or 2°C [27]. Thus, if countries are to comply with their climate pledges and goals, the deployment of CCUS has to increase sharply in the upcoming years. In fact, a global deployment of around 1 Gt of CO_2 capture capacity is required by 2030 according the IEA "Net-Zero Emissions by 2050" Scenario (NZE) which is compatible with limiting the temperature rise to 1.5 °C. Moreover, the POLES-JRC[8] energy system model projects in its recent Global *CETO 2°C scenario 2024* that the global amount of annually captured CO_2 reaches 118 M by 2030 and 4.8 Gt by 2050 (see Figure 9). In the *Global CETO 2°C scenario 2024* (Figure 9) global CO_2 capture from industry experiences steady growth over the decades and emerges as the primary application for CCS by 2050. Furthermore, CO_2 capture in power generation assumes a significant role by 2050, with hydrogen production and direct air capture (DAC) holding the third and fourth largest shares in capture usage, respectively. Consequently, and due to the relatively low share of DAC in the global expected CO_2 capture capacity (partly caused by the recent increases in DAC cost projections [28]), the *Global CETO 2°C scenario 2024* estimates that around 93% of the total CO_2 captured in 2050 to be stored in permanent storage with the remaining used to manufacture synthetic fuels.

Figure 9. Projected global CO_2 capture by source, 2025-2050 according to the Global CETO 2°C scenario 2024.



Source: JRC analysis based on the POLES-JRC model.

Within the EU, the latest projections released by the European Commission in the Industrial Carbon Management strategy [5] as part of the EU's 2040 climate target Communication [29] indicate that approximately 50 Mtpa will be captured by 2030, 280 Mtpa will have to be captured by 2040 and around 450 Mtpa by 2050. As it is shown in Figure 10, most of the CO_2 captured is expected to come from industrial process emissions, which is in line with the predictions published as part of the Fit-for-55 package [30].

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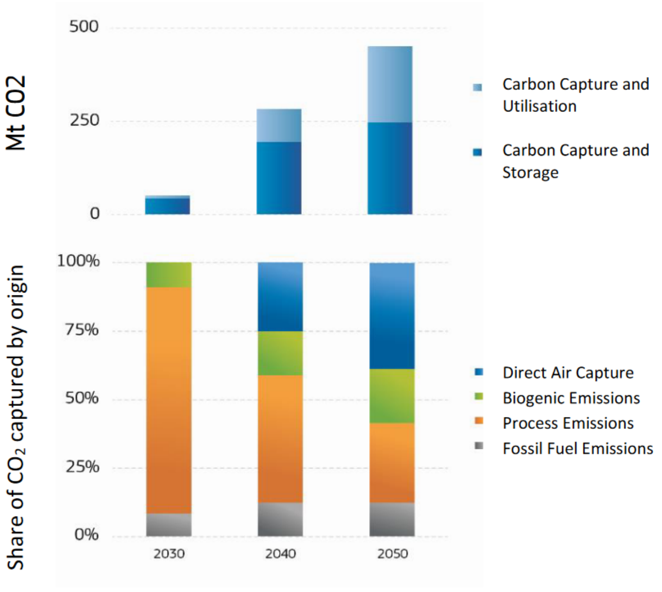
[8] POLES (Prospective Outlook on Long term Energy Systems) is a global energy model to assess the contribution of the various energy types (fossil fuels, nuclear, renewables) and energy vectors, to future energy needs developed by JRC. Description of the model and the scenarios are given in Annex 2.

Figure 10. Volume of CO_2 (in Mtpa) captured for storage and utilisation in the EU (top chart) and share of the CO_2 captured by origin (bottom chart) according to the EU's climate target modeling.



Source: European Commission [5]

Figure 11 displays projected CO_2 capture by source of the *POTEnCIA CETO 2024 scenario*, which was computed by the POTEnCIA[9] energy system model. Solid biomass and waste-incineration plants (also known as Bioenergy with CCS, or BECCS) and cement production are expected to capture the largest amount of CO_2 emissions, respectively 113 Mtpa and 92 Mtpa by 2050. This can be explained by the fact that CCS represents the most cost-effective (BECCS) or sole avenue (cement) for mitigating the inevitable process emissions in these sectors. It can also be seen in Figure 11 that while the BECCS and Waste-related CO_2 capture increases largely until 2050, the CO_2 captured in cement and iron and steel sectors peaks in 2040/2045 and decreases slightly by 2050 due to i) the development of the H2-DRI route in the steel sector and ii) the deployment of electric kilns abating fossil emissions.

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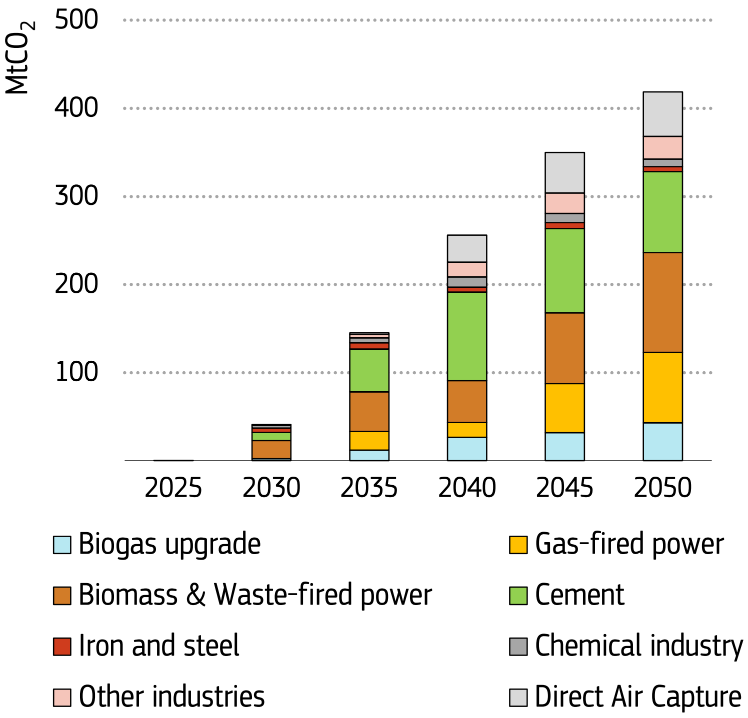
[9] POTEnCIA (Policy Oriented Tool for Energy and Climate Change Impact Assessment) is a modelling tool that allows a robust assessment of the impact of different policy futures on the EU energy system developed by the JRC. Description of the model and the scenarios are given in Annex 2.

Figure 11. Projected CO_2 capture by source in the EU, 2025-2050.



Source: JRC analysis based on the POTEnCIA model

In the beginning of 2024, JRC published a report on the potential extent and evolution of the most effective main transport network configuration within the EU that transports projected CO_2 captured amounts to the storage sites at the lowest possible investment costs [31]. Based on the modelling results, the European CO_2 transport network could reach a length up to 19 000 km and require investment up to EUR 23.1 billion by 2050. The extent and the cost of the network could be reduced by developing storage capacities in regions where current capacities are insufficient (e.g. southern and eastern Europe) to avoid transporting CO_2 over long distances. The modelling further indicates that the transport infrastructure could evolve into a large network that links numerous countries, as well as into several regional networks. It could also see the development of interconnections exclusively between pairs of countries, along with a substantial transport routes that connect specific capture and storage sites. This underscores the imperative for establishing uniform CO_2 transport standards across Europe and a shared regulatory framework to guide such developments.

The expected roles of carbon removal technologies such as DAC and BECCS are somewhat diverse. Globally, according to the IEA NZE scenario, almost 980 Mtpa are required to be captured using DAC by 2050, and already 85 Mtpa by 2030 [20]. Projections from the scenarios within the EU long-term strategy (LTS) to reach carbon neutrality by 2050, allocate 210 Mtpa and 123 Mtpa to DAC in the 1.5TECH and 1.5LIFE scenarios respectively [32]. However, the DAC plants currently operational in the world are capturing only around 0.01 Mtpa, in total [20]. The recently launched Carbon Dioxide Removal Mission, under Mission Innovation, aims to enable CDR technologies to achieve a net reduction of 100 Mtpa globally by 2030. In August 2022, the Mission published an Innovation Roadmap [33] to serve as a starting point for Mission Innovation members to build an Action Plan and uncover specific opportunities to achieve the above target by 2030. More recently, the European Commission's Climate Modeling results attributed DAC and BECCS more than half of the captured CO_2 by 2050 (see Figure 10).

2.3 Technology Cost

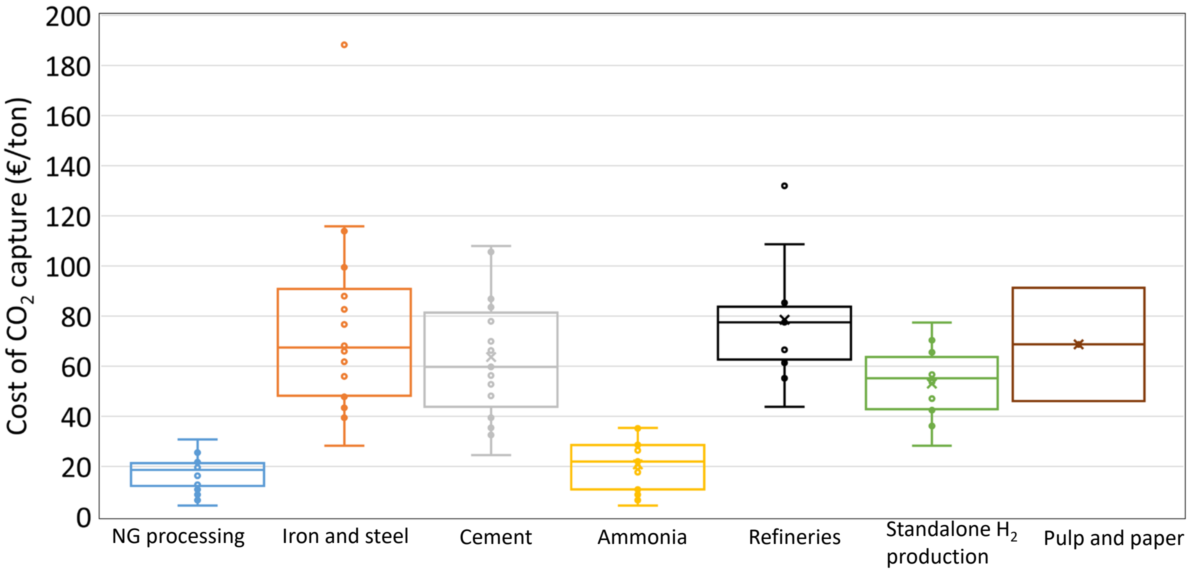
2.3.1 Current

Cost estimates of CCUS technologies are complex and broad, with large differences across sectors, specific industries and plants, countries and continents. In fact, and due to the installed capacity described in Section 2.2, most of the available economic data pertains to U.S. projects. Apart from project data, theoretical cost estimations are often linked to an accuracy of ±30%, and discrepancies on how to estimate the transition between First-of-its-kind (FOAK) and Nth-of-its-kind (NOAK) estimates exist.

As for the technology readiness levels, the cost of CCUS technologies must be assessed individually within each step of the value chain. For the capture, the cost is mainly a function of the volume, concentration and pressure of the CO_2-rich stream (such characteristics are typically linked to the emitting process), the capture technology employed (some being more CAPEX-intensive, some characterized by larger OPEX), the possibility to retrofit the emitting plant, the heat integration potential and the capture rate (i.e., the share of captured CO_2 for which the capture plant is designed). Larger capture plants have higher capital costs, but lower specific cost per ton of CO_2, if the capture system is run at high utilisation rate.

Figure 12 displays the capture cost of different industrial sectors mapped across the literature [34], [16], [17], [35], [15], [18]. The cost of capturing CO_2 can vary from a range of 10-30 EUR/t CO_2 for industrial processes generating highly concentrated CO_2 streams (such as ammonia production and natural gas processing) to 25-120 EUR/t CO_2 for processes with medium concentration gas streams, such as cement, iron and steel or pulp and paper production. The large range in costs is also due to that while some CO_2 capture technologies are commercially available, others are still in development and hence, prohibitively expensive. It can also be seen in Figure 12 the amount of data points found for each sector (lowest for pulp and paper industries) as well as the variability of the estimations, being the largest for iron and steel and cement productions as these processes are characterized by different production routes and therefore different alternatives for CO_2 capture.

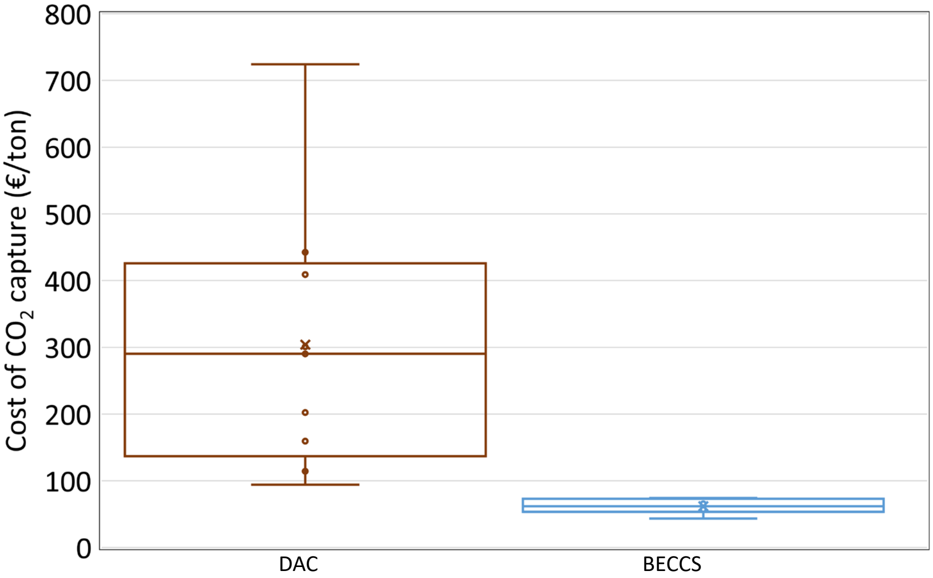
Figure 12. Cost of CO_2 capture by industrial sector. The vertical lines represent the variability outside the upper and lower quartiles (boxes). The mean values are shown with an X.



Source: JRC based on the literature reviewed.

Regarding the capture costs of CDR technologies (i.e., DAC and BECCS, see Figure 13), cost estimates for BECCS vary depending upon the sector of application (40–75 EUR/tCO_2 according to the mapped sources). Prices for DAC currently range anywhere between 100 to 800 EUR/tCO_2. There is no clear pricing trend with larger DAC providers being necessarily cheaper. Many suppliers claim costs can be brought down to 300-500 USD/tCO_2 by 2030 [36], while a recent publication [28] concluded that costs will not be below 300 EUR/tCO_2 when deployed at the Gt scale.

Figure 13. Cost of carbon dioxide removal technologies (capture step only). The vertical lines represent the variability outside the upper and lower quartiles (boxes). The mean values are shown with an X.



Source: JRC based on literature reviewed

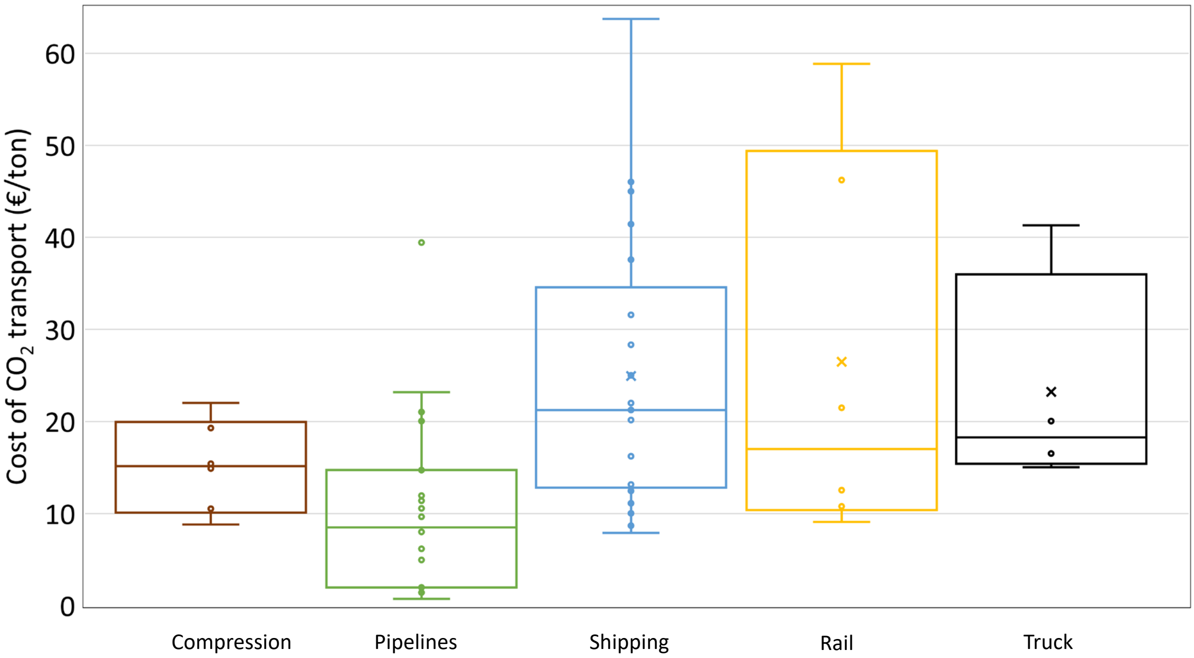
The cost of CO_2 transport can also vary greatly on a case-by-case basis, depending mainly on scale (CO_2 volumes), transport modes, geography, transport distances and quality levels of the transported gas. Figure 14 shows the different cost estimates of pipeline-, ship-, rail- and truck-based transport reported in the mapped literature [23], [37], [22], [38], [18], together with the cost of compression (data on CO_2 transportation costs using barges were not available at the time of writing this report).

According to BNEF [39], the levelised cost of CO_2 transport by pipeline is heavily dependent on capacity. For an onshore pipeline of around 135 km of length, the transport costs for transporting 10 Mtpa are around 1.9 EUR/tCO_2. Below 10 Mtpa, costs are closer to 3.62-7.24 EUR/t CO_2, and for smaller emitters they can reach up to more than 25 EUR/t $CO_{2.}$ It should be noted that the higher end of the pipeline costs reported in Figure 14 correspond to offshore pipelines while the lower end is for onshore ones. It should be added that according to BNEF [40] land transport by trucks is more cost effective than pipelines for quantities less than 1.7 Mtpa and intermittent demand.

Ship-based transport is less capital intensive compared to pipelines and it is more independent on distance and scale of transport, but OPEX represent a large fraction of their cost [17]. Therefore, shipping is preferred for larger distances and when flexibility and rapid deployment are prioritized. The distance at which shipping breaks-even pipeline transport depends on the flow rate. For a low flow rate pipeline transport is not economic and the breakeven distance of shipping is low (at 160 km for a flow rate of 0.5 Mtpa). For a higher flow rate (5 Mtpa), pipeline transport unit costs decrease and the breakeven distance of shipping increases to 500 km [41]. The Clarksons/CSSA Report provided estimates for 18 different shipping routes, primarily focusing on the North Sea. The routes varied in distance from approximately 500 kilometres to 2000 kilometres. The ships used for their estimates had capacities ranging from 7,500 cubic meters (CBM) to 22,000 CBM, and the containment pressures were categorized as low, medium, and elevated. According to the report, the cost of transporting CO_2 using a ship with a capacity of 20,000 CBM at medium containment pressure was found to range from 19 to 34 EUR /tCO_2 [22]. The Northern Lights project targets combined CO_2 transport and storage costs ranging from 30 to 55 EUR/tCO_2 [42].

It should be noted that both for pipelines and ships, repurposing the existing infrastructure for oil and gas to CO_2 transport may lead to reducing the costs of a new one that would need to be built [16], with some estimates suggesting cost reductions up to 83% [43].

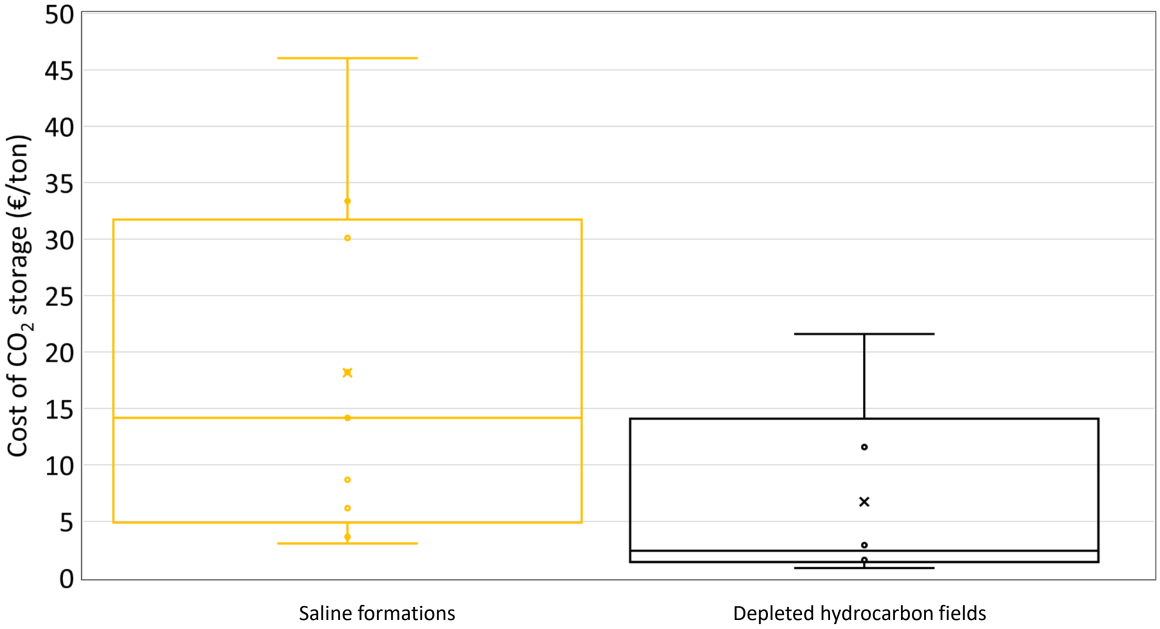
Figure 14. Cost of selected CO_2 transport technologies. The vertical lines represent the variability outside the upper and lower quartiles (boxes). The mean values are shown with an X.



Source: JRC based on literature reviewed

Regarding the costs of CO_2 storage, the authors note that there are fewer detailed cost analyses available as compared to other steps within the CCUS chain. Given that the number of operational storage projects is still limited, the majority of available studies are based on projects in the development phase and tend to provide cost estimates in the form of broad ranges. Storage costs (depicted in Figure 15) can differ significantly between projects and regions (site- and region- specific), spanning from 1 to 34 EUR/t of CO_2, with average costs below 10 EUR/tCO_2. Generally, onshore storage, including assessment, development, and operations, is usually less expensive than offshore storage and the saline aquifers often necessitate more extensive and costly data collection compared to depleted oil and gas fields. Regarding CAPEX, saline aquifers might have a lower available pressure margin, potentially requiring more injection wells to inject due to pressure. On the other side, depleted oil and gas fields offer the possibility of repurposing or re-abandoning existing infrastructure, which can lead to cost savings or additional expenditure.

Figure 15. Cost of selected CO_2 storage technologies. The vertical lines represent the variability outside the upper and lower quartiles (boxes). The mean values are shown with an X.



Source: JRC based on literature reviewed

On the assumption that the cheaper available storage sites will be developed first, ZEP suggested that storage costs for the early commercial phase will be at the level of 2-12 EUR/t as defined for onshore saline aquifers. However, onshore CO_2 storage has been largely prohibitive in Europe, thus, a more realistic assumption is to consider CO_2 storage cost in the offshore (for example in depleted oil gas reservoirs) which is in the range of 2 to 20 EUR/t of CO_2 [44]. Table 3 lists detailed cost estimates when accounting for the type of storage resource, location (onshore/offshore), and the potential for infrastructure reuse.

Table 3. Cost estimates of CO_2 storage as a function of location, type and re-use of infrastructure.

Location	**Storage type**	**Re-use of infrastructure**	**Cost (EUR/t)**
Onshore	Depleted oil and gas field	Yes	1-7
		No	1-10
	Saline aquifers	No	2-12
Offshore	Depleted oil and gas field	Yes	2-9
		No	3-14
	Saline aquifers	No	6-20

Source: JRC based on literature reviewed

In the United States, the mean storage costs range between approximately 5 and 15 EUR/t CO_2 both in saline aquifers and depleted oil and gas fields [42]. According to [18], more than half of onshore storage in is estimated to be below approximately 8 EUR/tCO_2 and about half of the offshore storage is estimated to be available at costs below 29 EUR/tCO_2.

Long-term maintenance and oversight costs of storage must be also considered. The need for continuous monitoring, evaluation and planning indicates storage site developers must commit substantial amounts of financial, human and technical resources to storage operations, beyond eventual closure. Monitoring costs are generally a small fraction of the whole project (less than 5% of the total costs which is significant in comparison to capital and operating costs of capture facilities). Commercial scale projects storing on the order of 1 Mtpa usually incur costs on monitoring alone between USD 1 and 4 million per year [45]. Other key aspects to consider are the existing infrastructure and social acceptance [16].

When captured CO_2 is used as a commodity for utilisation processes, the capture cost and therefore the selling cost of the CO_2 will influence the production cost of the final materials/fuels. Thus, the cost of CO_2 utilization technologies shows extreme variations (even within the same product, e.g., methanol, variations can be in the range of 300-2500 EUR/t depending on assumptions). In addition, other clean energy technologies outside the scope of the current work (such as electrolysers) play a crucial impact in the cost of these processes. Thus, the reader should refer to the Hydrogen[10] and RFNBO[11] reports of CETO for further information on CO_2 utilization costs.

It is important to mention that while the present analysis has focused on costs, CO_2 capture plants can also offer revenues, not only in connection to the emission avoidance and potential subsidies or tax reductions in place, but also via by-products generated by the capture technology. These are typically energy production and/or energy storage [46], although such novel capture technologies are still under development.

2.3.2 Expected cost reductions

As the scale increases, the costs of capture, transport (especially of pipelines), utilization and storage decline considerably [16]. In the case of capture, some studies [47] suggest that learning rates could follow those of flue gas cleaning technology back in 1970-2000, which were in the range of 12 % - 14 %. These findings provide a great opportunity for cost reductions through modularisation, i.e., the standardised production of capture units under mass production techniques. According to the Global CCS Institute [15], modular carbon capture plants also help reduce costs through standardised plant foundations, standardised plant designs and drawings, automated operation and modular packaging, as well as reduced construction time. Aker Carbon Capture is an excellent example of the modularisation approach with its commercially available “Just Catch” brand.

Full-chain CCUS costs can be lower when CO_2 emissions from several sources are clustered, transported and stored using the same infrastructure. This will result in CCUS hub formation and can be critical in regions that will store CO_2 offshore, such as Europe, as running the sites with low volumes could make the projects expensive and unviable. Wood and Mackenzie also forecast cost reductions of around 20 % by 2050, as the industry scales up and technology improves [48]. IEAGHG [49] argues that pipeline costs are dominated by CAPEX only and modest reductions in project costs are expected (up to 4 % by 2040). However, reductions in OPEX of 45 % and 26 % for onshore and offshore pipelines respectively can be expected in the 2040 scenario due to the reduced supply chain losses, with the primary technologies driving overall cost reductions from novel sensors and robotics.

The cost and origin of the energy used for capture is also a significant contributor of the capture cost. Depending on the emitting facility and capture technology, energy can be provided via low-pressure steam, on-site combined heat and power units or electricity, among others. Additionally, waste heat available on-site or in the industrial clusters around the capture facility can represent an opportunity for cost reductions. According to the Global CCS Institute, using waste heat can reduce the cost of capture by around 10-20 EUR/t [15].

Learning by doing is another key element regarding the cost reductions expected across the CCUS chain. As an example, the cost of CO_2 capture from sources such as in coal-fired power generation has been reducing over the past decade and is projected to decrease 50% by 2025 compared to 2010 [15]. The two coal-fired power plant CCS retrofits that have been constructed in Canada and the United States, even if not directly comparable, demonstrate the difference in actual capture and compression costs. Capture costs for Boundary Dam in Canada, operating since 2014, are approximately 93 (USD_{2020} 105) EUR / tCO_2 [50]. The Petra Nova CCS project in the United States, which started operation in 2017, with expected capture and compression costs of approximately 62 (USD_{2020} 70) EUR / tCO_2 [51]. For Longship, the Norwegian full chain CCS project, the total capital expenditure (CAPEX) is estimated at nearly EUR 1.66 billion (USD 1.86 billion, both capture plants included, capturing CO_2 from cement and waste to energy plants respectively). The annual operating expenditure (OPEX) is around 4-5 % of CAPEX for each part of the chain [52]. When it comes to storage costs, learning by doing can contribute to optimisation in resource assessment, development and monitoring. In addition, the CCUS

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[10] https://setis.ec.europa.eu/water-electrolysis-and-hydrogen-european-union_en

[11] https://setis.ec.europa.eu/renewable-fuels-non-biological-origin-european-union-0_en

sector in general could significantly benefit from competency and technology spill over from other industries (e.g. oil and gas).

Global CCS Institute states that injecting, storing and monitoring CO_2 within the subsurface are well established technologies [15]. Thus, the drivers for future cost reductions can be expected in three key areas: site selection, deployment and technology advancement. Similarly, the IEA shares this line of thought and reports that the size and quality of the storage site, along with the economies of scale, exert the most significant impact on the overall costs of CO_2 storage and therefore in the potential reductions [24]. The most effective strategy to minimize CO_2 storage expenses is to develop the appropriate resource, which can be supported by employing advanced assessment technologies. IEAGHG [49] also states that for storage sites operating in 2025, overall reductions of 2 % in lifetime costs can be expected for onshore and offshore sites, resulting from 8-9 % less OPEX costs and a reduction of 10 % in supply chain losses. By 2040, 19 % overall cost reductions are projected in offshore projects and 26 % in onshore; a result of a 7-9 % CAPEX reduction, 50 % OPEX reduction and 50 % reduction in injection facility downtime. For an offshore saline aquifer example, these reductions could equate to a saving of over USD 45 million in CAPEX and up to USD 60 million in OPEX. In addition, they report that digital innovations will have the greatest impact on CAPEX, OPEX and downtime costs of a storage operation, mainly through automation and predictive maintenance. Site appraisal is another application that would benefit the cost structure, with an estimated reduction of 23 % in site appraisal costs in 2040 due to a 40 % decrease in seismic appraisal costs and 15 % saving in well drilling appraisal. Additive manufacturing could contribute a saving through composite pipelines, both in CAPEX and OPEX.

RD&I holds a key role on cost reductions, as there are several emerging and transformational capture technologies in R&D stage that have the potential to significantly reduce costs via enhanced materials, advanced heat integration and lower energy requirements. RD&I also plays a crucial role within the storage step, both in terms of emerging technologies but also regarding site exploration and site selection, which is proven to have a clear effect on the storage costs. In addition, improvements are expected by using technologies such as fibre-optics, artificial intelligence, machine learning and advanced automation in different stages across the CCUS chain [24].

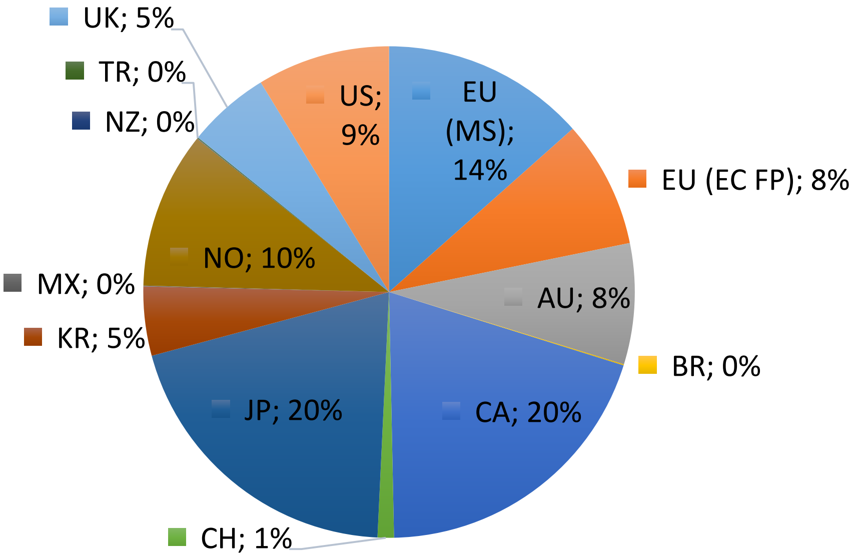
Although significant cost reductions have been achieved so far and further cost reductions in many aspects of the CCUS chain are expected, it is important to note that recent events (such as Russian aggression on Ukraine, inflation and delays) have shown that the overall costs of the projects can be significantly higher than initially estimated (e.g. Porthos).

2.4 Public RD&I funding and Investments

Public RD&I investment can positively impact technology development and deployment, promoting private initiatives and increasing relevant publications and patent applications. Therefore, it is an important indicator of the level of development and competitiveness in a given technological field. The information presented below is based on data obtained from the IEA [53].

Globally, Canada and Japan lead the public RD&I funding within CCUS technologies in the period investigated (2013-2022, see Figure 16) with 20% of the mapped investments (equivalent to more than EUR 1000 Million each). The funding from EU Member States (EU MS) follows closely with 14% of the investments. If accounting also from the EU funding programs (EU FP), a total of 1440 EUR million would be allocated to the EU, i.e., exceeding Canada and Japan. In fact, since 2021 the EU is the global leader in yearly RD&I funding followed by Japan.

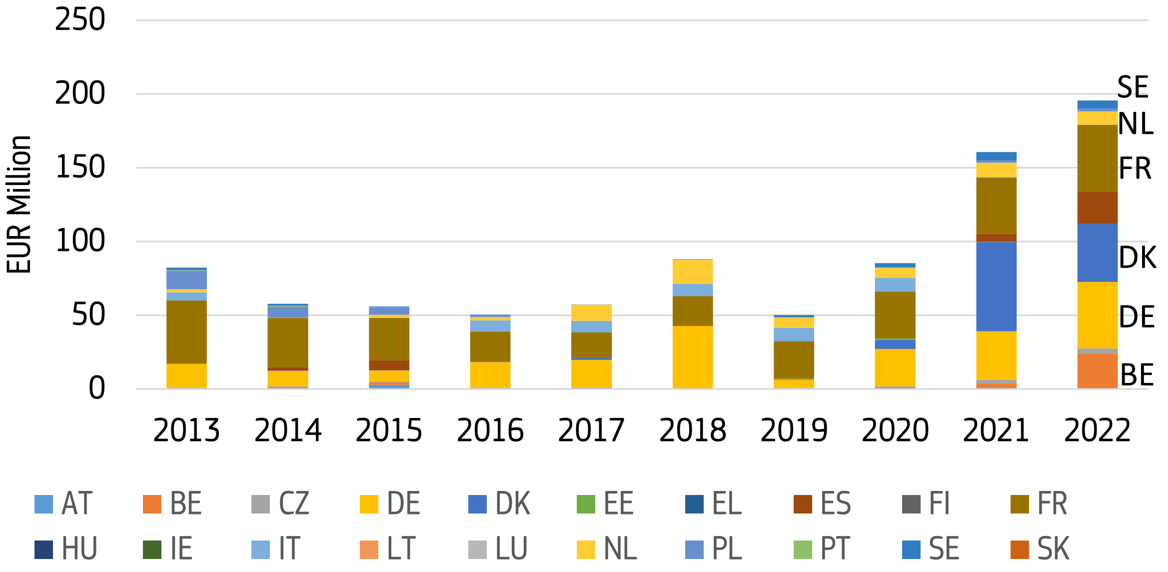
Figure 16. Cumulative public RD&I investments (EUR Million) in CCUS within the 2013-2022 period globally.



Source: JRC based on IEA.

In 2022 the public investment in CCUS-related RD&I in the EU reached a maximum within the period evaluated (2013-2022, see Figure 17). Increased investments in the EU can be seen also in 2013 and 2018. In 2022, Germany (45 EUR Million), France (44 EUR Million) and Denmark (30 EUR Million) were the leading MS in annual RD&I funding, with Germany and France being the cumulative leaders within the period. The majority of the investments (60% within the 2013-2022 period) are classified generically without specifying any part of the CCUS chain. Out of the ones that provide detailed information, the majority of the investments were channelled toward CO_2 storage (EUR 207 Million, with a sharp increase in 2021 and 2022), followed by CO_2 capture/separation (EUR 175 Million) and CO_2 transport (EUR 3 Million).

Figure 17. Public RD&I investments (EUR Million) in CCUS in the EU by year and by MS.



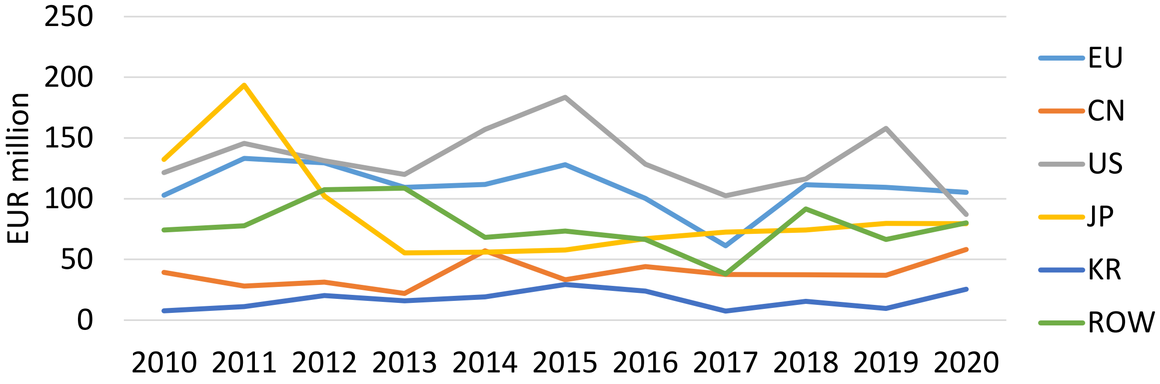
Source: JRC based on IEA

2.5 Private RD&I funding

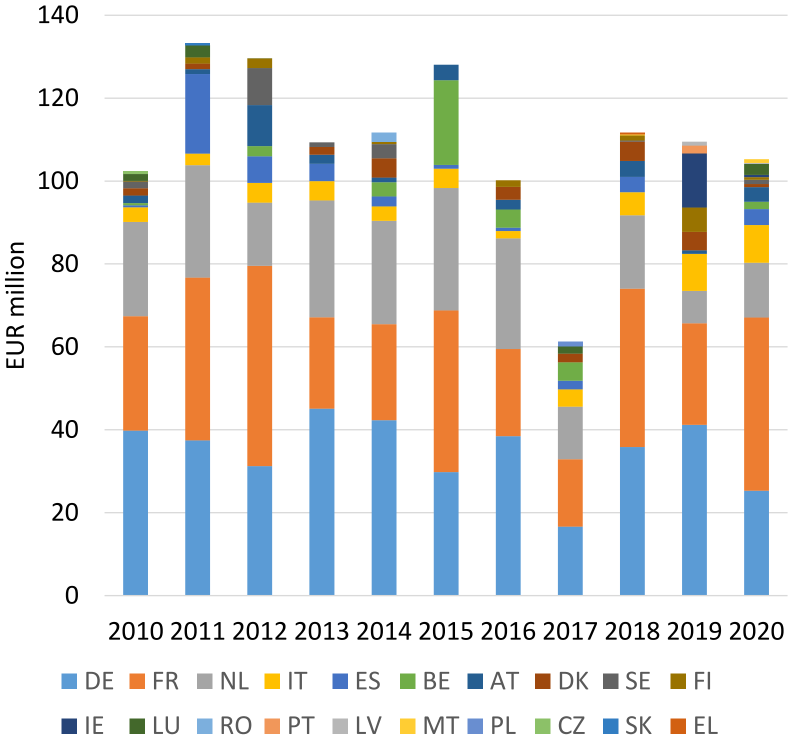
Detailed information on RD&I spending of the private sector is very limited, particularly when the interest is on small and medium enterprises or focuses on companies active in multiple technology areas. The analysis included here is based on a JRC in-house methodology [9], [10] that estimates RD&I expenditure in the private sector. This approach is then applied to assess private RD&I spending in Europe in the context of climate change mitigation technologies.

Our analysis indicates that since 2012, the US has been the top investor in private RD&I. The EU ranks second with relatively stable level of funding for private RD&I, aside from a decrease in 2017 (Figure 18a). Yearly private RD&I investments average EUR 460 Million. According to the latest year assessed, in 2020 the EU yearly surpassed the US with investments of around EUR 105 Million against EUR 87 Million. Within the EU, over the period of time analysed, Germany, France, the Netherlands, Italy and Spain are the top five countries with the largest private RD&I investment in CCUS (Figure 18b).

Figure 18. 2010-2020 private RD&I investments (EUR Million/year) in CCUS in the a) globally and b) EU by MS.



a)

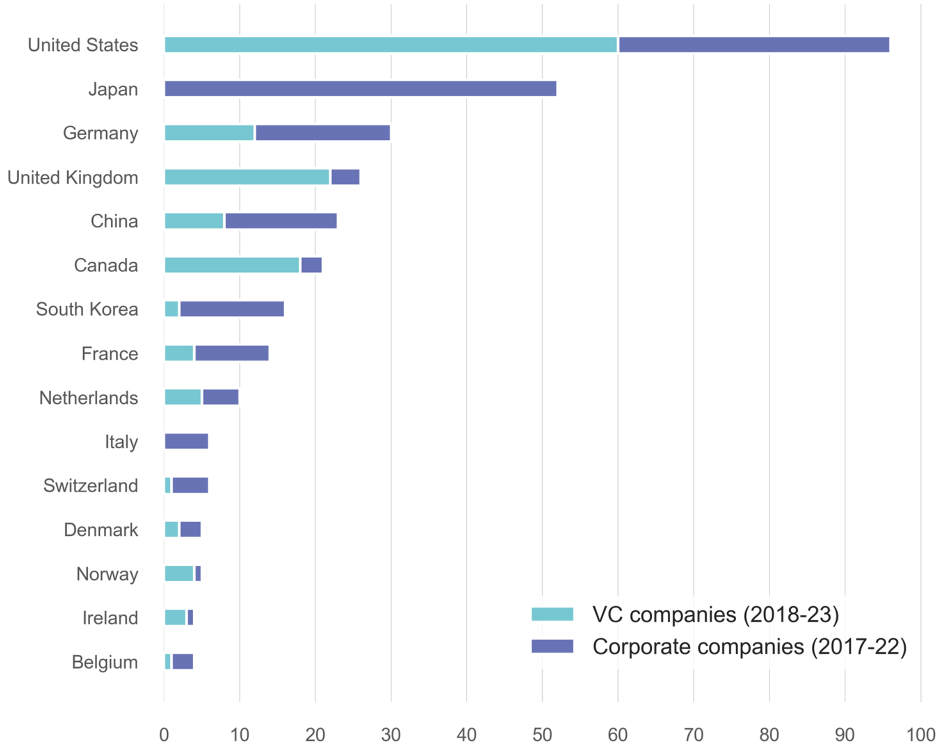


b)

Source: JRC

Private Equity refers to capital investments (ownership or interest) made into companies that are not publicly traded. Venture capital (VC) is a form of private equity and a type of financing that investors provide to start-up companies and small businesses that have long-term growth potential. Figure 19 provides an outlook of the countries that host the highest number of innovative companies active on the development of CCUS solutions between 2018 to 2023. The analysis includes both VC companies (i.e. start-ups and scale-ups that attracted VC funding or have been founded over the period) and corporate companies (i.e. subsidiaries of top RD&I investors with a relevant patenting activity over the 2017-2022 period). When accounting for both types, the US, Japan and Germany are the leading countries hosting the largest number of companies. Three countries (the US, the UK and Canada) host most of VC companies and account together for 67 % of all active VC companies identified worldwide. The US hosts by far the largest share (38 %) of active VC companies and half of the top 30 companies that have raised the most funds. The EU as a whole accounts for 18 % of identified VC companies – of which one third are located in Germany – and stands just ahead of the UK and Canada.

Figure 19. Venture capital (VC) (2018-2023) and corporate companies (2017-2022) by country



Source: JRC analysis based on Pitchbook and PATSTAT

In 2022, global VC investment experienced a four-fold increase as compared to 2021, reaching an all-time high of EUR 1.9 Billion, being the large majority in later-stage[12] deals (the increase can be seen both in and outside the EU, see Figure 20). However, VC investments in 2023 decreased down to 2021 levels (slightly above 0.5 EUR Billion). The US companies attracted most VC investment, reinforcing its leading position in the CCUS industry from the very beginning, while the EU companies managed to attract 18 % of the global VC investments (see Figure 20). Over 40% of VC companies were founded after 2020, with a majority in the US and only a few in the UK and in the EU.

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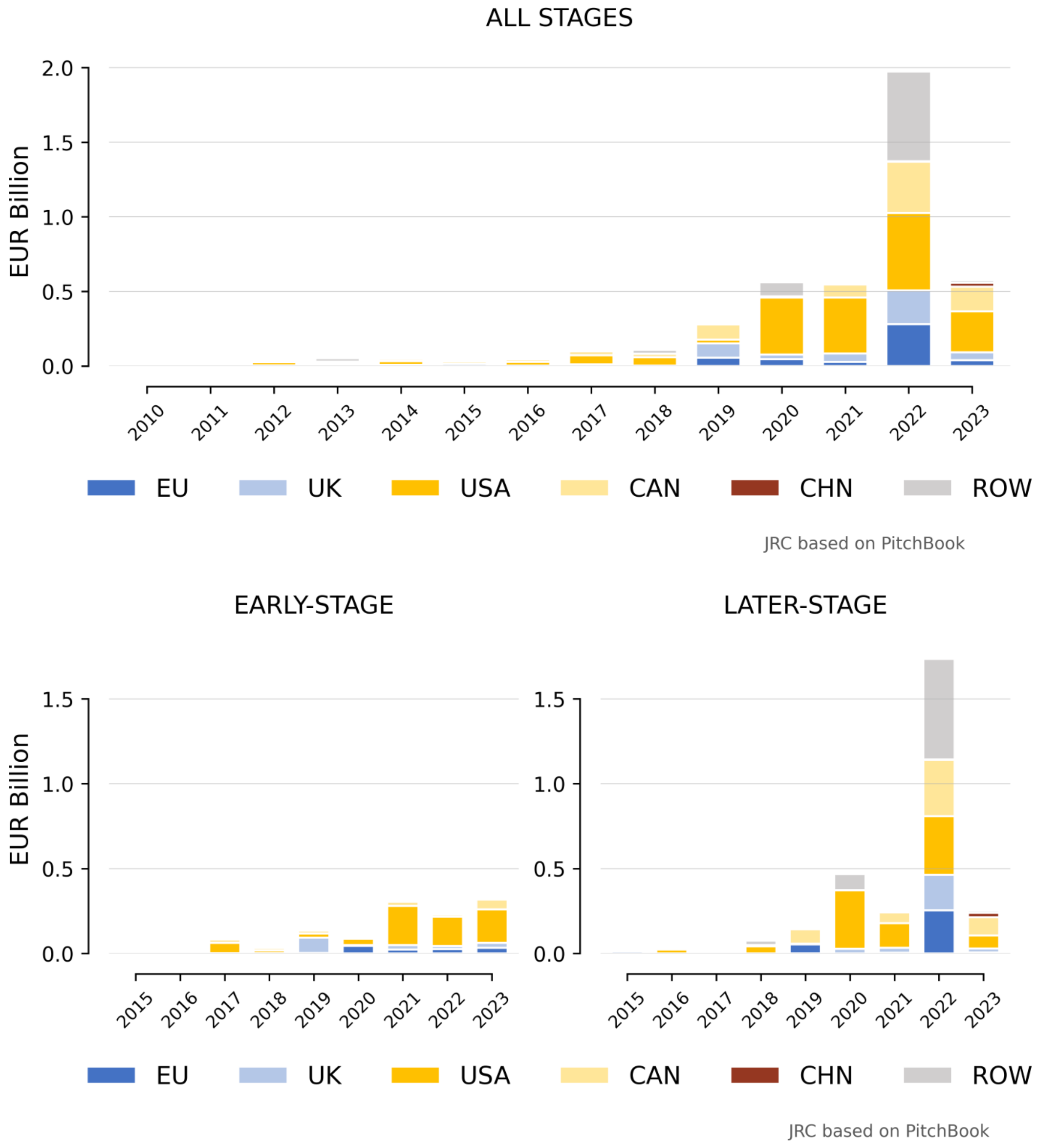
[12] Later-stage investment include: Late stage VC, Small M&A and Growth Private Equity. Small M&A refers to the acquisition by an operating company of a non-control stake in a pre-venture or VC company.

Figure 20. Global Venture Capital / Private Equity investment by region showing all deal types (top), early-stage (bottom left) and later-stage (bottom right).



Source: JRC based on Pitchbook data

From 2017 to 2023, the VC investment share in the EU as compared to the rest of the world has dropped to 11.0% as compared to 11.4% reported in the 2017-2022 period. This decrease is linked to the reduction of later-stage deals (10.8% of world share as compared to 11.6% in the previous period) as the share of early-stage[13] deals has increased (11.6% of the global as compared to 11.0% in 2017-2022). Within the EU, Germany and Denmark lead the overall VC investments, although Denmark and Sweden are the top 2 member states when it comes to early-stage deals.

It is interesting to note that although global early stage investments in the 2017-2024 period amount to EUR 775 Million, early-stage investment outside of the EU display a sharp drop in 2022 (- 32 %) compared to 2021, as early ventures are scaling-up and newly created firms have not yet raised funds. On the other hand, early-stage investment in the EU remain stable in 2022 and the EU improves its competitive position. We note also that the amount of identified grant funding per VC company is more than two times lower in the EU than elsewhere in the world**.**

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[13] The early-stage indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed, Early stage VC investments as well as public grants.

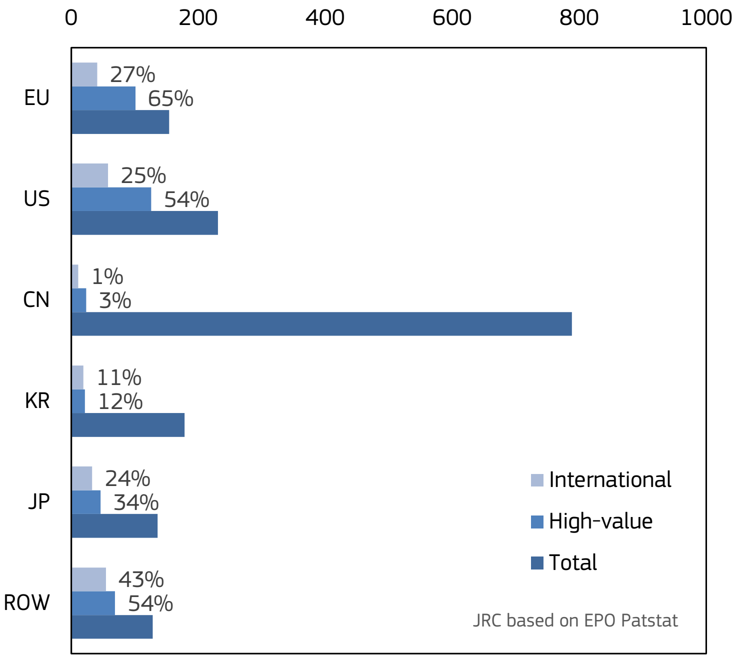
2.6 Patenting trends

Patenting activity is an important indicator to evaluate the technological development and competitiveness in a particular area. The analysis is based on data from the Worldwide Patent Statistical Database (PATSTAT[14]) and follows a method developed by JRC[15]. Patents on CCUS are identified using the class Y (specifically subclass Y02C and Y02P) of the Cooperative Patent Classification (CPC) System, a partnership between European Patent Office (EPO) and United States Patent and Trademark Office (USPTO). We note that it can take up to 30 months from an initial patent application to subsequent filings in other countries. 2020 is the last year for which complete data are available, but our analysis included also partial data from 2021.

In the 2019-2021 period, the EU had in total[16] 158 CCUS-related inventions (versus 198 in the 2018-2020 period), with 65% being high-value[17] - the highest percentage compared to the other regions and to rest of the world (ROW) (Figure 21). Despite increased inventive activity in China (788 total inventions, increasing compared to the 2018-2020 period), the high-value inventions account for only 3% (less than in the previous period). The US, the EU and Japan have the most high-value inventions between 2010 and 2021 (Figure 22). Among EU Member States, France has highest number of high-value inventions (more than 35), followed by Germany and the Netherlands (25 and 14 respectively).

With regards to the companies that have been leading in high-value inventions from 2019 to 2021 (Figure 23), L'air Liquide (FR) is the leading company in both global and EU top companies. Linde (DE) ranks second in the EU and sixth in the world in the top 10 companies based on the number of high-value inventions.

Figure 21. Number of inventions and share of high-value and international activity (2019-2021)



Source: JRC based on EPO Patstat

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[14] EPO - PATSTAT. Worldwide Patent Statistical Database

[15] Pasimeni, F., Fiorini, A., and Georgakaki, A. (2021). International landscape of the inventive activity on climate change mitigation technologies. A patent analysis. Energy Strategy Reviews, DOI: 10.1016/j.esr.2021.100677, https://www.sciencedirect.com/science/article/pii/S2211467X21000638#

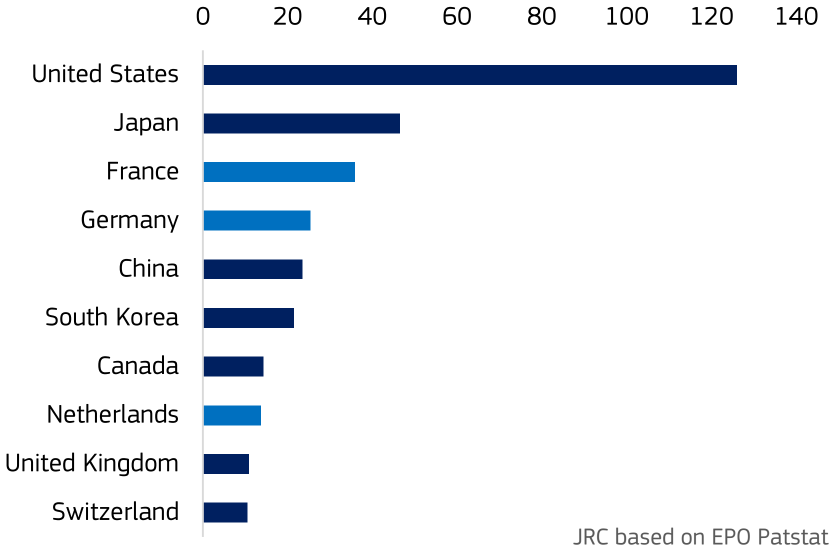
Pasimeni, F. and Georgakaki, A. (2020). Patent-Based Indicators: Main Concepts and Data Availability. JRC121685, https://setis.ec.europa.eu/patent-based-indicators-main-concepts-and-data-availability_en

Pasimeni, F. (2019). SQL query to increase data accuracy and completeness in PATSTAT. World Patent Information, 57, 1-7. https://doi.org/10.1016/j.wpi.2019.02.001

[16] The total includes international, national, high-value patents etc.

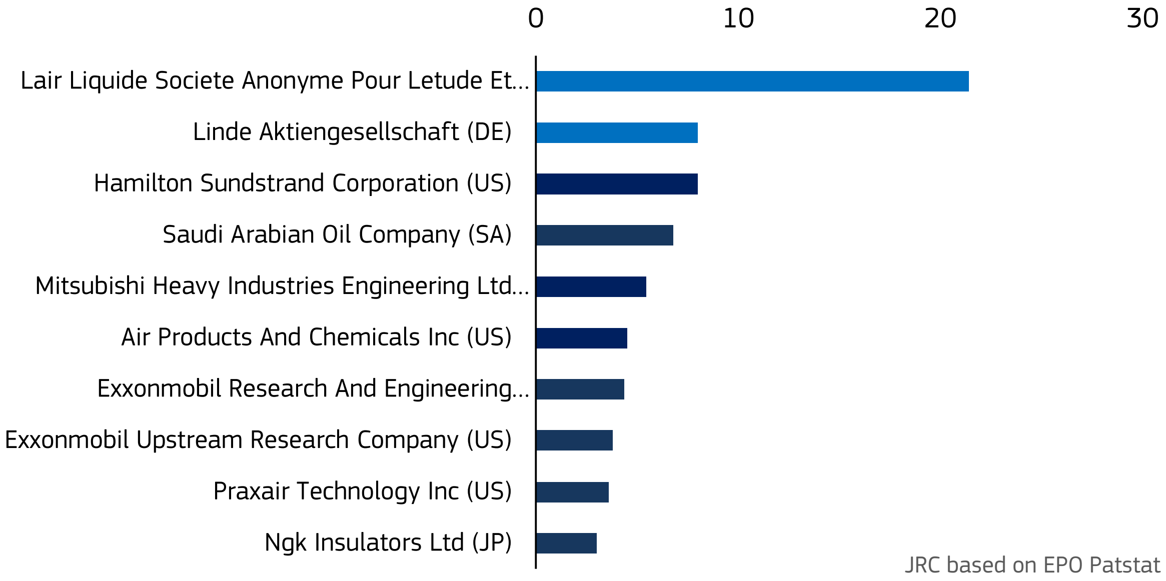
[17] High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.

Figure 22. High-value inventions – Top 10 countries (2019-2021). Light blue refers to EU Member States and dark blue to other countries.

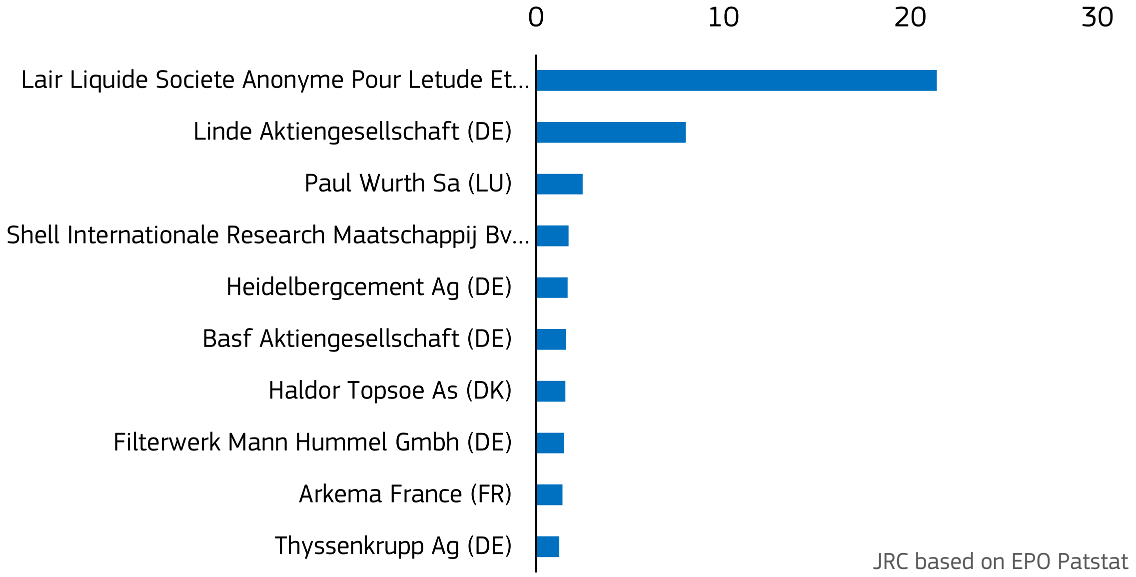


Source: JRC based on EPO Patstat

Figure 23. High-value inventions (2019-2021), a) global top 10 companies and b) EU top 10 companies. Light blue refers to EU Member States and dark blue to other countries.



a)

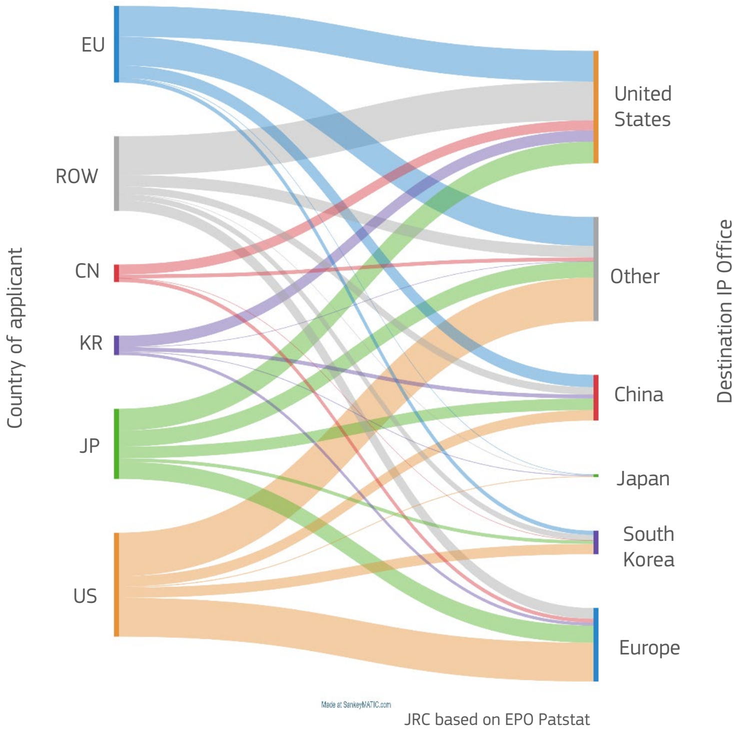


b)

Source: JRC based on EPO Patstat

Lastly, Figure 24 displays the international flows of high-value inventions between major economies, i.e., how patent applicants fill in to different offices. It can be seen that US applicants file with European as well as Chinese offices. Japan applicants seek protection by filing mainly with the United States Patent and Trademark Office (USPTO), the EPO and the Chinese Patent Office. The European applicants seek to protect their invention by filing with the US, Chinese, but also with other offices.

Figure 24. International flows of high-value inventions between major economies (2019-2021)



Note: EU represents the 27 Member States; EPO is the European Patent Office.
Source: JRC based on EPO Patstat

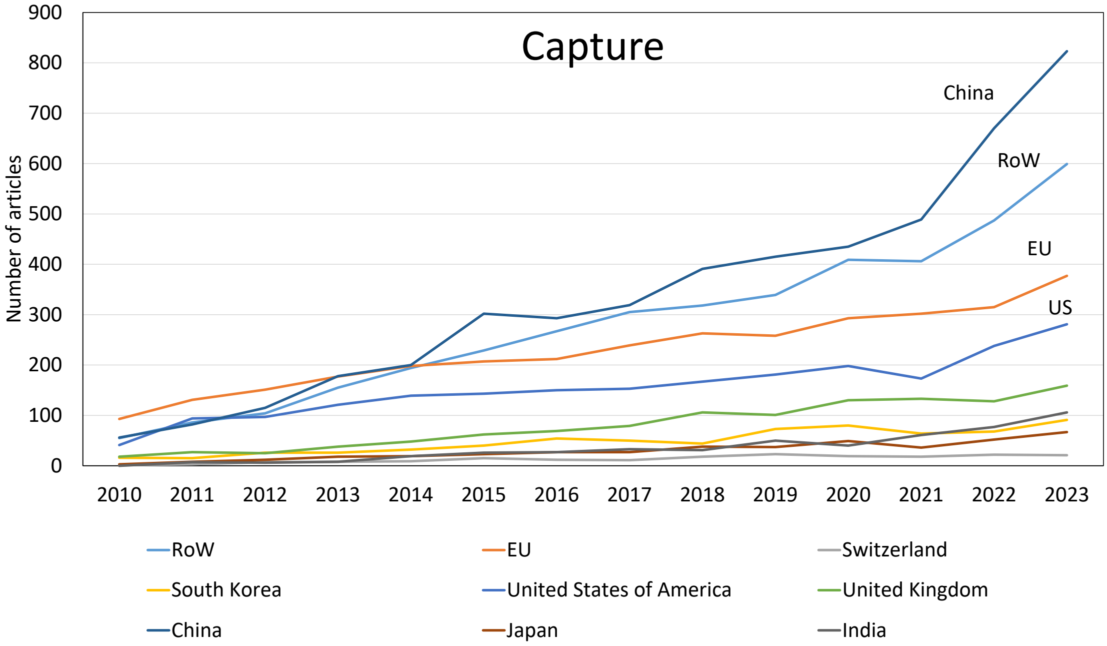
2.7 Scientific publication trends

To identify bibliometric trends in this study, we used the JRC Tools for Innovation Monitoring (TIM) Scopus database. The keywords used to create the datasets were based on the technology classification presented in Table 1.

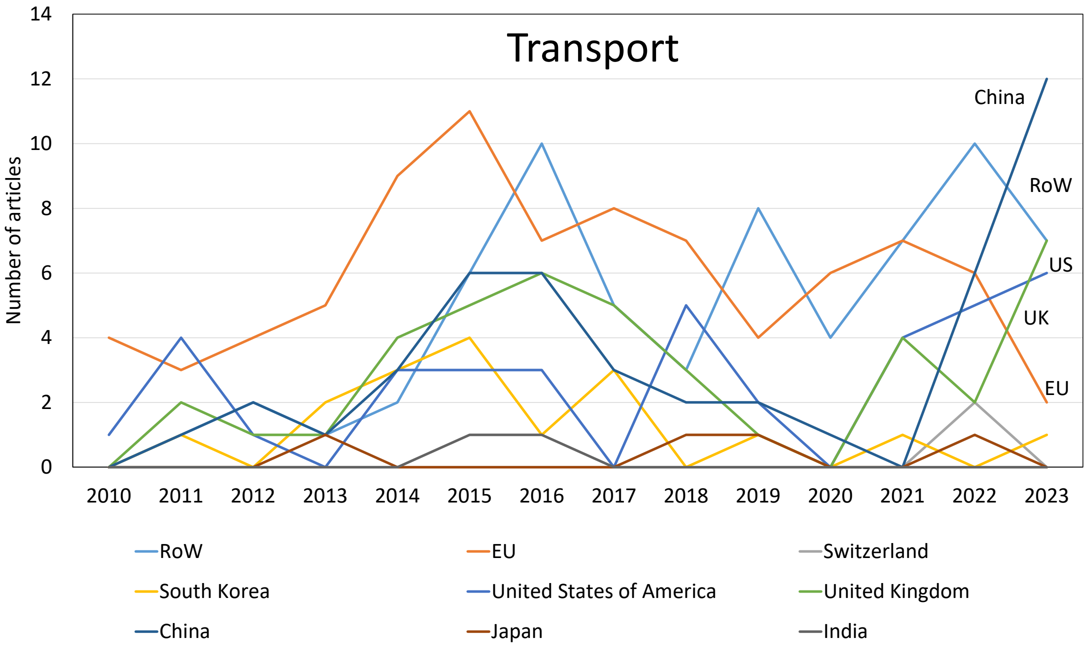
Publications dealing with CO_2 capture (including DAC and BECCS) have been steadily increasing over the last eleven years. The EU has been leading the way on the number of peer-reviewed articles per year until 2013, but China has since taken over, reaching over 800 publications in 2023 as compared to the 400 of the EU (Figure 25a). More specifically, China is the leading country when it comes to publications regarding absorption, adsorption (these two fields account for most of the capture-related publications), and membrane-based capture, while the EU leads in BECCS- (Sweden, Austria and Netherlands were the top 3 publishing countries in 2023) and high-temperature looping – (Spain, Sweden and Italy lead in 2023) related publications. The US has the most publications when it comes to DAC systems, followed by the EU and China.

Regarding the total number of transport-related publications (according to the keywords based on Table 1), the EU has the most publications cumulatively in the period studied, although in 2023 China was the world leader (see Figure 25b). China is also leading when it comes to CO_2 utilisation (Figure 25c), with more than 270 publications in 2023 versus the 113 in the EU. Lastly, although the US is the cumulative leader of publications dealing with CO_2 storage, the growth of China over the past years has been exponential (Figure 25d) reaching over 200 publications in 2023 (the EU's output in this field has been rather constant in the past few years, oscillating around 50 publications per year).

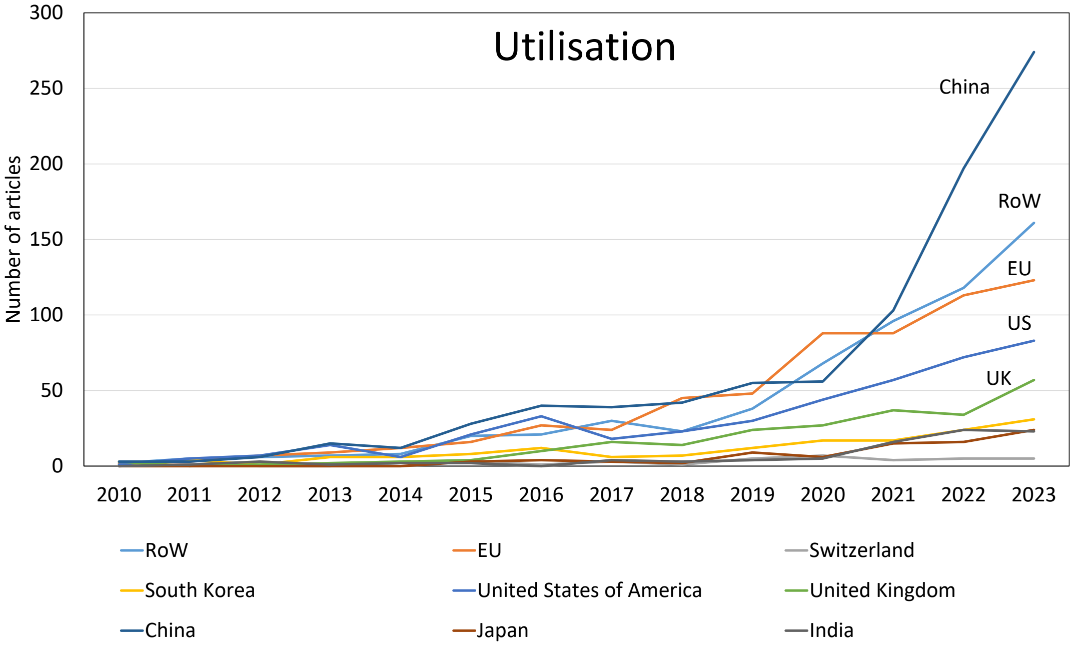
Figure 25. Worldwide series of peer-reviewed articles per year (2010-2023) concerning a) CO_2 capture, b) CO_2 transport, c) CO_2 utilisation and d) CO_2 storage.



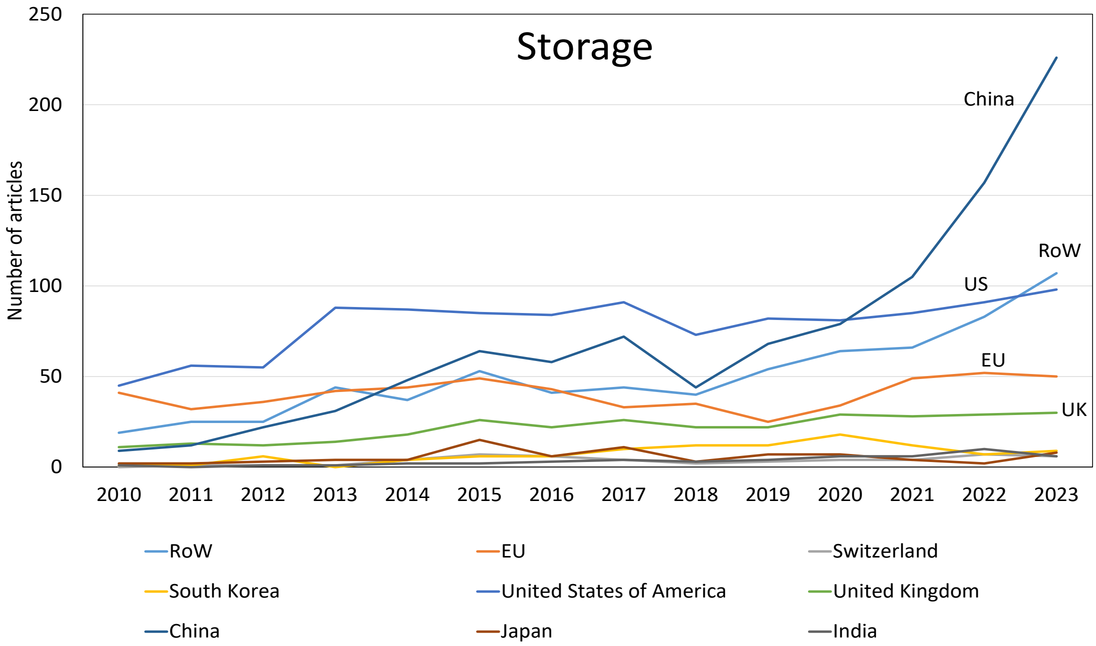
a)


Transport
Number of articles
0
2
4
6
8
10
12
14
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
China
RoW
US
UK
EU
RoW
EU
Switzerland
South Korea
United States of America
United Kingdom
China
Japan
India

b)


Utilisation
Number of articles
0
50
100
150
200
250
300
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
China
RoW
EU
US
UK
RoW
EU
Switzerland
South Korea
United States of America
United Kingdom
China
Japan
India

c)



d)

Source: JRC based on TIM

The h-index is used as a metric to evaluate the impact and productivity of peer-reviewed articles. The h-index of a country is defined as the largest number h such that at least h articles of that country for that topic were cited at least h times each. The h-indexes of the 2010-2023 period for the 10 leading EU countries, together with the EU as a whole, China, US and UK have been ranked in Table 4.

Table 4. H-index of the EU (including top 10 MS), China, US and UK in CCUS-related research

	Capture	**Transport**	**Utilisation**	**Storage**
EU	133	25	67	63
Spain	86	6	23	30
Germany	75	10	40	33
Netherlands	70	10	24	19
Italy	65	10	28	21
Sweden	60	5	17	17
France	58	4	14	41
Poland	39	5	14	9
Belgium	37	2	18	9
Austria	34	3	8	7
Portugal	33	1	10	11
China	141	13	76	58
US	142	18	66	85
UK	92	17	44	53

Source: JRC TIM

2.8 Assessment of R&I project developments

Since 2018, the European Climate, Infrastructure and Environment Executive Agency (CINEA) has built up a portfolio of 103 projects involving EUR 4.5 Billion in EU contributions across the entire CCUS value chain. These are funded by three EU programmes: Connecting Europe Facility for Europe (CEF Energy), Horizon Europe (HE) and the Innovation Fund (IF). In addition, the SET plan and Mission Innovation also support the development of CCUS value chains. The R&I projects can be grouped as follows[18]:

Research

The objective of research projects is to support low TRL technologies to establish new knowledge and/or explore the feasibility of new or improved technologies. Until 2024, the EU has contributed with EUR 120 Million in the form of 28 projects through the HE program (and its predecessor Horizon2020), with a rather intensive focus on novel utilization processes. Examples of ongoing projects include:

- TAKE-OFF: the TAKE-OFF technology will be based on converting carbon dioxide and green hydrogen into fuel via ethylene as an intermediate. In this process, carbon dioxide is captured from industrial flue gases and reacts with hydrogen produced by renewable electricity to create light olefins.
- SolDAC: the project aims at converting CO_2 into ethylene. It features a photo-electrochemical (PEC) conversion unit. Specifically, the PEC exploits bandwidth-selected light from a solar collector (FSS) that splits the solar spectrum for electricity and heat generation. Heat is used in an innovative DAC unit.

Demonstration of viability

The objective here focuses on projects at higher TRL to demonstrate viability of CCUS technologies from technological and economical points of view. Funding of demonstration projects is done both through HE and IF and the EU has contributed so far with EUR 350 Million across 25 different projects. Examples of ongoing projects are:

- CaLby2030: the project will construct three pilot plants, in Sweden, Germany and Spain, to test calcium looping using circulating fluidised bed technology. These pilots will investigate the decarbonisation of hard-to-abate CO_2 sources: flue gases from modern and future steel-making processes as well as emissions from modern cement plants that use limestone and from waste-to-energy and biothermal power plants.
- E-fuel Pilot: utilising CO_2 from the blast furnace gas from a local Ferro/Silicon-Manganese plant, the project will set up and operate and first-of-its-kind plant for synthetic fuel production in Norway. The refined syn-crude products will be used to replace fossil-based fuels in the aviation and other hard-to-abate sectors, as they can be used in existing engines without any modifications
- CFCPILOT4CCS; the project aims to develop and pilot a carbonate fuel cell (CFC) technology to capture CO_2 from dilute industrial streams. CFC technologies are especially attractive as they have the ability to generate electricity, hydrogen and useful heat while capturing CO_2, which largely enhances the economics of the process.
- ACCSESS: it aims to provide safe, cost-efficient, flexible and replicable CCUS addressing a range of sectors – from pulp and paper to bio-refining. The project will demonstrate cost-efficient CO_2 capture and use in industrial facilities. It will provide access routes for CO_2 captured from European industries to transport and storage infrastructures under development in the North Sea.
- MOF4AIR: the project will unite partners from eight countries to study and develop the most effective metal organic frameworks (MOF) technologies. These will be validated for stability and selectivity, and the most efficient will be optimised for mass production.

Deployment of CO_2 value chains

The objective of these actions is to support commercialisation of technologies and building new cross-border CO_2 networks with a focus on implementation of the entire value-chains and full-scale deployment of CCUS

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[18] https://webgate.ec.europa.eu/cineaportal/apps/storymaps/stories/9340ba62369c4f15bc99662070691120

technologies. Funding is done through the IF and CEF Energy, and the EU contribution adds up to EUR 3.542 Billion by 2024 realized in 37 different projects, such as:

- GO4ECOPLANET: the project aims to fully decarbonise cement production at the Lafarge plant in Kujawy (Poland). The project involves a wold-unique technology for capturing and liquefying CO_2 capturing 95% of the plant's emissions.
- ANRAV: it aims at being the first full chain (capture to storage) project in Eastern Europe, linking the emitter in Bulgaria with the storage in a depleted gas field in the Black Sea through on- and off-shore pipelines.
- AIR: a combination of CCU, renewable hydrogen and biomethane is used to create the first-of-a-kind large-scale production of methanol. The CO_2 will be captured from Perstorp plant in Stenungsund, Sweden.
- CalCC: using Air Liquide's Cryocap FG technology at a lime production plant, CO_2 will be captured at Lhoist Group's Rety site, following liquefaction, transport (via pipelines and shipping) and storage in an offshore site.
- Porthos: the project involves the construction of a CO_2 transport backbone in the port of Rotterdam area able to transport CO_2 to the depleted gas fields in the North Sea via an existing offshore platform. It includes the construction and commissioning of a 33 km onshore pipeline connecting industrial emitters in the port of Rotterdam, a 20 MW compressor station and a 20 km offshore pipeline transporting the compressed captured CO_2 for storage in the Dutch section of the North Sea
- K6: the project will capture process emissions in a cement plant through the deployment of a first-of-its-kind industrial scale combination of an oxy-fuel kiln and carbon capture. The captured CO_2 will be partly stored geologically in the North Sea and partly integrated into concrete making.
- CODA: it aims to be the world's first carbon mineral storage terminal. Using sustainable propulsion, captured CO_2 will be shipped to Iceland for injection into basaltic rocks and permanent storage.

In the 2024 edition of the annual knowledge sharing report of the IF [54], CINEA highlights that despite the tremendous advancements in the past years, only one project (Silverstone) has reached Financial Closure. Several challenges are identified when analysing how CCUS projects can advance, among others:

- Limited availability of CO_2 storage sites on the market within relevant timeframes.
- Uncertainty around storage costs and complexity of contractual risk-sharing discussions.
- Lack of common CO_2 standards for transport infrastructure.
- In CDR projects, difficulties in monetising generated negative emissions.

Others

SET-Plan

The integrated SET-Plan identifies 10 actions for research and innovation including CCUS. CCUS is recognised by the SET-Plan as an essential solution towards an economy with net-zero greenhouse gas (GHG) emissions by 2050. In 2016, the European Commission, the SET-Plan countries and industry agreed on ten ambitious targets for Action 9, outlined in a Declaration of Interest (DoI). In 2017, the associated working group (IWG9) elaborated the Implementation Plan of Action 9 that presents eight Research and Innovation Activities to reach the DoI targets for 2020 and further actions to meet key performance indicators for 2030. In October 2021, the CCUS Roadmap to 2030 was published updating those targets.

According to [55], the 10 CCUS SET-Plan targets for 2030 are to be reached by the following points:

- Solving challenges and barriers by undertaking R&I in parallel with large-scale activities;
- R&I projects addressing specific challenges and barriers, with the results then implemented in large-scale projects;
- Reducing the cost and energy requirements of CCS and CCU;
- Testing and deploying CCUS technologies at scale during the 2020s to ensure achieving net zero by 2050.

Mission Innovation

Mission Innovation is a global initiative to catalyse action and investment in research, development and demonstration to make clean energy affordable, attractive and accessible to all this decade. The aim is to accelerate progress towards the Paris Agreement goals and pathways to net zero.

Non-technological projects

Besides technology projects, funding has been channeled to initiatives that are crucial for the technological advancement: professional networks, personal training, social opinion and policy advice.

- H2020 IMPACTS9 – Starting on May 2019 (finished April 2022), aimed to support the realisation of the SET Plan Implementation Plan on CCS and CCU.[19]
- CCUS Knowledge Network - Building on the work of the European CCS Demonstration Project Network, which operated from 2009 to 2018, this EC-funded project aimed to support sharing knowledge and learning within project members toward the delivery and deployment of CCS and CCU.
- H2020 STRATEGY CCUS – Finishing in July 2022, the aim was to elaborate scenarios taking into account the needs and concerns of key regional and national stakeholders, as well as the positive environmental impact of CCUS in the lifecycle of carbon.

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[19] As part of the deliverables, the project is published an extended list of SET Plan related deliverables (available here) as an Annex to the SET Plan CCUS Roadmap to 2030 (available here).

3 Value chain Analysis

3.1 Turnover

There is no new data regarding turnover at the time of writing. For the most recent data available the reader is referred to the 2023 edition of this report [56].

3.2 Gross value added

There is no new data regarding gross value added at the time of writing. For the most recent data available the reader is referred to the 2023 edition of this report [56].

3.3 Environmental and socio-economic sustainability

There is no new data regarding environment and socio-economic sustainability at the time of writing. For the most recent data available the reader is referred to the 2023 edition of this report [56].

3.4 Business models and role of EU Companies

Deployment of CCUS value chains is experiencing development in all fronts, including the business models and roles of the companies involved. These depend, among others, on industry specific, location and policies in place, as well as market conditions. In this section we review the different alternatives, their main advantages and drawbacks and provide examples of EU companies and projects within each model.

The majority of CCS projects in operation were deployed following the full value chain model, according to which the CO_2 is captured from one facility and transported to an injection site, all owned and operated by a single entity (see Table 5 for a summary and some examples in Europe). This model, although useful and simple for first-of-a-kind technologies, falls short when it comes to scalability and incentivizing competition.

The partial value chain models, (see Table 5) are recently gaining attraction as a way to solve the issues inherent to the full-chain model. These break the value chain into 2 or more parts. The simplest is when a single emitter sells captured CO_2 to a single transport/storage third party, as it was the case of the well-known Boundary Dam CCS project in Canada. However, when relying on a single party (both from the emitter and the transport/operator sides) high risks remain. To further mitigate the risks, networks and hubs with capture as a service and transport/storage as a service is currently the leading model, as it makes use of economy of scale and it decouples the parties from relying on single entities. Recent examples of this model include Porthos and Aramis projects in the Netherlands and Northern Lights in Norway.

Table 5. Overview of various CCUS business models

Business model		**Advantages**	**Challenges**	**Examples**
Full value chain		Simple coordination Fewer sync efforts	High risk Complexity High CAPEX Difficult to expand	Sleipner (Norway) MOL Szank field (Hungary)
Partial value chain	Capture as a service	Availability of wider commercial solutions Less risk	Potential lack of demand Lack of established supply chains for core components	Just Catch (Aker Carbon Capture) CANSOLV (Shell) Cryocap (Air Liquide
	Transport and storage as a service	Relatively low risk for transport and storage operator	Long lead time Need planning before customers	Greensand (Denmark) Porthos and Aramis (NL) Ravenna (Italy) Northern Lights (Norway)
	Self-capture with 3rd party off-take	Simplicity	High risk if emitter relies on a single 3rd party (and vice versa).	Boundary Dam CCS (Canada) Mikawa Power Plant BECCS (Japan)

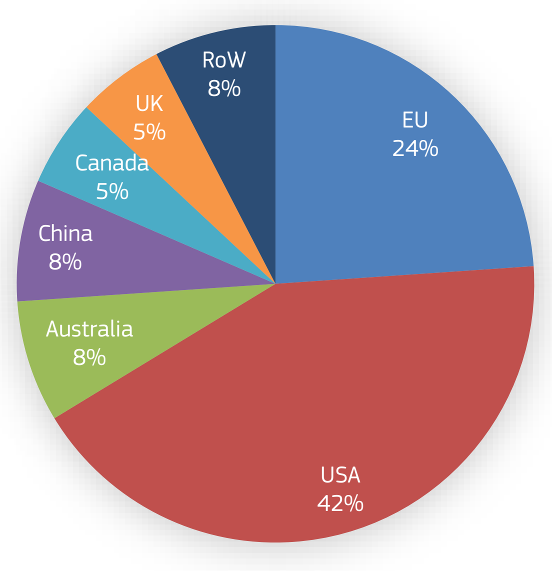
Source: JRC

While companies originally involved in CCUS value chains were oil and gas enterprises (and still remain heavily involved in CCUS projects), new players are emerging as a consequence of the business model shift. These, according to the IEA [16] involve:

- Chemical companies developing proprietary capture technologies and offering capture solutions to third parties (e.g., BASF).
- Engineering companies and original equipment manufacturers, both developing proprietary capture solutions and capture-as-a-service (e.g., Aker Carbon Capture).
- Infrastructure companies providing CO_2 management both building and operating e.g., CO_2 pipelines (e.g., Gasunie).
- Liquefied natural gas carriers and shipping companies expanding their operations to CO_2 shipping (e.g., Capital Maritime).

Market research identified 186 key companies world-wide with activity in CCUS. Out of them, 45 (24%) are European or are active in the field through their European subsidiaries. The USA is leading the way as 42% of the key companies identified are American or are based in the USA. See Figure 26 for a detailed disclosure.

Figure 26. Key companies identified with activity in CCUS by country



Source: JRC with data from Polaris Market Research Analysis.

In the EU during the mid-2000s, most of the emitting companies linked to CCUS projects were utilities companies. In the recent years, the focus has shifted towards hard-to-abate industries. HeidelbergCement is the company primarily active on developing CCUS in the cement industry. Initiatives such as the Antwerp@C and Porthos demonstrate the interest of chemical and oil and gas companies such as AirLiquide, BASF, Borealis, TOTAL, ExxonMobil and Ineos to get involved. The recently announced projects benefitting from the Innovation Fund also revealed certain interest in BECCS, as Stockholm Exergi is a project developer of such project. Oil companies such as ENI and Shell are assessing hydrogen projects. Regarding steel, ArcelorMittal is pursuing several CCUS options by building pilot plants at its Dunkirk and Ghent steel plants and the company is also interested in CO_2 use. ThyssenKrupp's is active on CO_2 use and its pilot plant is synthesising methanol from blast furnace and basic oxygen furnace gas. It aims also to produce ammonia, using the nitrogen by-product from waste separation. Tata Steel has been running a pilot plant with a capacity of 0.06 Mt/year at their steel plant site in IJmuiden, Netherlands, since 2010. To scale up the technology, however, Tata Steel is currently considering building a larger demonstration plant in India and it is not clear whether this technology will be deployed in the EU [57].

In the US, on the other hand, most of CCUS development and projects are linked to ethanol production, natural gas processing and power generation. This puts the EU in a leading position when it comes to developing CCUS in industry.

A recent publication from the Global CCS Institute [58] provides a technology compendium intended to showcase commercially-available CCS technologies worldwide. In terms of CO_2 capture they listed 16 companies as technology providers with commercially available (TRL 9) technologies. Four of these can be classified as EU companies (Air Liquide (FR), BASF (DE), Linde (DE), and Shell (NL)), although there are 5 EU companies more offering technologies at TRL 8 (Axens, Novonesis, Saipem, Sumitomo and Value Maritime). However, none of the companies listed offering TRL 9 technologies within the transport and storage steps pertain to the EU. These lists show that the EU is relatively well positioned on CO_2 capture technologies but when it comes to transport, storage and full value chain the EU is far behind and is striving to get a share against the USA and Canada.

Our in-house analysis showed that from 2015 onwards, four EU companies, Air Liquide (FR), Shell (NL), Linde (DE), and BASF (DE) were amongst the top 20 companies in CCUS research and innovation investment. Within the EU, these companies remain in the top 10, along with Anheuser Busch Inbev (BE), Sabic (NL), Merck (IE), Solvay (BE) and Haldor Topsoe (DK).

Venture capital analysis showed that the EU is lagging behind on this front. Out of the 92 companies identified only 8 are within the EU (287K (HR), Caphenia (DE), Carbon Collect (IE), Carbonworks (FR), Liquid Wind (SE), Purcity (DK), Redoxnrg (EE), and Sunfire (DE)).

3.5 Employment

There is no new data regarding gross value added at the time of writing. For the most recent data available the reader is referred to the 2023 edition of this report [56].

3.6 Energy intensity and labour productivity

In most of carbon capture technologies, energy is required mainly to regenerate the solvent/sorbent/bed or to generate pure oxygen (in the case of oxy-fuel combustion). Not only the amount of energy required varies largely across technological choices, but also its form (heat or electricity) and in the case of heat, its temperature requirements. In addition to the capture technology, the energy requirement is fundamentally a function of the CO_2 captured (i.e., capture rate) as well as of the initial CO_2 concentration: larger concentrations and lower capture rates require less energy than lower concentrations and high capture rates. In this sense, DAC yields the largest energy requirements as compared to point-source capture.

The energy intensity of carbon capture technologies is a major topic that has been a central research area in the last decade. Table 6 summarizes the ranges of energy requirement of some capture technologies. Nonetheless, energy requirement of capture technologies is a major research topic under continuous development and thus these values are often changing.

Table 6. Energy requirement of selected CO_2 capture technologies

Capture technology	**Energy Consumption (GJ/tCO_2)**
Absorption	1.5-9.2
Adsorption	4.0-6.0
Membrane	0.5-6.0
Cryogenic	2.4-5.2

Source: JRC based on scientific literature

Transport of CO_2 represents the second largest energy requirement of the CCS (and CCU) chain, mainly linked to compression and liquefaction. Transportation energy requirements largely depend on various factors such as the distance between the CO_2 capture site and the storage site, the choice of the transport mode, the choice of the storage site, the average pressure of transportation, and the details of the overall design characteristics of the CO_2 transport [59]. The analysis in [59] shows that the conditioning of CO_2 at the interface between CO_2 capture and transportation, could require between 90 and 120 kWh/tCO_2 [60]. Energy required for transport can weight up to 45-50 % of the total energy required.

Given the fact that CO_2 is a thermodynamically stable molecule, most CO_2 utilization processes require substantial amounts of energy, either in the form of hydrogen, electricity or heat. In addition, according to the most recent Life Cycle Analyses [61], it is utterly important that the energy used is carbon-free as otherwise the climate benefit of the utilization process becomes negligible or negative (depends on the origin of the CO_2).

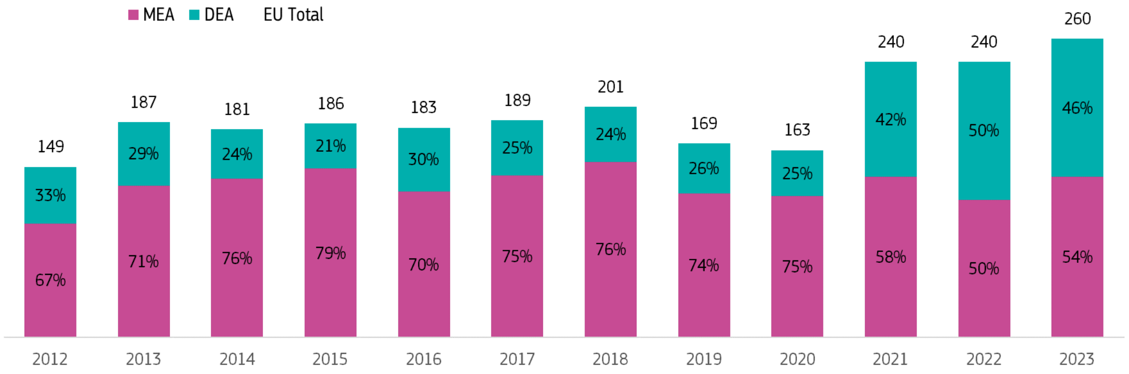
There is no new data available regarding labour productivity at the time of writing. For the most recent data available the reader is referred to the 2023 edition of this report [56].

3.7 EU Production Data

Absorption by amine solvents is the most industrially mature process for large scale CCUS projects currently in operation [62]. Thus, they are used here as proxy to map the EU capabilities in terms of production of key CCUS components. However, uses of amine solvents also extend to feedstock for detergent, emulsifier, polishes, pharmaceuticals, corrosion inhibitors, and chemical intermediates [63], and therefore it is important to note that Prodcom[20] codes[21] can offer only limited insight into the CCUS technology trends.

The EU production of amine solvents increased by 8%, reaching EUR 260 Million in 2023 compared to the previous year (Figure 27). The production of DEA remained stable at EUR 120 Million. MEA production increased by 17%, reaching EUR 140 Million. Most Member States keep their production data confidential; therefore, there are no insights about the leading EU producers.

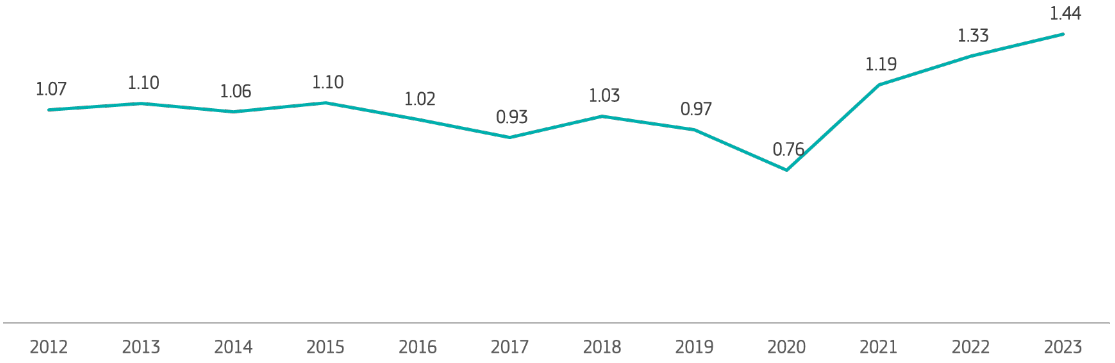
Figure 27: EU production value per commodity [EUR Million]. MEA: Monoethanol amine. DEA: Diethanol amine



Source: JRC based on PRODCOM data

The average production value over the past 10 years (2014-2023) is 1.08 EUR/kg. Since 2020 the average production value has been increasing, and, in 2023, it saw an 8% increase, reaching 1.44 EUR/kg (see Figure 28).

Figure 28: EU production value of amine solvents [EUR per kg]



Source: JRC based on PRODCOM data

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[20] Prodcom provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries. https://ec.europa.eu/eurostat/web/prodcom (accessed 08-08-2023)

[21] Prodcom codes monitored were 20144233 Monoethanolamine and its salts (MEA) and 20144235 Diethanolamine and its salts (DEA). No codes for Methyldiethanolamine (MDEA) were identified.

4 EU Market Position and Global Competitiveness

4.1 Global & EU market leaders

The CCUS industry has recently entered a period of rapid growth driven by the net zero targets set both at a country and corporate level and the pace of announcements must still increase to be on track for the net zero.

The EU market share in the CCUS industry remains difficult to assess. This is due to an incomplete disclosure of the value of the projects companies are involved in, unreliable and incomplete cost coverage and the lack of separation between CCUS costs and other project cost components. Additionally, the projects cover several supply-chain elements and a company's share is often uneven. An estimative JRC in-house analysis indicates that capture is addressed by a higher number of announced projects compared to transport and storage topics, while the number of EU projects involving the use of CO_2 is the smallest. The most significant market players for different elements in CCUS value chain have been identified in Section 3.4.

There is no new data regarding global & EU market leaders at the time of writing. For the most recent data available the reader is referred to the 2023 edition of this report [56].

4.2 Trade (Import/export) and trade balance

International trade is monitored using six-digit codes of the Harmonised System (HS) classification[22], based on Eurostat's Comext[23] and the United Nations' Comtrade[24] databases.

Considering that CCUS technologies do not have mass production in place yet, amine solvents[25], ethylene glycol (HS 290531) and potassium carbonate (HS 283640) have been used as a proxy for trade of CCUS technologies. However, we note that the amine solvents depicted by the HS codes used are not exclusively used for carbon capture, but have other applications as well. Hence, a direct correlation between EU imports and carbon capture capacity cannot be established. Similarly, ethylene glycol (tryethylene glycol (TEG) is a key component of CO_2 liquefaction) and potassium carbonate (alternative capture technology with promising features) are currently used for applications other than CCUS and the data shown here serves as to exemplify the situation in the case their CCUS-use ramps up.

In 2023, the extra-EU imports shrunk by -39 % compared to 2022, reaching EUR 96 Million, and extra-EU exports decreased by -22 % at EUR 100 Million. The trade balance turned positive at EUR 4 Million from EUR 29 Million in 2022 (Figure 29). Overall, the extra-EU imports and exports of amine solvents range at similar levels, and the trade balance fluctuates between surplus and deficit. Belgium and Sweden were the Member States with the biggest trade surpluses (EUR Million +44, +24, respectively, in 2023), while Spain, Italy and Germany had the biggest trade deficits (EUR Million -44, -31, -9, respectively, in 2023).

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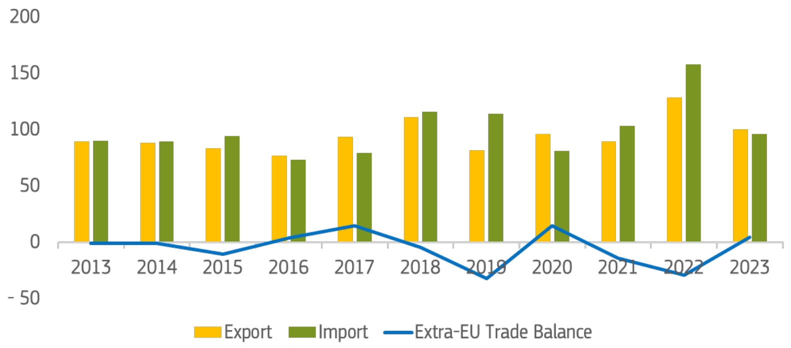
[22] World Customs Organization (WCO), HS Nomenclature 2022 Edition https://www.wcoomd.org/en/topics/nomenclature/instrument-and tools/hs-nomenclature-2022-edition.aspx

[23] https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/focus-on-comext

[24] https://comtradeplus.un.org/

[25] HS codes: 292211 Monoethanolamine and its salts - **MEA**
292212 Diethanolamine and its salts - **DEA**
292213 Triethanolamine and its salts, discontinued in 2017 - **TEA**
292215 Triethanolamine, as of 2017 – **TEA**
292217 Methyldiethanolamine and ethyldiethanolamine, as of 2017 – **MDEA**

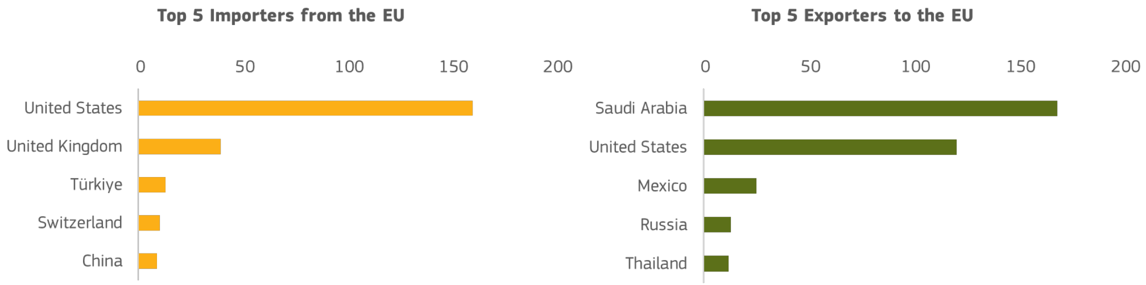
Figure 29. Extra-EU trade of amine solvents, EUR Million.



Source: JRC based on COMEXT data

In the 2021-2023 period, the US was the biggest importer from the EU, receiving 45% of the extra-EU exports (mainly MEA and TEA), and the second biggest exporter to the EU, holding 38% of the extra-EU imports (mainly DEA (Figure 30). Saudi Arabia was the biggest exporter to the EU, holding 53% of the extra-EU imports (mainly MEA and TEA).

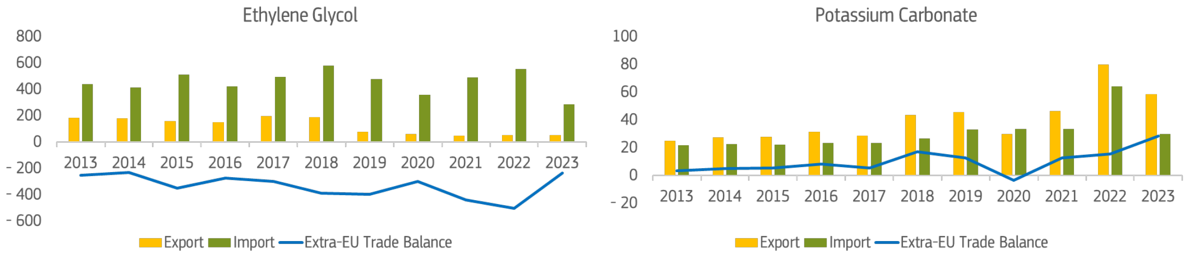
Figure 30: Top countries importing amine solvents from (left) and exporting to (right) the EU (2021-2023) [EUR Million]



Source: JRC based on COMEXT data

The EU has a negative trade balance in ethylene glycol, with the deficit reaching EUR 235 Million in 2023 (Figure 31). Trade balance in potassium carbonate is positive with an increasing trend, reaching EUR 28 Million in 2023. During 2021-2023, EU held 54% of the total global exports in potassium carbonate and only 11% in ethylene glycol. These numbers shrink to 24% and 1%, when it comes to extra-EU share (non-internal trade) in the global exports. In both cases, more that 60% of the trade needs were covered through the Single Market (intra-EU).

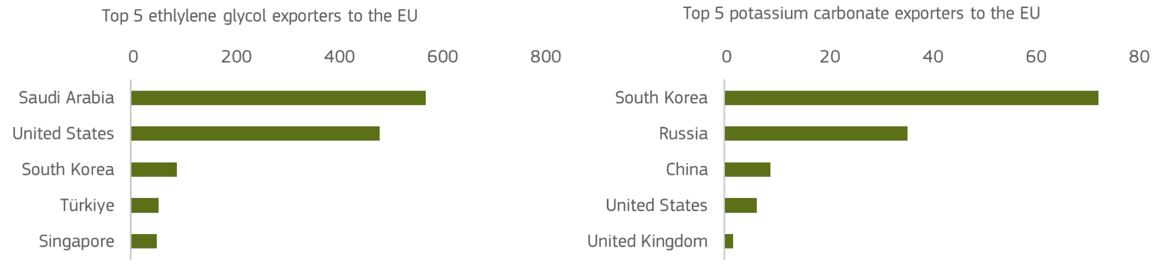
Figure 31: Extra-EU trade for ethylene glycol (left) and potassium carbonate (right) [EUR Million]



Source: JRC based on COMEXT data

During 2021-2023, 43% of extra-EU ethylene imports came from Saudi Arabia and 36% from the US (Figure 32). For the same period, 57% of the extra-EU potassium carbonate imports came from South Korea and 28% from Russia.

Figure 32: Top countries importing ethylene glycol (left) and potassium carbonate (right) from the EU (2021-2023) [EUR Million]


Top 5 ethlylene glycol exporters to the EU

Top 5 potassium carbonate exporters to the EU

Source: JRC based on COMEXT data

Overall, the EU has a stronger presence in the potassium carbonate market. However, the total value of trade is about ten times lower than that of the ethylene glycol. If the EU consumption of potassium carbonate were to increase, then imports would increase turning the EU trade balance negative, unless internal production could follow-up.

4.3 Resources efficiency and dependence in relation to EU competitiveness

The issues of resource efficiency and critical material dependency have received little attention in relation to CCUS, mainly due to the fact that there is not mass production of CCUS technologies in place. A brief discussion of these aspects is presented below.

In the previous section covering production and trade (3.7 and 4.2) we focused on chemical solvents as this is the technology that is used in the majority of commercial CO_2 capture projects in operation. However, other materials such as membranes (polymeric, ceramic, etc.) or adsorbents could also be used. At present, the main commercially available adsorbents are activated carbons, zeolites, hollow fibres, and alumina [64]. Limestone is also used in carbon capture by calcium looping and oxygen carrier materials used in chemical looping operation include monometallic oxides of nickel, copper, manganese and iron.

Both CO_2 shipping and piping infrastructure rely heavily on steel. Ships used for transportation resemble hydrogen vessels, could be used for transport of ammonia and LPG and utilize similar kinds of materials, though various grades of steel, membrane lines, and insulation. The amount of steel, its grade and how it is lined depend on pressure under which the CO_2 is transported. The construction of CO_2 pipelines requires tubular steel, whose availability is unlikely to limit deployment [16].

The bulk materials required for CO_2 storage are mainly to build injection wells and are therefore similar to those needed in oil and gas wells. They include well casing, tubing, and wellheads at the storage sites and rely heavily on steel and will require large amounts of cement. Table 7 lists materials that are used for CO_2 injection wells [65]. The availability of well construction materials and components is unlikely to constrain the developments of storage capacity. Additionally, the construction of pipelines and storage infrastructure requires specialised equipment such as drilling rigs and mechanical devices, along with skilled technicians to operate them. CO_2 storage sites require monitoring equipment.

Table 7. Typical construction materials for CO_2 injection wells.

Component	**Materials**
Upstream metering and piping runs	316SS, Fibreglass
Christmas tree	316SS, Ni, Monel
Valve packing and seals	Teflon, Nylon
Wellhead	316SS, Ni, Monel
Tubing Hanger	316SS, Incoloy
Tubing	GRE lined carbon steel, IPC carbon steel, CRA
Tubing joint seals	Seal ring (GRE), coated threads and collars (IPC)
ON/OFF tool, profile nipple	Ni-plated parts, 316SS
Packers	Internally coated hardened rubber of 80-90 durometer strength (Buna N), Ni-plated parts
Cements and cement additives	API cements and/or acid resistant speciality cements and additives

Source: [65]

In addition to injection wells, pipelines and ships, steel will also be required for the construction of equipment such as absorption towers, contactors, drums, boilers, heat exchangers, and of hundreds of pumps and compressors. Steel manufacturing relies on iron-ore and corrosion resistant materials for alloys. Depending on their composition, they may contain strategic materials, such as manganese, silicon, phosphorous, vanadium, titanium, copper, and nickel and others such as chromium. Due to the changing geopolitical context and competing demand from other technologies, surging prices and shortages in the supply chain could be expected. Prevention and mitigation strategies have to be considered in order to overcome these situations [66].

A thorough analysis is required to identify the challenges in the supply of all the materials used in the CCUS value chain. In Europe, in the last two years shortages have been reported[26] for aluminium, copper, iron, manganese and steel. Alloying elements such as phosphorus, vanadium and manganese show a high supply risk, with sourcing largely dependent on China (79 % for phosphorus, 62 % for vanadium and 51 % for manganese) [66]. On the contrary, Europe is amongst the world leaders in supplying the world's demand for natural zeolites[27]. Furthermore, the captured CO2 can be used to produce high value chemicals and building materials, which could provide additional streams of revenue that the EU companies can benefit from.

Regarding solvent resource availability and efficiency, research suggests that using MEA in a global scale would have a large impact on its production and cost [67]. Sections covering production and trade (3.7 and 4.2) do not indicate an imminent risk in the sense that the import countries are relatively diversified. The availability of MEA precursors, i.e. ammonia and ethylene oxide should also be considered. The agriculture industry dominates the global ammonia market, accounting for more than 80 % of global ammonia demand, with top producing countries being China (48 Mt), Russia (12.5 Mt) and India (11 Mt). Currently, the MEA market is not large enough to accommodate CCUS needs raising concerns if the demand spikes suddenly. Another aspect to consider is that increased MEA production leads to negative environmental consequences due to CO_2 emissions and energy demands.

Large-scale deployment of DACCS requires a considerable amount of energy, depending on the type of technology, water, and sorbents. Hydroxide solutions used in high temperature DAC are currently being produced as a by-product of chlorine, but the replacement (make-up) requirement of such materials at scale exceeds the

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[26] Bloomberg, 2022; Financial Times, 2021; S&P Global Market Intelligence, 2020.
[27] Chemeurope.com

current market supply [68], [27]. Liquid solvent DACCS systems need substantial amounts of water [69], although much less than BECCS systems [70], which could negatively affect SDG 6 (clean water and sanitation).

5 Conclusions

- There are commercially available technological options for CO_2 capture, transport, storage and utilisation for most industries.
- The number of projects under different stages of development is increasing exponentially, but more is needed to achieve ambitious decarbonisation targets. Despite the efforts made so far, there has still not been a significant number of final investment decisions (FIDs) made across the CCUS chain in the EU.
- CCUS costs are still relatively high but are expected to fall as/if/when capacity increases.
- CO_2 transport is a key enabler of CCUS technologies. For the cost-optimal use of transport technologies it is necessary to have a multi-modal CO_2 transport approach (fixed and flexible transport infrastructure).
- In 2022, Germany, France and Denmark were the leading EU Member States in annual RD&I funding, with Germany and France being the cumulative leaders within the 2013-2022 period.
- Germany, France, the Netherlands, Italy and Spain are the top five countries with the largest private RD&I investment in CCUS within the EU in the past ten years.
- Considering the potential ramp-up of manufacturing of CCUS technologies and the recent European Commission Net Zero Industry Act, there is a need for thorough value chain identification and mapping.
- In summary, the EU is in a good position when it comes to publications, patents and private and public RD&I, but lags behind on venture capital companies compared to other regions (US, Japan and Canada).
- The US remains the historical and current global leader in commercial CCUS facilities in operation, with most of the projects related to natural gas processing, ethanol production and/or enhanced oil recovery. EU projects on the other hand are shifting focus to hard-to-abate industries such as the cement, iron and steel, waste to energy and chemical sectors.
- New business models are arising as a way to overcome the financial barriers present in the deployment of CCUS projects. The most common are partial value chain models as opposed to the traditional full-chain model, where the CCUS value chain is split into two or more parts. CO_2 transport and storage hubs are a typical example of such new models.

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List of abbreviations and definitions

ASU – Air Separation Unit
BECCS – Bioenergy with CCS
CAPEX – Capital Expenditure
CCS – Carbon Capture and Storage
CCUS – Carbon Capture, Use and Storage
CEF – Connecting Europe Facility
CLC – Chemical Looping Combustion
COP – Conference of the Parties
CSLF – Carbon Sequestration Leadership Forum
DAC – Direct Air Capture
DEA – Diethanol amine
HER – Enhanced Hydrocarbon Recovery
EOR – Enhanced Oil Recovery
EGR – Enhanced Gas Recovery
ECBM – Enhance Coal Bed Methane
EU – European Union
EPO – European Patent Office
GDP – Gross Domestic Product
GWP – Global Warming Potential
IEA – International Energy Agency
JRC – Joint Research Centre
LCA – Life Cycle Analysis
LCOE – Levelised Cost of Electricity
MEA – Monoethanol amine
MS – Member State
Mtpa – Million tons per annum
NG: Natural gas
OPEX – Operational Expenditure
PSA – Pressure Swing Adsorption
RTIL – Room Temperature Ionic Liquid Membranes
ROW – Rest of the world
SET - Strategic Energy Technologies
SETIS - Information System
SEWGS - Sorption Enhanced Water Gas Shift
TRL – Technology Readiness level
TSA – Temperature Swing Adsorption
VSA – Vacuum Swing Adsorption
ZEP – Zero Emissions Platform

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Annex 1 Summary Table of Data Sources for the CETO Indicators

Theme	**Indicator**	**Main data source**
Technology maturity status, development and trends	Technology readiness level	JRC based on Global CCS Institute, IEA, IRENA and scientific literature.
	Installed capacity & energy production	JRC based on Global CCS Institute
	Technology costs	JRC based on Global CCS Institute, IEA, CCSA, IRENA and scientific literature.
	Public and private RD&I funding	JRC based on IEA and Pitchbook
	Patenting trends	JRC based on EPO Patstat
	Scientific publication trends	JRC based on Tools for Innovation Monitoring (TIM)
	Assessment of R&I project developments	JRC based on CINEA
Value chain analysis	Turnover	Not assessed for 2024
	Gross Value Added	Not assessed for 2024
	Environmental and socio-economic sustainability	
	Business models, EU companies and roles	JRC based on IEA, Global CCS Institute and Polaris Market Research
	Employment	Not assessed for 2024
	Energy intensity and labour productivity	JRC based on scientific literature
	EU industrial production	JRC based on Prodcom data
Global markets and EU positioning	EU market share vs third countries share, including EU market leaders and global market leaders	Not assessed for 2024
	EU trade (imports, exports) and trade balance	JRC based on COMEXT
	Resource efficiency and dependencies (in relation EU competiveness)	JRC based on scientific literature

Source: JRC

Annex 2 Energy System Models and Scenarios: POTEnCIA and POLES-JRC

AN 2.1 POTEnCIA Model

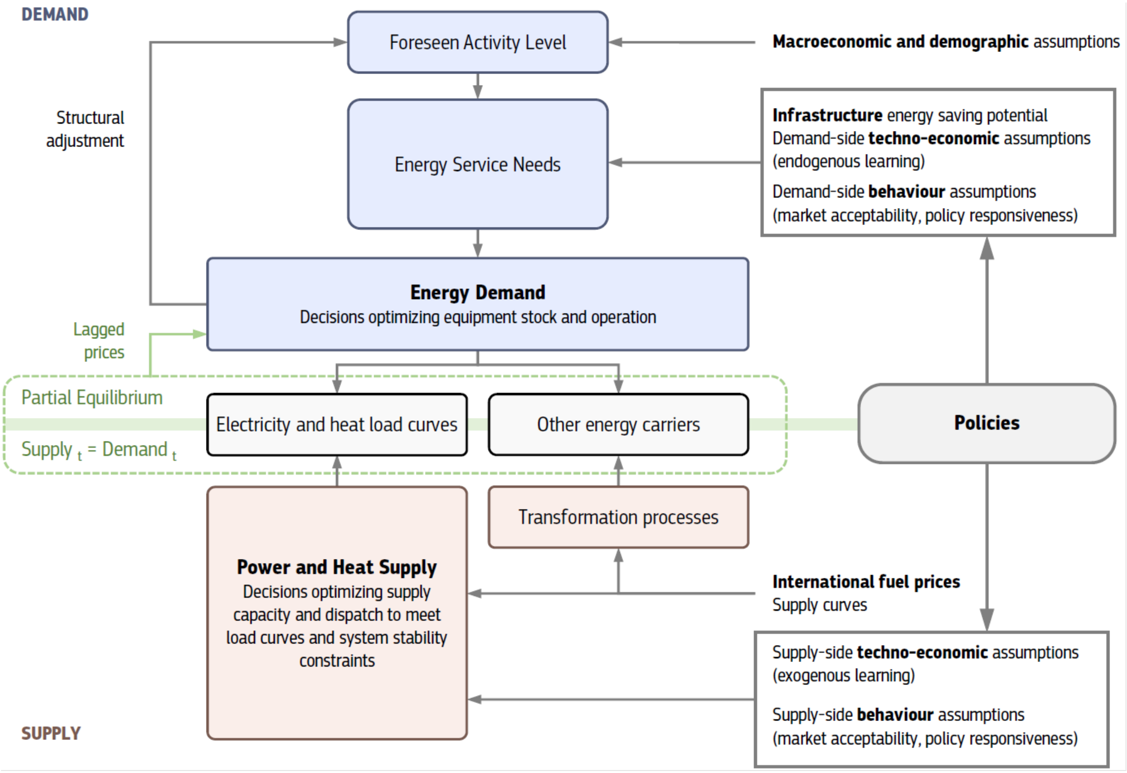
AN 2.1.1 Model Overview

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the European Commission's Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the joint evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. To this end:

- By simulating decision-making under imperfect foresight at a high level of techno-economic detail, POTEnCIA realistically captures the adoption and operation of new energy technologies under different policy regimes;
- By combining yearly time steps for demand-side planning and investment with hourly resolution for the power sector, POTEnCIA provides high temporal detail to suitably assess rapid structural changes in the EU's energy system;
- By tracking yearly capital stock vintages for energy supply and demand, POTEnCIA accurately represents the age and performance of installed energy equipment, and enables the assessment of path dependencies, retrofitting or retirement strategies, and stranded asset risks.

The core modelling approach of POTEnCIA (Figure A1; detailed in Mantzos et al., 2017, 2019) focuses on the economically-driven operation of energy markets and corresponding supply-demand interactions, based on a recursive dynamic partial equilibrium method. As such, for each sector of energy supply and demand, this approach assumes a representative agent seeking to maximize its benefit or minimize its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies.

Figure A33 The POTEnCIA model at a glance



Source: JRC adapted from (Mantzos et al., 2019)

This core modelling approach is implemented individually for each EU Member State to capture differences in macroeconomic and energy system structures, technology assumptions, and resource constraints. The national model implementation is supported by spatially-explicit analyses to realistically define renewable energy potentials and infrastructure costs for hydrogen and CO_2 transport. Typical model output is provided in annual time steps over a horizon of 2000-2070; historical data (2000-2021) are calibrated to Eurostat and other official EU statistics to provide accurate initial conditions, using an updated version of the JRC Integrated Database of the European Energy System (JRC-IDEES; Rózsai et al., 2024).

AN 2.1.2 POTEnCIA CETO 2024 Scenario

The technology projections provided by the POTEnCIA model are obtained under a climate neutrality scenario aligned with the broad GHG reduction objectives of the European Green Deal. As such, this scenario reduces net EU GHG emissions by 55% by 2030 and 90% by 2040, both compared to 1990, and reaches net zero EU emissions by 2050. To model suitably the uptake of different technologies under this decarbonisation trajectory, the scenario includes a representation at EU level of general climate and energy policies such as emissions pricing under the Emissions Trading System, as well as key policy instruments that have a crucial impact on the uptake of specific technologies. For instance, the 2030 energy consumption and renewable energy shares reflect the targets of the EU's Renewable Energy Directive and of the Energy Efficiency Directive. Similarly, the adoption of alternative powertrains and fuels in transport is consistent with the updated CO_2 emission standards in road transport and with the targets of the ReFuelEU Aviation and FuelEU Maritime regulations. A more detailed description of the *POTEnCIA CETO 2024 Scenario* will be available in the forthcoming report (Neuwahl et al., 2024).

AN 2.2 POLES-JRC model

AN 2.2.1 Model Overview

POLES-JRC (Prospective Outlook for the Long-term Energy System) is a global energy model well suited to evaluate the evolution of energy demand and supply in the main world economies with a representation of international energy markets. It is a simulation model that follows a recursive dynamic partial equilibrium method. POLES-JRC is hosted at the JRC and was designed to assess global and national climate and energy policies.

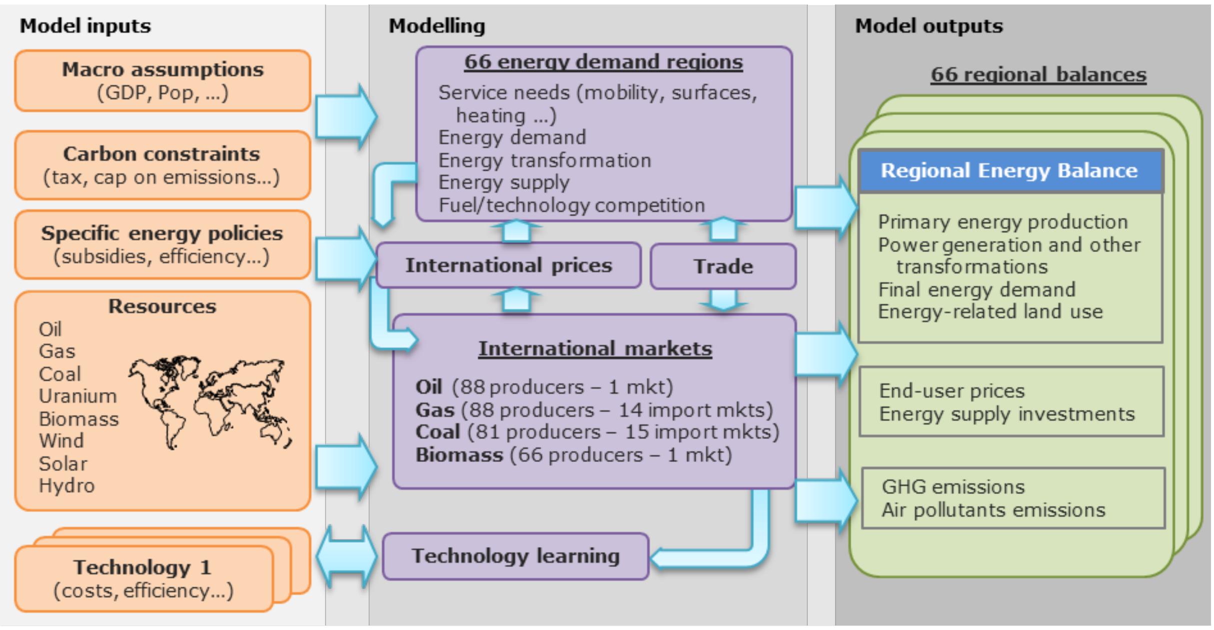
POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables) to transformation (power, biofuels, hydrogen and hydrogen-derived fuels such as synfuels) and final sectoral demand (industry, buildings, transport). International markets and prices of energy fuels are calculated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all detailed OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global frame: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2100 and is updated yearly with recent information.

The POLES-JRC model applied for the CETO project is specifically enhanced and modified to capture learning effects of clean energy technologies.

POLES-JRC results are published within the series of yearly publications "Global Climate and Energy Outlooks" – GECO. The GECO reports along with detailed country energy and GHG balances and an on-line visualisation interface can be found at: https://joint-research-centre.ec.europa.eu/scientific-activities-z/geco_en

A detailed documentation of the POLES-JRC model is provided in (Després et al., 2018).

Figure A34: Schematic representation of the POLES-JRC model architecture.



Source: POLES-JRC model

AN 2.2.2 POLES-JRC Model description

Power system

The power system considers all relevant power generating technologies including fossil, nuclear and renewable power technologies. Each technology is modelled based on its current capacities and techno-economic characteristics. The evolution of cost and efficiencies are modelled through technology learning.

With regard to the power technologies covered by CETO, the model includes solar power (utility-scale and residential PV, concentrated solar power), wind power (on-shore and off-shore), hydropower and ocean power. Moreover, clean thermal power technologies are taken into account with steam turbines fuelled by biomass, biomass gasification, CCS power technologies and geothermal power. Furthermore, electricity storage technologies such as pumped hydropower storage and batteries are also included.

For solar and wind power, variable generation is considered by representative days with hourly profiles. For all renewables, regional resource potentials are considered.

Electricity demand

Electricity demand is calculated for all sectors taking into account hourly fluctuations through the use of representative days. Clean energy technologies using electricity consist of heat pumps (heating and cooling), batteries and fuel cells in transport, and electrolysers.

Power system operation and planning

Power system operation allocates generation by technology to each hour of representative days, ensuring that supplying and storage technologies meet overall demand, including grid imports and exports. Capacity planning considers the existing power mix, the expected evolution of electricity demand as well as the techno-economic characeristics of the power technologies.

Hydrogen

POLES-JRC takes into account several hydrogen production routes: (i) low temperature electrolysers using power from dedicated solar. wind and nuclear plants as well as from the grid, (ii) steam reforming of natural gas (with and without CCS), (iii) gasification of coal and biomass (with and without CCS), (iv) pyrolysis of gas and biomass as well as (v) high temperature electrolysis using nuclear power.

Hydrogen is used as fuel in all sectors including industry, transport, power generation and as well as feedstock for the production of synfuels (gaseous and liquid synfuels) and ammonia. Moroever, hydrogen trade is modelled, considering hydrogen transport with various means (pipeline, ship, truck) and forms (pressurised, liquid, converted into ammonia).

Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM-G4M model (IIASA, 2024). This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass-for-energy potential, production cost and reactivity to carbon pricing.

Biomass is used for power generation, hydrogen production and for the production of 1st and 2nd generation of liquid biofuels.

Carbon Capture Utilization and Storage (CCUS)

POLES-JRC uses CCUS technologies in:

- Power generation: advanced coal using CCS, coal and biomass gasification with CCS, and gas combined cycle with CCS.
- Hydrogen production: Steam reforming with CCS, coal and biomass gasification with CCS, and gas and biomass pyrolysis.
- Direct air capture (DAC) where the CO_2 is either stored or used for the production of synfuels (gaseous or liquid).
- Steel and cement production in the industrial sector.
- Second generation biofuels production.

The deployment of CCS technologies considers region-specific geological storage potentials.

Endogenous technology learning

The POLES-JRC model was enhanced to capture effects of learning of clean energy technologies. To capture these effects, a one-factor learning-by-doing (LBD) approach was applied to technologies and technology sub-components, aiming at endogenising the evolution of technology costs.

POLES-JRC considers historical statistics and assumptions on the evolution of cost and capacities of energy technologies until the most recent year available (this report: 2022/2023). Based on the year and a capacities threshold, the model switches from the default time series to the endogeneous modelling with the one-factor LBD approach. Within the LBD, the learning rate represents the percentage change of the cost of energy technology based on a doubling of the capacity of the energy technology.

This generic approach is applied on a component level to capture spillover effects as well. For instance, a gasifier unit is used as component for several power generating technologies (e.g. integrated gasification combined cycle, IGCC) as well as for several hydrogen production technologies (e.g. gasification of coal and biomass). Therefore, the component-based LBD approach allows to model spillover effects not only across technologies, but also across sectors. Also, it allows to estimate costs for emerging technologies for which historical experience does not yet exist.

Moreover, for each component a floor cost is specified which marks the minimum for the component's investment cost and serves as limitation for the cost reduction by endogenous learning. Cost reductions by learning in POLES-JRC slow down when the investment cost approaches the floor cost.

The described method above applies not only for the overnight investment cost of energy technologies, but as well for operation and maintenance (OM) costs, which also decrease as technologies improve, and for efficiencies. In the model, OM costs diminish synchronously to the decrease of total investment cost of the technology. The efficiency of renewables is implicitly taken into account in the investment cost learning and the considered renewable potentials. For most technologies the efficiencies are endogenously modelled.

AN 2.2.3 Global CETO 2°C scenario 2024

The global scenario data presented in the CETO technology reports 2024 refers to a 2°C scenario modelled by the POLES-JRC model in a modified and enhanced version to address the specific issues relevant for the CETO project.

The *Global CETO 2°C scenario 2024* and its specific POLES-JRC model configuration is described in detail in the forthcoming report "*Impacts of enhanced learning for clean energy technologies on global energy system scenario*" (Schmitz et al., 2024).

The *Global CETO 2°C scenario 2024* is designed to limit global temperature increase to 2°C at the end of the century. It is driven by a single global carbon price for all regions that reduces emissions sufficiently so as to limit global warming to 2°C. This scenario is therefore a stylised representation of a pathway to the temperature targets. This scenario does not consider financial transfers between countries to implement mitigation measures. This is a simplified representation of an ideal case where strong international cooperation results in concerted effort to reduce emissions globally; it is not meant to replicate the result of announced targets and pledges, which differ greatly in ambition across countries.

As a starting point, for all regions, it considers already legislated energy and climate policies (as of June 2023), but climate policy pledges and targets formulated in Nationally Determined Contributions (NDCs) and Long-Term Strategies (LTSs) are not explicitly taken into account. In particular, the EU Fit for 55 and RePowerEU packages are included in the policy setup for the EU. Announced emissions targets for 2040 and 2050 for the EU are not considered.

The *Global CETO 2°C scenario 2024* differs fundamentally from the *Global CETO 2°C scenario 2023* used in the CETO technology reports in 2023 in various aspects[28]:

- The version of the POLES-JRC model used for the Global CETO 2°C scenario has been further enhanced and modified to capture effects of endogenous learning of clean energy technologies and, furthermore, several technology representations were further detailed, e.g. DAC (composition

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[28] A description of the *Global CETO 2°C scenario 2023* can be found in Annex 3 of (Chatzipanagi et al., 2023).

of renewable technologies, batteries and DAC unit), fuel conversion technologies (for hydrogen transport) and batteries in transport.

- The techno-economic parameters have been thoroughly revised and updated taking into account the expertise of the authors of the CETO technology reports.

As a result, major scenario differences occur in the *Global CETO 2°C scenario 2024* regarding DAC, synfuels, CCS power technologies, wind power and ocean power.

AN 2.3 Distinctions for the CETO 2024 Scenarios - POLES-JRC vs. POTEnCIA

The results of both models are driven by national as well as international techno-economic assumptions, fuel costs, as well as policy incentives such as carbon prices. However, on one side these two JRC energy system models differ in scope and level of detail, on the other side the definitions of the POTEnCIA and POLES-JRC scenarios presented in this document follow distinct logics, leading to different scenario results:

- The *Global CETO 2°C scenario 2024* (POLES-JRC) scenario is driven by a global carbon price trajectory to limit global warming to 2°C, where enacted climate policies are modelled, but long-term climate policy pledges and targets are not explicitly considered. Scenario results are presented for the global total until 2100.
- The *POTEnCIA CETO 2024 scenario* is a decarbonisation scenario that follows a trajectory for EU27's net GHG emissions aligned with the general objectives of the European Climate Law (ECL) taking into consideration many sector-specific pieces of legislation. Scenario results are presented for the EU27 until 2050.

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