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CARBON CAPTURE UTILISATION AND STORAGE IN THE EUROPEAN UNION

*STATUS REPORT ON TECHNOLOGY
DEVELOPMENT, TRENDS, VALUE CHAINS &
MARKETS*

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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 and globally. In 2022, the CCUS industry experienced unprecedented growth and will continue to do so in the future. The costs of CCUS vary widely depending on the industry, technology, location, plant design and regulatory frameworks in place. The US, EU, and Japan have patented the most high-value inventions, and within the EU, the leading Member States in this context are France, Germany and the Netherlands. Denmark is the new leader in public R&D investment in CCUS for 2021. Global venture capital investment more than doubled from 2021 to 2022, with the US attracting most VC investment. CCUS offers circular carbon economy benefits, but there are concerns about leakages, safety, and public acceptance. CCUS hubs aim to cluster local emitters and pair them with transport and storage developers, for example at Porthos hub in the port of Rotterdam.

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

Objectives

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

Key findings

In 2022, globally the CCUS industry saw unprecedented growth, with an increase in capacity of 44% over the year.

The cost of CCUS today is still difficult to assess. It varies based on sectors, technologies, and plant design factors. The capture costs can be anywhere between EUR 13 and EUR 103 per tonne of CO₂ depending on the industry and CO₂ concentration. Transport and storage costs can also vary significantly depending on distance, volume, geographical location and storage conditions.

The US filed the most high-value inventions between 2009 and 2020, followed by the EU and Japan. Among the EU Member States, France has highest number of high-value inventions, followed by Germany and the Netherlands. These countries are also in the EU top five regarding the number of peer-reviewed publications related to various aspects of the CCUS value chain.

2021 was a record high year for public R&D investment in CCUS. At EU level, Denmark is the new leader, attracting 39% of the funds, followed by France (23%) and Germany (21%). Globally, over the last decade, the US has maintained its place as the leader with a 23% share, followed by Canada (18%), Japan (13%), Norway (12%) and the EU (10%). However, in 2021, the EU ranked first (25%), surpassing the US (22%) and Japan (17%).

The US has been the top investor in private R&D since 2012. The EU ranks second with relatively stable level of funding for private R&D. Germany, France, the Netherlands are the top three countries with the largest private R&D investment in CCUS from 2010 to 2019.

Global venture capital (VC) investment more than doubled from 2021 to 2022, reaching a new all-time high of EUR 1.5 billion. The US attracted most VC investment (38%), reinforcing its leading position in the CCUS industry from the very beginning, while the EU managed to secure 18% of global VC investment. Investment in direct air capture (DAC) companies set funding records for 2022. Swiss company Climeworks raised EUR 582 million. DAC is expected to see significant growth, as the first source for captured CO₂ in 2050.

The CCUS industry is not yet operating at scale and does not have specialised supply chains yet. Various CO₂ 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 CO₂ is dried using triethylene glycol and then liquefied for transportation. The transportation options currently under consideration are pipelines and ships – both of which rely heavily 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 CO₂ 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 US generated the highest revenue in the CCUS value chain in 2021 at EUR 1.945 billion. The estimated value for Europe is EUR 92 billion. Czechia, Ireland, Italy, France and Spain achieved the highest estimated value added as a percentage of their gross domestic product among EU Member States.

Approximately 6 400 people are employed in the CCUS chain worldwide, with the majority in the US (4 000 jobs) followed by Australia (400) and Norway (350). The Global CCS Institute estimates that up to 1.4 million jobs could be created globally in the CCUS industry by 2040, with a significant proportion in Europe. The industry needs a skilled workforce that is trained in various aspects of CCU; this can be achieved by retaining existing workers in energy-intensive industries.

The environmental impacts of deploying CCUS in the industrial sector have not been studied in depth, with most studies focusing on the power sector. Life cycle assessments have shown that post-combustion capture at a

90% capture rate significantly reduces the greenhouse gas intensity of coal-based electricity. CCUS offers circular carbon economy benefits, but there are concerns about leakages, safety and public acceptance.

The US has been the world leader in CCUS from the beginning, accounting for almost half of large-scale commercial projects. Most likely, it will maintain its leading place in 2030, despite the upcoming geographical diversification of the industry. The EU is largely unrepresented in the global market and has no operational CO₂ storage projects to date. In continental Europe, Norway has been a leader in the CCUS market with capture, transport and storage facilities in operation since 1996.

CCUS hubs will come online early in 2024 to cluster local emitters and pair them with transport and storage developers, in an effort to mitigate risks and reduce costs. In the EU, CCUS hubs will develop in industrial port cities. The Porthos hub in the Port of Rotterdam will capture CO₂ from Air Liquide, Shell and ExxonMobil and store it in the North Sea. Other CCUS hubs in Europe include Longship in Norway, Coda Terminal in Iceland, and Acorn and East Coast Cluster in the UK. In the US, most CCUS hubs will emerge along the major onshore pipeline and a few with offshore storage in the Gulf of Mexico. In the US, hubs have been announced by Summit Carbon Solution, Valero and Navigator, Houston hub, CarbonSAFE and Bayou Bend.

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

Strengths	Weaknesses
• Broad application • Growing political and public support • Strong pipeline of projects to be developed in Europe by 2030	• Perceived risks and lack of investor confidence • Relatively expensive • Limited track record • Environmental concerns
Opportunities	Threats
• Target hard-to-abate sectors to drive deep decarbonisation • Accelerate project development through international collaboration • New jobs and businesses • More affordable and reliable renewable energy • Cost reduction can be achieved through increased project capacity • Mathematical modelling can help decision-making	• Further cost reductions are crucial for mass adoption • 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 along with the methodology and data sources used in this desktop study. Chapter 2 describes the technology readiness level and development trends. In Chapter 3, we take a look at the CCS value chain, including environmental and socio-economic aspects, employment and EU production values for manufactured goods related to CCUS. Chapter 4 presents results and discusses the EU market position and global competitiveness. This is followed by Chapter 5, which outlines general conclusions.

1 Introduction

1.1 Scope and context

Carbon capture, storage and utilisation (CCUS) has been acknowledged in the context of the European Energy Union as a fundamental research and development priority to achieve the 2050 climate objectives in a cost-effective way (European Commission, 2015). The European Green Deal included CCUS in the technologies necessary toward a transition to climate neutrality (European Commission, 2019). More recently, 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 (European Commission, 2021a). In March 2023, the Commission proposed the Net Zero Industry Act (NZIA), which sets an annual injection capacity target of at least 50 million tonnes of CO₂ by 2030 in storage sites located in the EU. The legislation provides no financial incentives or direct investment and relies on Member States and domestic companies to meet them.

2022 has seen unprecedented advances for CCUS technologies. In this report, the sectors covered include power generation and industry. Given that industrial applications are also considered, the standard classification used (pre-, post- and oxy-combustion) may not be representative. In industrial processes, CO₂ may not arise exclusively from fuel combustion, but can be produced during processes like calcination, where calcium carbonate is transformed into calcium oxide or the reduction of iron ore with coke in a blast furnace or the alumina reduction with a carbon anode in an aluminium smelter.

CO₂ utilisation processes include the chemical transformation of CO₂ into another product with commercial value. However, not included in this report are enhanced oil recovery (EOR), or other uses – such as in the food industry or as a supercritical solvent – where CO₂ is subjected to physical and long-term chemical changes. The overview covers all applications related to the synthesis of fuels, chemicals and materials. Regarding CO₂ storage, the focus is on both offshore and onshore aquifers, but also on considering alternative ways such as storage in basalts. On transport, both shipping and pipelines are considered.

1.2 Methodology and data sources

The review of each topic is organised following two main blocks: (i) a literature review and technology analysis to depict the state-of-the-art of CCS and CO₂-use technologies; and (ii) a technology assessment, taking into account the evolution of the technology readiness level (TRL) according to literature and to European R&D projects.

The review of the technology status is based on academic literature including scientific articles published in peer-reviewed journals; the SETIS webpage and associated SET Plan actions; the Carbon Sequestration Leadership Forum (CSLF); and online information from the International Energy Agency (IEA), the Global CCS Institute and the Global Status of CCS series.

In the patenting activities section, data is used from the Joint Research Centre (JRC), based on data from the European Patent Office (EPO) PATSTAT database. The methodology behind the indicators is provided in (Fiorini *et al.*, 2017; Pasimeni, 2019; Pasimeni, Fiorini and Georgakaki, 2019). The current version of the report includes data up to 2020.

The *Impact and Trends of EU-supported Research and Innovation* makes use of CORDIS and internal databases to identify EU co-funded projects¹. Aside from the straightforward technological routes, the projects' relevance was also determined based on their connection technologically to the SET Plan actions. The projects were further used as a cross reference to identify any additional ones, based on the call/funding scheme under which they were funded. It should be noted that many H2020-funded projects are still ongoing, and whether they have achieved their aims and targets may be inconclusive. Projects that do not consider the separation of CO₂ directly, or its immediate reuse, such as, for example, specific catalyst development with chemical functionalisation, artificial photosynthesis and technologies aiming to advance CO₂ reduction, have been excluded from the analysis. Technologies focusing on the molecular level are also excluded.

On the technology readiness assessment from European R&D projects, the focus is on CCS and CO₂ utilisation projects granted H2020 (2014-2020) funding. Technologies that refer to standalone techniques, envisioned to

¹ The keywords used were: carbon capture, carbon dioxide, CO₂ capture, carbon utilisation and use, carbon use, surplus, CO₂ storage, CO₂ transport, CO₂ monitoring and CCS.

be part of CO₂ capture or utilisation chain, have not been considered (for example, the study of integrated platforms for photocatalytic water splitting and CO₂ reduction). It should be noted that in most cases the technology readiness level achieved at the end of a project is not clearly indicated within the project outputs. In such cases, expert judgement of results is applied.

The TRL assessment follows the definitions as described in (Kapetaki and Miranda-Barbosa, 2018). For CO₂ utilisation technologies, processes for the synthesis of fuels, chemicals or materials are also examined. TRL levels for CO₂ storage, transport and monitoring follow the classification given by (European Commission and EC, 2014) and (DOE/NETL, 2015a). Finally, to determine the TRL of a sub-technology we assume that there should exist at least one project at the specific TRL assigned.

For the identification of the technology trends, needs and barriers, apart from the sources used for the state-of-the-art of the technology, we have used the technology roadmaps and reports from various organisations and initiatives such as the International Energy Agency (IEA), Mission Innovation, the Zero Emissions Platform (ZEP), the Strategic Energy Technology (SET) Plan CCUS working group and CSLF, which are fully cited where relevant.

2 Technology status and development trends

Carbon capture is already implemented in processes like natural gas processing and industrial hydrogen production. The first large-scale CCS project launched in 2014 is Boundary Dam in Canada (coal power plant, PostC, 110 MW). Petra Nova in Texas (coal power plant, post-combustion, 240 MW) is another full scale CCS project which started operation in January 2017, but is currently on hold. Shell Quest started in September 2015 and removed CO₂ from the process gas streams of the three hydrogen manufacturing units, within the Scotford upgrader facility. To the end of 2022, Quest has successfully captured and injected over 7.7 Mt of CO₂ in three injection wells.

Commercial uses of CO₂ also exist, and CO₂ utilisation can contribute in a number of sectors, such as synthesis of chemicals, organic and inorganic carbonates, fuels and olefins. Each product synthesis, and each synthesis pathway, is at a different TRL level.

From the source to the sink of CO₂ in both onshore and offshore, it is necessary to transport it and to have a deep knowledge of the geological structure of the site of injection. To create safe storage, avoiding any CO₂ leakage, an advanced and accurate system of monitoring is required.

Table 1 summarises the main sub-technologies identified for CCUS as defined in (Kapetaki and Miranda Barbosa, 2018, 2020). Other research areas of a more trans-technological and cross-technological nature are included in Table 2.

Table 1. Sub-technologies identified for CCUS.

Sub-technology
Capture
Absorption
Adsorption
Membrane Technology
High Temperature Looping
Hybrid Approaches
Utilisation
Boosting commercial processes (e.g. urea)
CO ₂ use without transformation: EOR, EGR, ECBM
CO ₂ use without transformation (as solvent): supercritical CO ₂
Chemicals and polymeric materials
Fuels: alcohols, hydrocarbons and derivatives, hydrogen carriers (e.g. methanol, formic acid)
Mineralisation
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
Ship transport
Pipeline transport and network design
Safety aspects of transport

Table 2. Other research areas identified for the CCUS.

Area
Materials and corrosion
Storage (natural analogues)
Ocean storage
CO ₂ storage in other geological sites: reactive basaltic rocks.
Synergy with renewables such as geothermal energy, biomass, CSP, wind/H ₂
Integration among the overall CO ₂ value chain (capture, transport, utilisation, storage): CO ₂ emissions evaluation. Cost competitiveness of the overall project and new business models.

2.1 Technology readiness level (TRL)

2.1.1 Carbon capture and utilisation technology

Until now, CO₂ capture configurations were described with definitions mainly referring to their relation to combustion as applied in power generation: post-combustion, pre-combustion and oxy-combustion.

First generation capture technologies correspond to (i) amine-based solvents, (ii) physical solvents and (iii) cryogenic air separation (air separation unit – ASU) to obtain pure oxygen. These technologies are currently available, but research and development (R&D) on necessary improvements is 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, or 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 challenges 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 technology readiness levels of different technologies are shown in Table 3.

According to the Global CCS Institute, there are 30 commercial CCUS facilities operating worldwide, of which one is operated in the EU, in Hungary in the field of enhanced oil (EOR) and gas recovery (EGR). We note three additional facilities in European continent: one in Iceland (in the field of DAC and storage) and two in Norway (in the field of capture and storage) (Global CCS Institute, 2022a). The facilities in Hungary and Norway operate in natural gas processing. The only project in power generation (CarbFix) is in Iceland and includes the capture of CO₂ and its injection in solution into a basaltic subsurface formation nearby, where it forms solid carbonate minerals. In the initial pilot tests, the CO₂ was sourced from a pilot gas separation station at the Hellisheiði geothermal plant. Currently, the nearby Hellisheiði geothermal power plant supplies renewable energy to the DAC process.

Table 3. TRL assessment and key technology vendors of the CO₂ capture technologies.

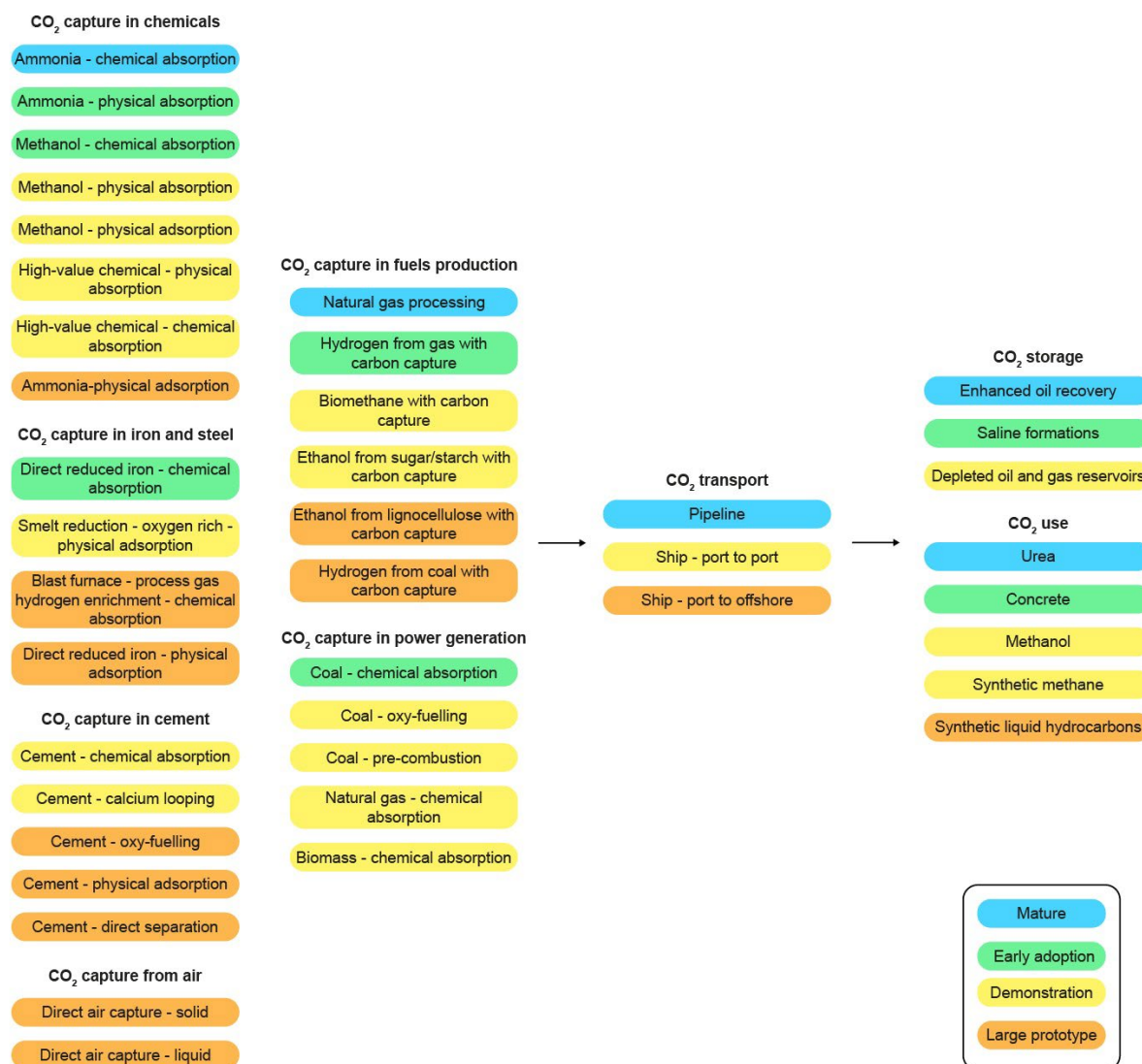
Technology		TRL 2020	Key vendors
Liquid solvent	Traditional amine solvents	9	Fluor, Shell, Dow, Kerr-McGee, Aker Solutions, etc.
	Physical solvents (Selexol, Rectisol)	9	UOP, Linde and Air Liquide
	Benfield process and variants*	9	UOP
	Sterically hindered amine	6-8	MHI, Toshiba, CSIRO, etc.
	Chilled ammonia	6-7	GE
	Water-lean solvent	4-7	Ion Clean Energy, CHN Energy, RTI
	Phase change solvents	5-6	IFPEN/Axens
	Amino acid-based solvent/Precipitating solvents	4-5	Siemens, GE
	Encapsulated solvents	2-3	R&D only
	Ionic liquids	2-3	R&D only
Solid adsorbent	Pressure Swing Adsorption (PSA)/ Vacuum Swing Adsorption (VSA)	9	Air Liquide, Air Products, UOP
	Temperature Swing Adsorption (TSA)	7	Svante
	Enzyme catalysed adsorption	6	CO ₂ solutions
	Sorbent-Enhanced Water Gas Shift (SEWGS)	5	ECN
	Electrochemically mediated adsorption	1	R&D only

Technology		TRL 2020	Key vendors
Membrane	Gas separation membranes for natural gas processing	9	
	Polymeric membranes	6	MTR
	Electrochemical membrane integrated with MCFCs	7	FuelCell Energy
	Polymeric membranes/Cryogenic separation hybrid	6	Air Liquide, Linde Engineering, MTR
	Polymeric membranes/Solvent hybrid	4	MTR/ University of Texas
	Room Temperature Ionic Liquid (RTIL) Membranes	2	R&D only
Cryogenics	Distillation, Condensation, Sublimation	5-9	Air Products, Linde, and ExxonMobi, Sustainable Energy Solutions
Oxyfuel combustion	Oxyfuel combustion	7-8	Endesa, Vattenfall, Total
Solid looping	Calcium Looping (CaL)	6-7	Carbon Engineering
	Chemical Looping Combustion (CLP)	5-6	Alstom
Direct CO ₂ separation	Allam-Fetvedt Cycle	6-7	8 Rivers Capital
	Calix Advanced Calciner	5-6	Calix
Direct air capture (DAC)	High temperature Low temperature	7	Carbon Engineering, Climeworks, Global Thermostat
Bioenergy with carbon capture and storage (BECCS)	Bioenergy with carbon capture and storage	5-6	Archer Daniels Midland, Drax Group, Global Bioenergies

Source: JRC adapted from (Global CCS Institute, 2021b).

Figure 1 shows a scheme of technology readiness through the CCUS value chain presented by the International Energy Agency which includes CO₂ use processes. We note that at the time of writing, the International Energy Agency's Clean Energy Progress has no updates since 2020 (IEA, 2020b) and it was not on track for CCUS.

Figure 1.TRL of select technologies along the CCUS value chain (IEA, 2020a)



Source: (IEA, 2020a)

Regarding utilisation, the synthesis of products from CO₂ is already taking place. So far, CO₂ has been a by-product of industrial processes such as in H₂ production by steam reforming of natural gas or ethanol production by fermentation. The largest CO₂ consumer is the fertiliser industry, followed by oil and gas. Other commercial applications include food and beverage production, metal fabrication, cooling, fire suppression and stimulating plant growth in greenhouses (IEA, 2019). The wide range of possibilities for the use of CO₂ as a raw material are at different scales and levels of development, and have different market prospects. Some technologies could be readily established in existing mature markets e.g. the use of CO₂ 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.

In October 2021, the Implementation Working Group on CCUS under the SET Plan published the CCUS Roadmap 2030. This Roadmap aims to identify and stress the actions necessary for the large-scale development and deployment of CCS and CCU in the 2020s, building on the work done within the SET Plan, and provides an overview of the status of the technologies today. The Roadmap proposes a target of at least three pilots of capture technologies at TRL 7-8 in different industrial applications, including one enabling low-emission hydrogen production, and at least six pilots of capture technologies at TRL 5-6, including at least two to test climate positive solutions such as Bio-CCS and DAC (SET Plan Working Group CCUS, 2021).

2.1.2 CO₂ transport and storage

Currently, CO₂ is compressed and transported primarily through pipelines. The transportation of gasses and liquids via any method such as through pipelines, by ships, truck and rail is mature (i.e. TRL 9). However, transportation of CO₂ at the very large scale associated with CCS has not yet been achieved using ships or rail. The TRL for CO₂ shipping ranges from 3 to 9 (Global CCS Institute, 2021b). Pipelines are the mode of transporting CO₂ at significant scale, primarily in the United States. In Europe, CO₂ pipelines are operating in Netherlands and Norway. In Norway, an offshore 153-kilometre long CO₂ pipeline is operating for the Snøhvit CO₂ storage facility.

CO₂ storage in saline formations is at TRL 9. CO₂ storage in saline formations has been carried out in the North Sea since 1996 when the Sleipner CCS project started operating. Since then over 20 Mt of CO₂ has been injected for storage. CO₂ storage through Enhanced Oil Recovery (CO₂-EOR) has been in operation for nearly 50 years (National Petroleum Council, 2019). Currently, there are over 40 CO₂-EOR operations, with most of them operating in the USA (Bui. M et al., 2018). While CO₂-EOR operations aim to maximise oil recovery, CO₂ is permanently stored during the process, becoming trapped in the pore space that was previously occupied by hydrocarbons (Global CCS Institute, 2021b). Geological storage in depleted oil and gas fields is technically mature but has a lower TRL of 5-8 as it has only been applied in demonstration projects (Bui. M et al., 2018). Finally, there are two leading unconventional options for CO₂ storage: storage in Basalt and ultramafic rocks (TRL 2-6) and storage in coal seams through Enhanced Coal Bed Methane (ECBM) production (TRL 2-3) (Global CCS Institute, 2021b).

2.2 Installed capacity and production

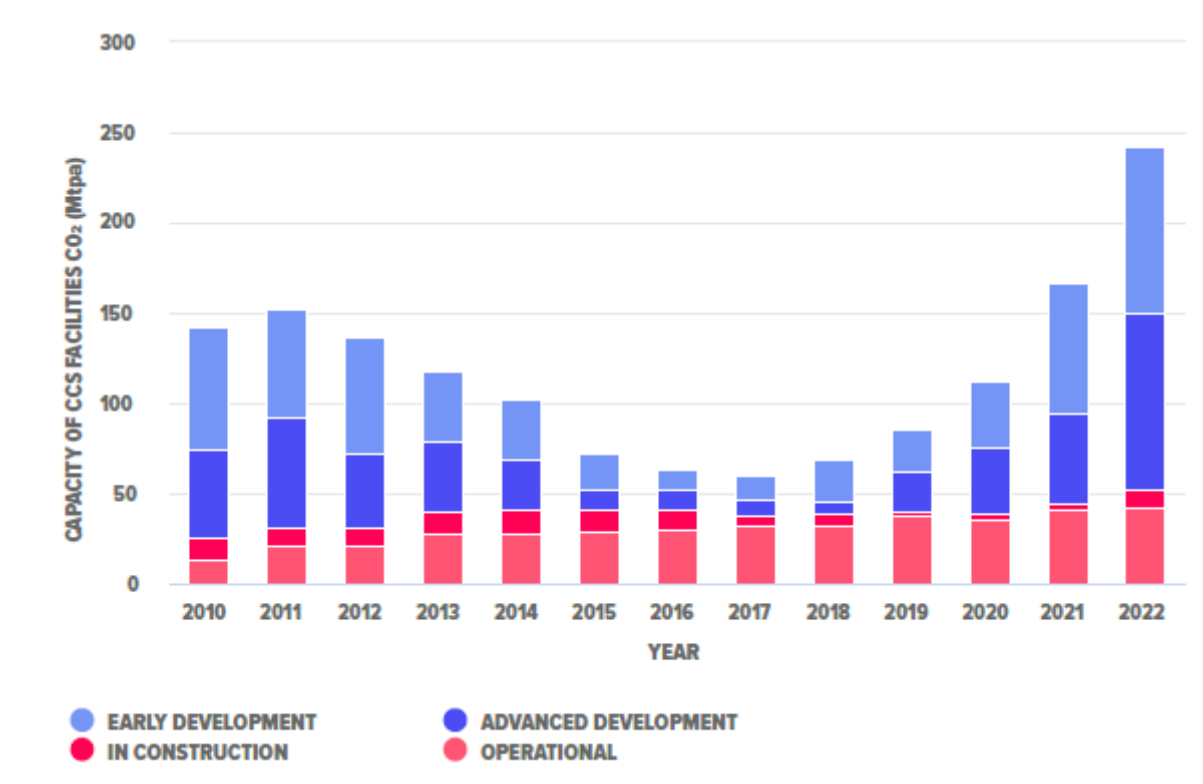
CCS has become increasingly commercial and competitive in many countries. As of September 2022, at the global scale, the total capacity of CCS projects in development was 244 million tonnes per annum (Mtpa) of CO₂, an increase of 44% over the past 12 months (Global CCS Institute, 2022a). These facilities 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, the latest IPCC report pointed out that current global rates of deployment are far below those in modelled pathways to limit global warming to 1.5 or 2°C (IPCC, 2022).

In Europe, promising projects in advanced phases of development are shifting focus towards CO₂ infrastructure such as the Porthos and Aramis projects in the Netherlands and Antwerp@C in Belgium as well as projects included in the projects of common interest lists for a cross-border carbon dioxide network. In Norway, the plan for Longship, a full-scale CCS project capturing emissions, is also progressing. Hydrogen production with CCUS has received a lot of attention in recent years. The Global CCS Institute lists six projects in hydrogen production in the EU (in Italy, the Netherlands and Sweden), albeit at different stages of development. It remains to be seen whether this trend will continue and develop further. DAC has also received a lot of attention besides the typical CO₂ separation technologies. Since its foundation in 2009, the Swiss company Climeworks has deployed 15 DAC facilities throughout Europe (Climeworks, 2021). The first commercial plant has been in operation since 2017, and in 2021, another commercial CCS facility, ORCA, entered into operation in Iceland. While CCS developments in power generation have stagnated in the last decade, one project, the Italian Adriatic Blue – ENI Power CCS, is in early development. Additionally, Ørsted Kalundborg Hub in Denmark will establish carbon capture at its wood chip-fired Asnæs Power Station in Kalundborg in western Zealand and at the Avedøre Power Station's straw-fired boiler in the Greater Copenhagen area.

Globally, there are 30 operational CCUS facilities with a capture capacity of nearly 42.5 Mt of CO₂ per year (Global CCS Institute, 2022a). The US leads the way globally with 47% of the market share. Other leading countries in the past year include Brazil (9%), Australia (8%) and Canada (8%) (BNEF, 2022). Norway is the only country in continental Europe that has built large-scale capture projects. Sleipner and Snøhvit, built in 1996 and 2008 respectively, add an average of 1.8 million tonnes per year of CO₂, representing 4% of the global market share (BNEF, 2022). The facility counts also include transport and storage projects, but to avoid double-counting project capacities, transport and storage do not include capture.

Figure 2 shows the increase in the capacity of CCS projects from 2010 until September 2022 (the 2022 bar represents the project development status as of mid-September 2022).

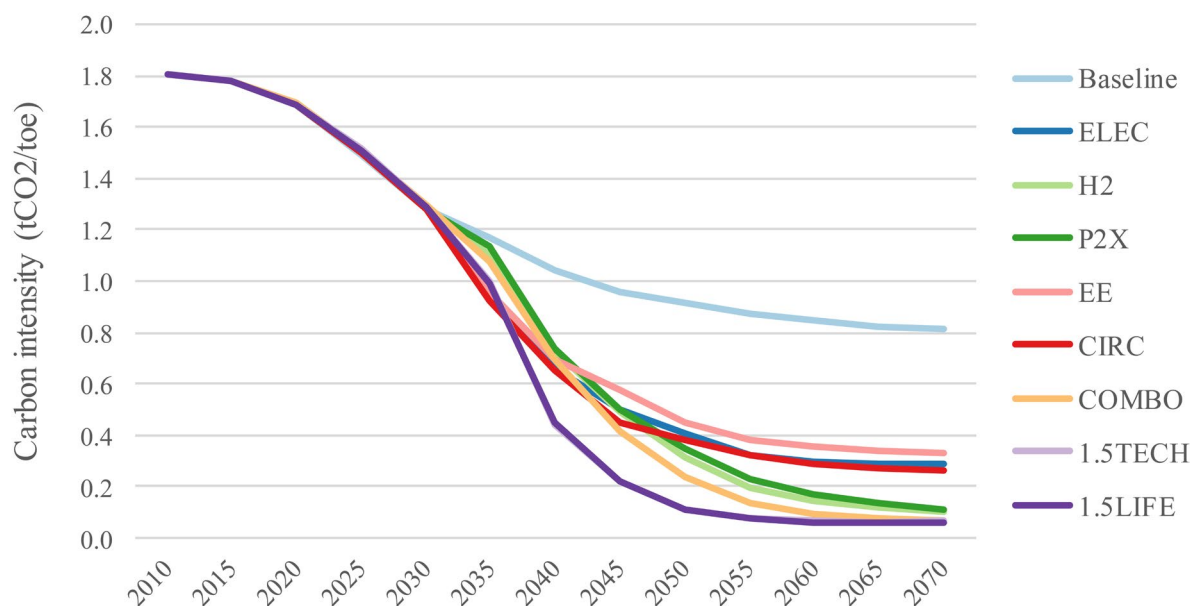
Figure 2. Pipeline of commercial CCS facilities from 2010 to September 2022 by capture capacity (Global CCS Institute, 2022a)



Source: (Global CCS Institute, 2022a)

The latest scenarios released by the European Commission as part of the Fit-For-55 package focus on 2030. Towards 2050, according to the European Commission's Long-Term Strategic Vision (European Commission, 2018b), the weight of fossil fuel-fired capacity in the total power mix decreases over time. Gas-fired capacities that can use both natural gas or biogas decrease, ranging in 2050 from 141 GW (P2X) to 226 GW (ELEC) in scenarios achieving 80% GHG reductions and decreasing up to 100 GW in the 1.5LIFE scenario, of which almost 30% is associated with CCS. Coal-fired capacities are progressively removed from the power mix, with only 20 GW left in all scenarios except for 1.5TECH, where 38 GW remains. In 2050, CCS plays a noticeable role only in 1.5TECH. In this scenario it reaches 5% of the total net electricity generation, mostly because of biomass power generation to generate negative emissions, with 66 GW of total capacity equipped with CCS installed. Nevertheless, the role of CCS for power generation in all scenarios is very limited. However, these projections might be updated in the future in view of the changes in the geopolitical equilibrium. No significant deployment of CCS for power generation by 2030 is projected in any of the considered scenarios in the modelling exercise undertaken for the Fit-for-55 exercise, i.e. "Stepping up Europe's 2030 climate ambition" (European Commission, 2021b). Both sets of scenarios foresee a much more prominent role for CCS in industry (European Commission, 2018b, 2020). More specifically, carbon intensity in industry decreases more in the scenarios where CCS is applied (1.5TECH and 1.5LIFE) as shown in Figure 3. In the Fit-for-55 exercise, CCS in industry is not expected to enter the market at scale at the carbon price levels observed in the projections in 2030, but closer to 2035 or 2040 (European Commission, 2020).

Figure 3. Carbon intensity in industry, according to various scenarios.



Source: (European Commission, 2018b)

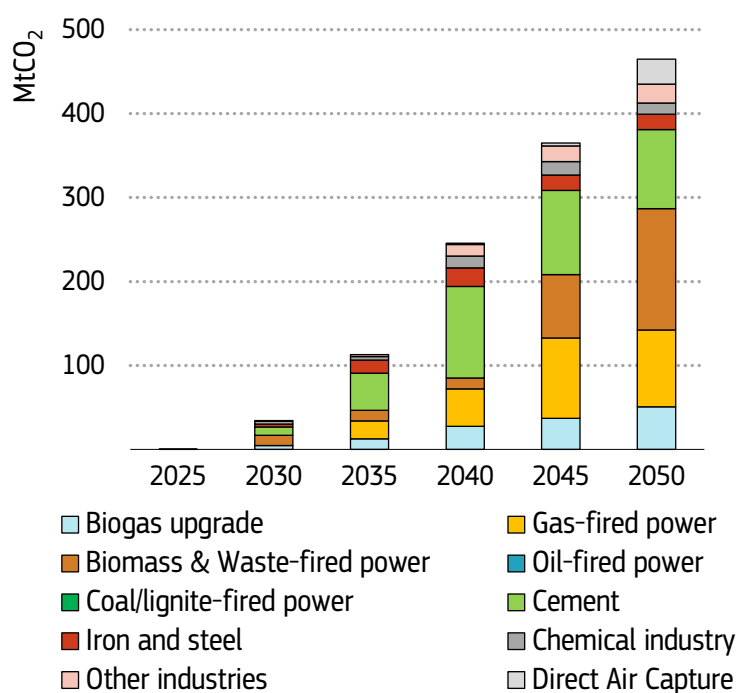
The role of carbon removal technologies such as DAC and BECCS is diverse. According to modelling for the recent Communication on Sustainable Carbon Cycles, to achieve climate neutrality in the EU by 2050, depending on the scenario, at least 300 Mt CO₂ and potentially more than 500 Mt CO₂ will need to be captured from various sources (power generation, industrial processes or directly from the air) for storage or to supply innovative routes to produce materials and fuels (European Commission, 2021a).

In the IEA “Net-Zero Emissions by 2050” Scenario (NZE), which is compatible with limiting the temperature rise to 1.5 °C, almost 980 Mt CO₂/year are projected to be captured using DAC by 2050, and already 85 Mt CO₂/year by 2030 (IEA, 2021a). Projections from the scenarios within the EU long-term strategy (LTS) to reach carbon neutrality by 2050, allocate 210 Mt CO₂ and 123 Mt CO₂ to DAC in the 1.5TECH and 1.5LIFE scenarios respectively (European Commission, 2018a). However, the DAC plants currently operational in the world are capturing only around 0.01 Mt CO₂/year, in total (IEA, 2021a). The recently launched Carbon Dioxide Removal Mission, under Mission Innovation, aims to enable CDR technologies to achieve a net reduction of 100 million metric tonnes of CO₂ per year globally by 2030. In August 2022, the Mission published an Innovation Roadmap (Mission Innovation, 2022) 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.

The European Commission scenarios towards climate neutrality performed using the POTEnCIA² energy system model concluded that reaching net-zero in the EU in 2050 is expected to require the capture of 465 Mt CO₂. 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 CO₂ emissions, respectively 144 Mt CO₂ and 94 Mt CO₂ in 2050. This can be explained by the fact that CCS represents the most cost-effective (BECCS) or sole avenue for mitigating the inevitable process emissions in industrial sectors, such as cement manufacturing. Additionally, DAC is expected to deliver negative emissions after 2035 and then it undergoes significant growth, capturing an estimated 30 Mt CO₂ in 2050, thus being the fifth largest carbon capture application. In 2050, most captured CO₂ is projected to be permanently stored underground (77%), with synthetic fuel (16%) and materials production (7%) utilising the remaining amounts (Figure 4).

² 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 3.

Figure 4. CO₂ captured by source in the EU, 2025-2050, based on the net-zero in the EU in 2050.

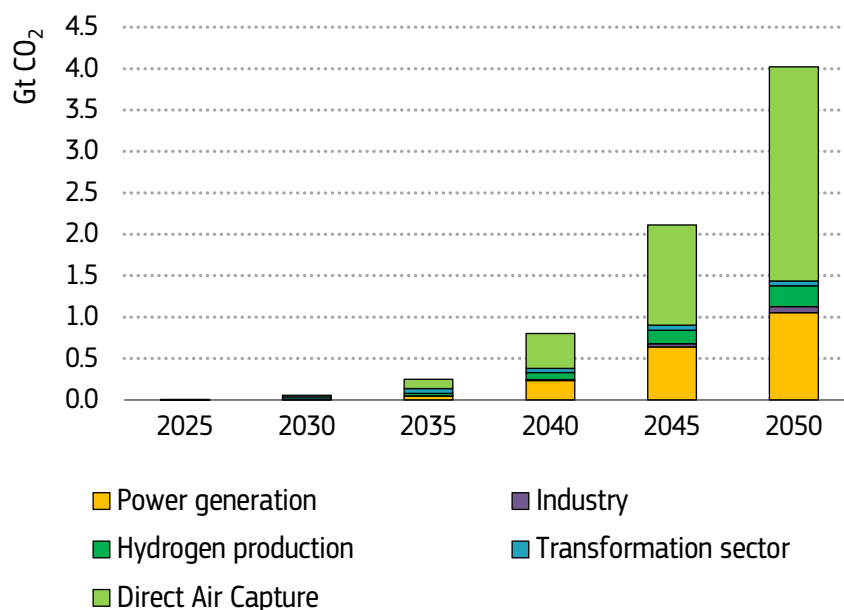


Source: JRC analysis based on the POTEnCIA model.

Globally, the POLES-JRC³ energy system model, in its CETO global 2°C scenario, estimates that 54 Mt CO₂ per year are captured in 2030. The global captured CO₂ is expected to rise to 4 Gt CO₂ in 2050. Around 78% of the total CO₂ captured in 2050 is foreseen to be stored in permanent geological storage with the remaining 22% used to manufacture synthetic fuels. CCS projects in the transformation sector are expected to add most capture capacity this decade, totalling 26Mt CO₂/year by 2030. CO₂ emissions captured from power generation steadily grow over the decades and become the second largest application for CCS in 2050. DAC is expected to see significant growth, rapidly scaling up from 17Mt CO₂ per year in 2030 to 2.6Gt CO₂ per year in 2050, being the first source for captured CO₂ in 2050. Hydrogen generation is projected to be the third largest market for capture by 2050 (Figure 5).

³ 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 3.

Figure 5. Global CO₂ capture by source, 2025-2050.



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

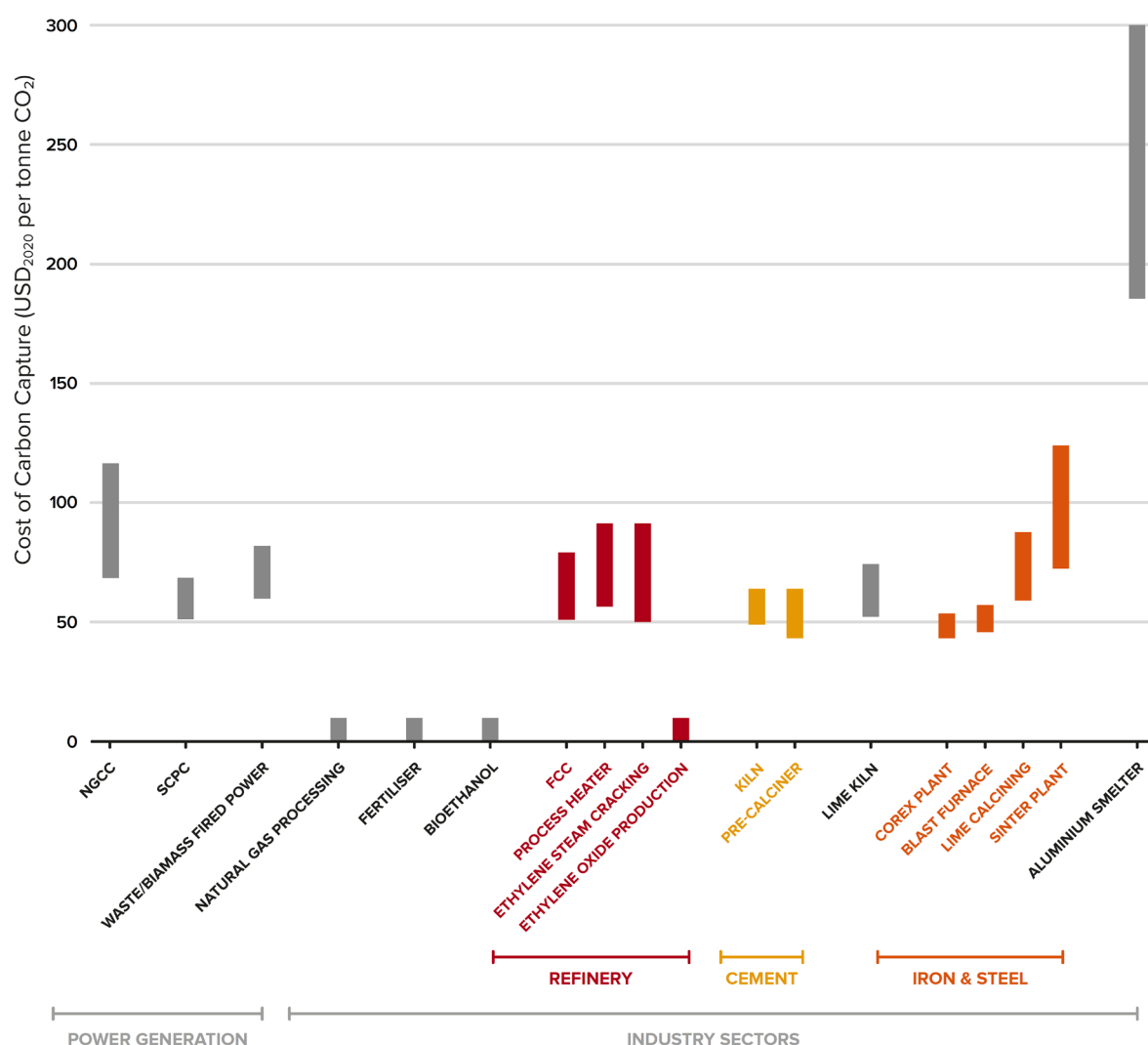
2.3 Technology cost

The cost of CCUS can vary significantly based on the sector (CO₂ volume, CO₂ concentration and pressure), the technology (IRENA, 2021) and on the design factors of the plant, especially if it is a greenfield site rather than a retrofit (BNEF, 2023). Technology costs reflect, and are directly impacted by what is available on the market, while design costs vary according to the size, location and power source used by the capturing equipment. Larger plants have higher capital costs, but a lower cost per tonne of CO₂, if the capture system is run at high utilisation rate. The location of the plant determines the labour costs, electricity prices, land tariffs and access to transport and storage.

The cost of capturing CO₂ can vary between EUR 13-22⁴ per tonne of CO₂ for industrial processes generating highly concentrated CO₂ streams (such as ethanol production and natural gas processing) to EUR 35-105 per tonne of CO₂ for processes with medium concentration gas streams, such as cement production and coal power generation. The large range in costs also reflects the fact that while some CO₂ capture technologies are commercially available, others are still in development and hence, prohibitively expensive (IEA, 2021c). Figure 6 indicates the cost of carbon capture for the major sectors based on process modelling for amine-based capture and the economies of scale in which it can be applied.

⁴ Original values in USD. 1 USD= 0.87738 EUR (Source: oanda.com. Accessed on 13/01/2022. Available at: <https://www.oanda.com/>).

Figure 6. Cost of carbon capture by sectors.



Source: (Global CCS Institute, 2021b)

The cost of transport can also vary greatly on a case-by-case basis, depending mainly on CO₂ volumes, geography, transport distances and storage conditions. In the United States, for example, the cost of onshore pipeline transport is between EUR 1.8 and EUR 12/t CO₂ (BNEF, 2020). In Europe, ZEP estimated the typical costs for a short onshore pipeline (180 km) and a small volume of CO₂ (2.5 Mtpa) to be just over EUR 5/t CO₂, reducing to approximately EUR 1.5/t CO₂ for a large system (20 Mtpa). Land transport by trucks is more cost effective than pipelines for quantities less than 1.7 Mtpa and intermittent demand (BNEF, 2020). Offshore pipelines are more expensive compared to onshore ones. Companies capturing CO₂ near the coast have the advantage of reduced shipping costs. For large transport volumes of CO₂ (20 Mtpa) by pipeline, costs are estimated to be approximately EUR 11/t CO₂ for 180 km; EUR 12/t CO₂ for 500 km and nearly EUR 16/t CO₂ for very long distances (1 500 km), including liquefaction. For a smaller volume of CO₂ (2.5 Mtpa), costs for 500 km are just below EUR 15/tonne, including liquefaction (ZEP, 2011a). Repurposing existing oil and gas infrastructure to transport CO₂ may be cheaper than building from scratch (IEA, 2023), ensuring there is sufficient remaining lifetime to operate.

Regarding CO₂ storage, the cost range is large, spanning EUR 1 to EUR 20 per tonne. On the assumption that the cheaper available storage sites will be developed first, ZEP has estimated that storage in the early commercial phase will cost EUR 2-12/t as defined for onshore saline aquifers. However, onshore CO₂ storage has been largely prohibited in Europe, thus, a more realistic assumption is to consider CO₂ storage costs offshore (for example in depleted oil gas reservoirs), which are in the range of EUR 2-20 per tonne (ZEP, 2011a). Long-term maintenance and oversight must be also considered. The need for continuous monitoring, evaluation and

planning means that storage site developers must commit substantial amounts of financial, human and technical resources to storage operations, beyond eventual closure.

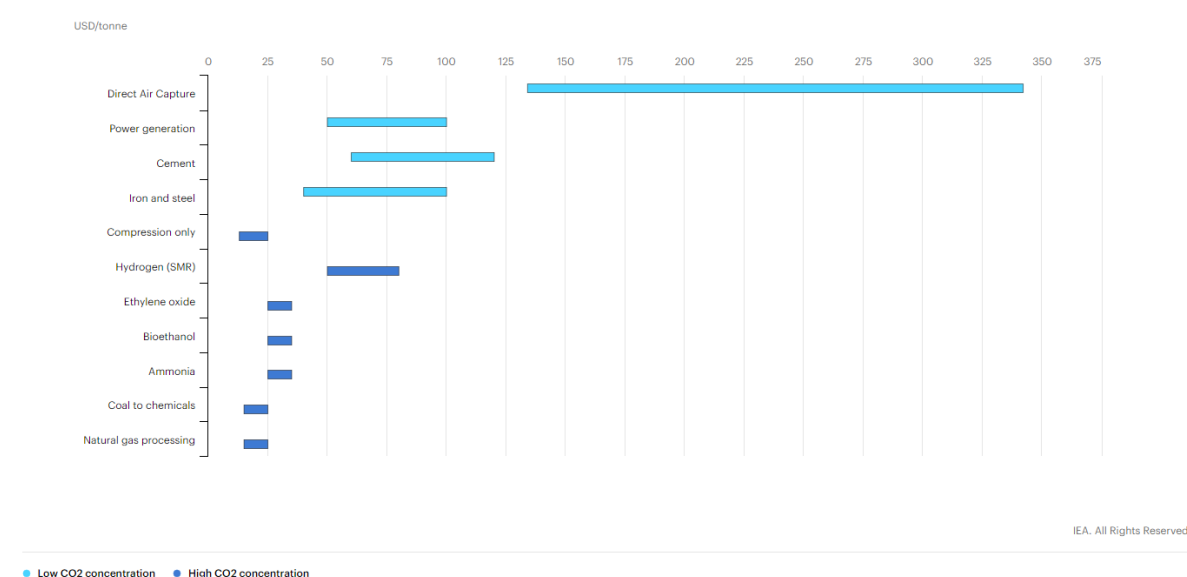
Captured CO₂ may generate additional streams of revenue when valorised in products. However, its potential utilisation depends on the price of CO₂. In the US, projects create revenue by selling CO₂ to be injected into oilfields to enhance production (enhanced oil recovery (EOR)). CO₂ for EOR can be often supplied at EUR 18.6⁵ t/CO₂, but prices may vary greatly, reaching EUR 140-280/t for food grade applications (BNEF, 2020).

Cost estimates for BECCS also vary significantly depending upon the sector of application (EUR 64–98/t CO₂) (IRENA, 2021). Prices for DAC currently range anywhere between EUR 93 and 2 144/t CO₂ (BNEF, 2023). There is no clear pricing trend, with larger DAC providers not necessarily being cheaper, and nor do certain technologies cluster around a specific price. Many suppliers claim costs can be brought down to EUR 280-466/t CO₂ by 2030 (BNEF, 2023). We note that DAC may be less expensive than transporting small amounts of CO₂ over distances greater than 500 km from a distant capture facility (BNEF, 2020).

Already in 2011, ZEP suggested that the capital intensity of fossil power plants will increase significantly with the addition of CCS (ZEP, 2011a). Boundary Dam CCS is the first commercial-scale project in the world combining post-combustion CCS with coal-fired power generation, operating since 2014. The project cost EUR 868 million (CAD⁶ 1.24 billion), of which EUR 420 million (CAD 600 million) was for CCS and the rest for modernising the plant (National Coal Council, 2015). However, published results from this project expect cost reductions as high as 67% for a further project to come online (International CCS Knowledge Centre, 2018). 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). The annual operating expenditure (OPEX) is around 4-5% of CAPEX for each part of the chain (Gassnova, 2022).

When it comes to levelised cost, Figure 7 shows values for CO₂ capture by sector and initial CO₂ concentration. This ranges from EUR 44 to EUR 88 (USD 50-100) t/CO₂ for the power generation sector.

Figure 7. Levelised cost of CO₂ capture by sector and initial CO₂ concentration, 2019



The cost of CO₂ capture from sources such as coal-fired power generation has been reducing over the past decade and is projected to decrease 50% by 2025 compared to 2010 (Global CCS Institute, 2021b). However, the levelised cost is sensitive to fuel price (for example, coal and gas). The current rise of coal and gas prices would obviously have an impact on the cost estimations.

⁵ Original values in USD. 1 USD= 0.93211 EUR (Source: oanda.com. Accessed on 07/09/2023. Available at: <https://www.oanda.com/>).

⁶ 1 CAD= 0.69992 EUR (Source: oanda.com. Accessed on 13/01/2022. Available at: <https://www.oanda.com/>).

In reality, 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 EUR 93 (USD₂₀₂₀ 105) per t CO₂ (International CCS Knowledge Centre, 2018). The Petra Nova CCS project in the United States, which started operation in 2017, achieved capture and compression costs of approximately EUR 62 (USD₂₀₂₀ 70)/t CO₂ (Petra Nova Parish Holding LLC, 2017). We note that Petra Nova plant didn't meet its capture goals, hence the real cost per ton would be higher.

Therefore, lessons relevant to plant design, maintenance, operation and financing are highly valuable to subsequent projects and may lead to significant cost reductions.

The IEA expects capture costs in power generation to be reduced by the adoption of various emerging technologies. For instance, electrochemical separation is projected to lower the LCOE with CO₂ capture by 30%; chemical absorption with advanced solvents and configurations, membrane separation, pressure swing adsorption (PSA) and temperature swing adsorption (TSA), calcium looping, and cooling and liquefaction by between 10% and 30%; and pressurised oxy-fuel combustion, chemical looping combustion and sorption-enhanced water gas shift by up to 10%. These cost reductions are based on the current development trajectory of these technologies, which have recently moved from the prototype to the demonstration phase. For CCUS applied to industrial process emissions, capture cost reductions can be achieved not only through innovative technologies, but also through strategies such as capturing from units emitting larger volumes of CO₂ (e.g. recovery boilers rather than lime kilns for pulp and paper production) and recovering excess heat (e.g. in steel production) (IEAGHG, 2019b, 2019a; IEA, 2020b).

The POTEnCIA energy system model estimates that in the power sector, renewable sources are expected to decarbonise the majority of the EU power supply by 2050, but conventional dispatchable power generation will also be needed to support intermittent wind and solar generation. The application of CCS to biomass-fired power plants is expected to add the most significant capacities from 2030 onward. Other CCS applications include gas and coal-fired power plants to enable faster and full decarbonisation of the grid. In the production of hydrogen from fossil fuels, CCS can also help meet the global targets for transitioning to low-carbon fuels.

For transport and storage, the main route for reducing costs is by exploiting economies of scale (IEA, 2020a).

Full-chain CCS costs can be lower when CO₂ emissions from several sources are clustered, transported and stored using the same infrastructure. This will result in CCUS hub formation and will be critical in regions that will store CO₂ 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 (Wood Mackenzie, 2021).

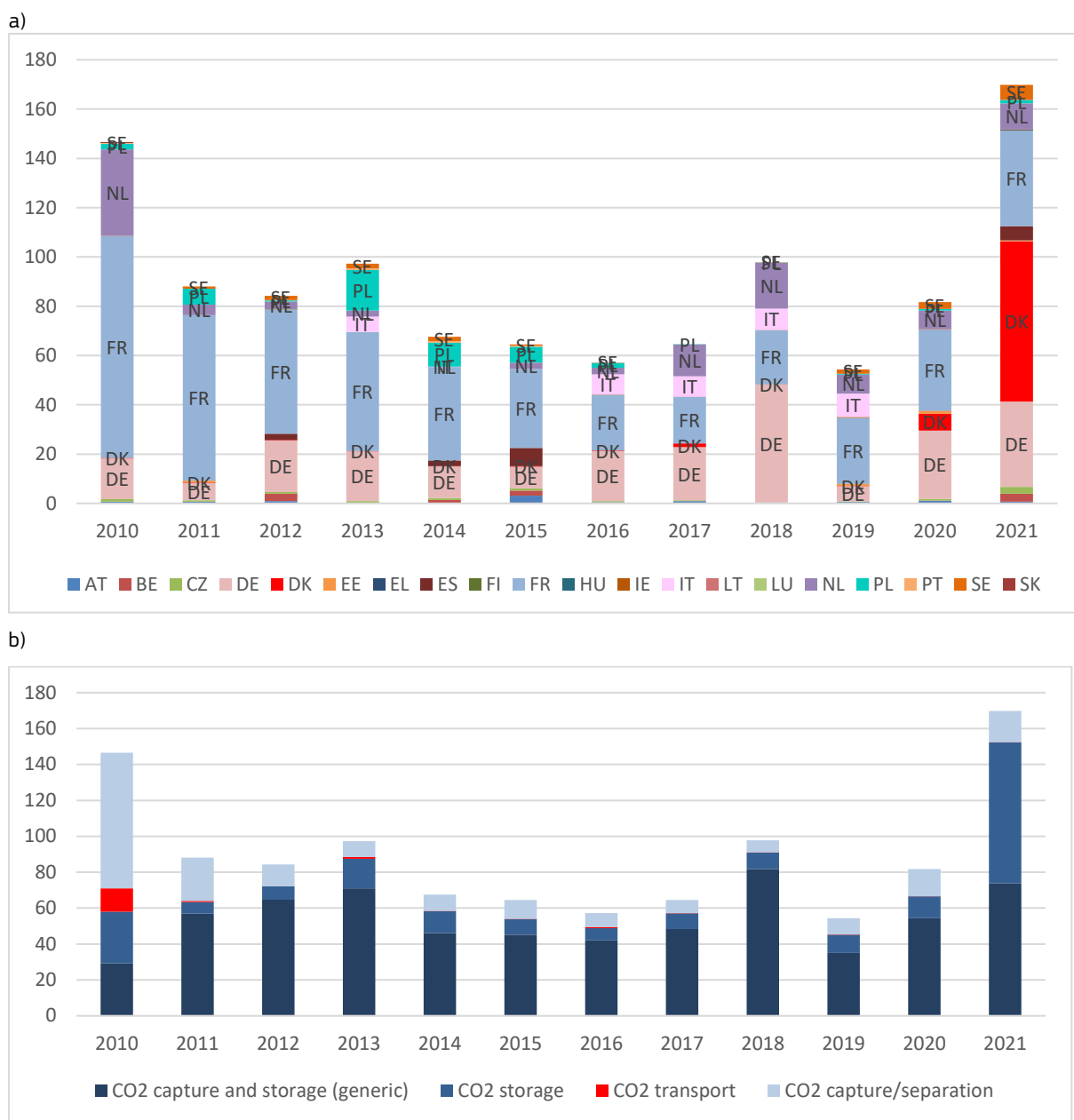
Overall, for industries with notable deployment potential, most learning is gained per added capacity. According to DNV, adding 60 full-scale new plants to the world's capacity would result in cost reductions of around 30% of today's level (Helle and Koefoed, 2018). This learning would apply globally, irrespective of location.

2.4 Public RD&I funding and investment

Public R&D 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 has been derived from an analysis conducted by the JRC using data obtained from the IEA (IEA, 2021b).

In 2021, public investment in CCUS R&D reached an 11-year maximum in the EU (Figure 9). Increased investment can also be seen in 2013 and 2018. The majority of the investments were classified generically, without specifying any part of the CCS chain. Of those which were more specific, the majority were channelled towards CO₂ storage (EUR 205.73 million), followed by CO₂ capture/separation (EUR 203.18 million) and CO₂ transport (EUR 16.12 million). In 2021, Denmark shows the highest public R&D investment, surpassing France, which was the leading country from 2010 onwards. France, Germany and the Netherlands follow based on the level of public investment attracted in 2021. This investment is focused on the area of carbon capture and utilisation, mostly for the production of chemicals.

Figure 8. a) Public R&D investment (EUR million) in CCUS in the EU by year and by MS; b) Public R&D investment (EUR million) in CCUS in the EU by year by CCUS component.

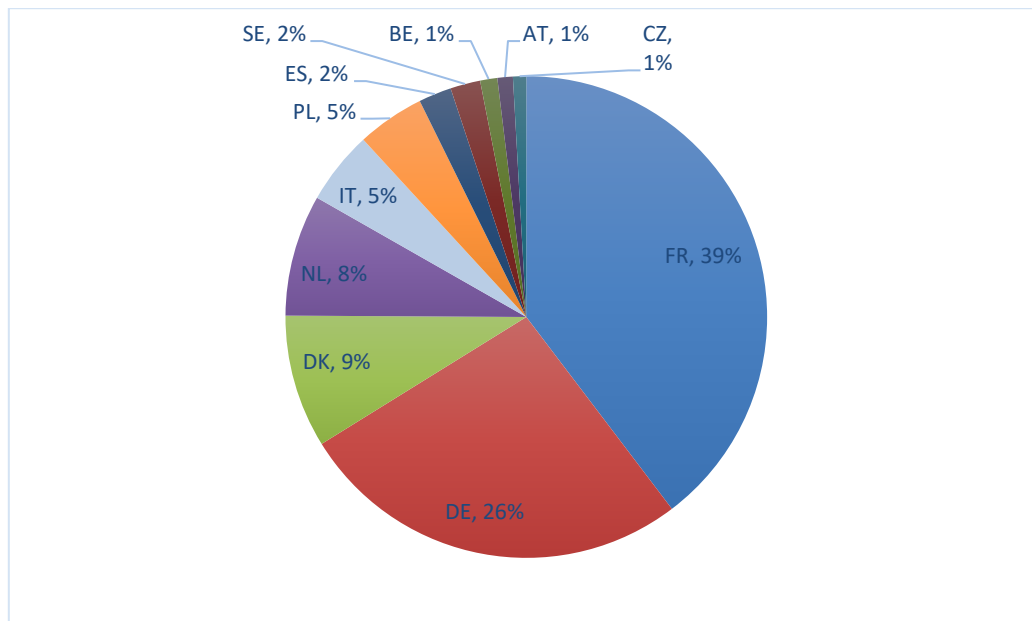


Source: JRC based on IEA

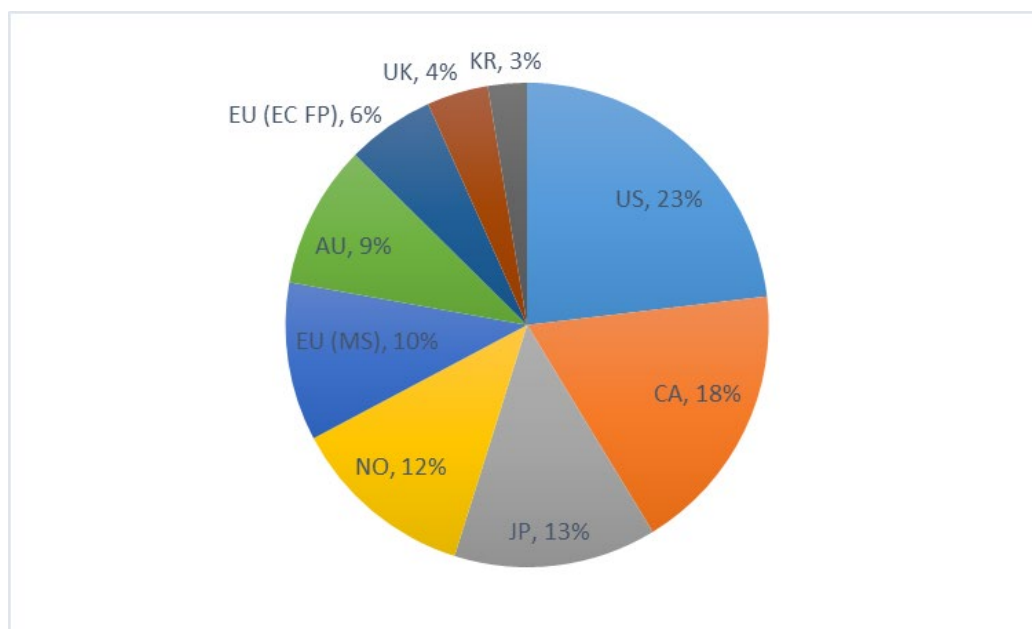
Figure 10 shows that cumulatively, between 2012 and 2021, France was the EU country with the highest share of public investment in CCUS research and development. Next was Germany (26%) and Denmark (9%), closely followed by the Netherlands (8%). Worldwide, the US (23%) and Canada (18%) have led the way in CCUS investment over the last decade. Europe ranks fifth, holding a 10% share of the global public investment made in CCUS.

Figure 9. 2012-2021 cumulative public R&D investment in CCUS in a) the EU by MS and b) globally (countries with a share of less than 1% are not illustrated in the pie chart).

a)



b)

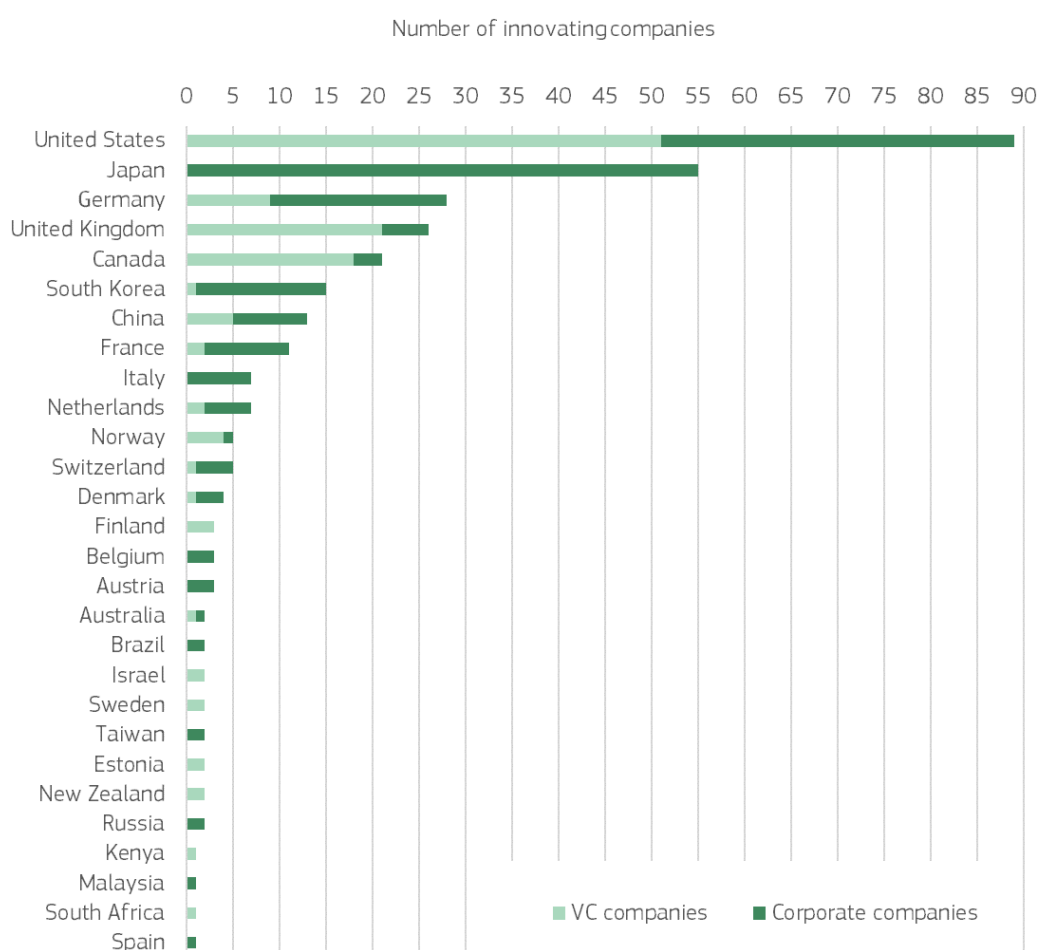


Source: JRC based on IEA

2.5 Private RD&I funding

Figure 11 provides an outlook of the countries that host the highest number of innovating⁷ companies active in the development of CCUS solutions between 2017 and 2022. The analysis includes both venture capital (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 relevant patenting activity over the period). Three countries (the US, the UK and Canada) host most of the 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 10. Venture capital (VC) and corporate companies by country, 2017-2022



Source: JRC analysis based on Pitchbook

Detailed information on the R&D spending of the private sector is very limited, particularly as regards small and medium enterprises or companies active in multiple technology areas. The following analysis is based on a JRC in-house methodology (Fiorini *et al.*, 2017; Pasimeni, Fiorini and Georgakaki, 2019) that estimates R&D

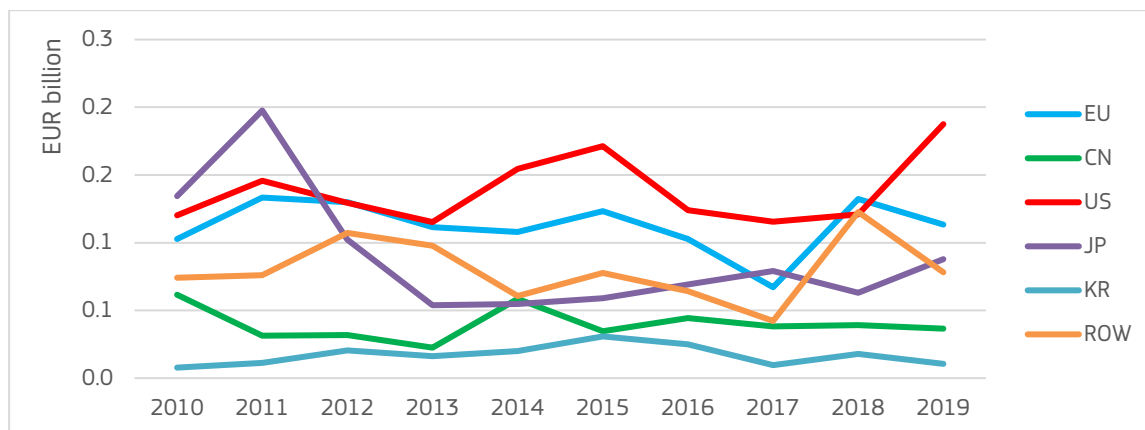
⁷ Innovating companies comprise a selection of corporate companies and VC companies. VC companies include pre-venture (that have received Angel or Seed funding, or are less than 2 years old and have not received funding) and venture capital companies (that have, at some point, been part of the portfolio of a venture capital firm). Corporate companies include subsidiaries of top R&D investors (from the EU Industrial R&D investment Scoreboard) that have a relevant patenting activity.

expenditure in the private sector. This approach is then applied to assess private R&D spending in Europe in the context of climate change mitigation technologies.

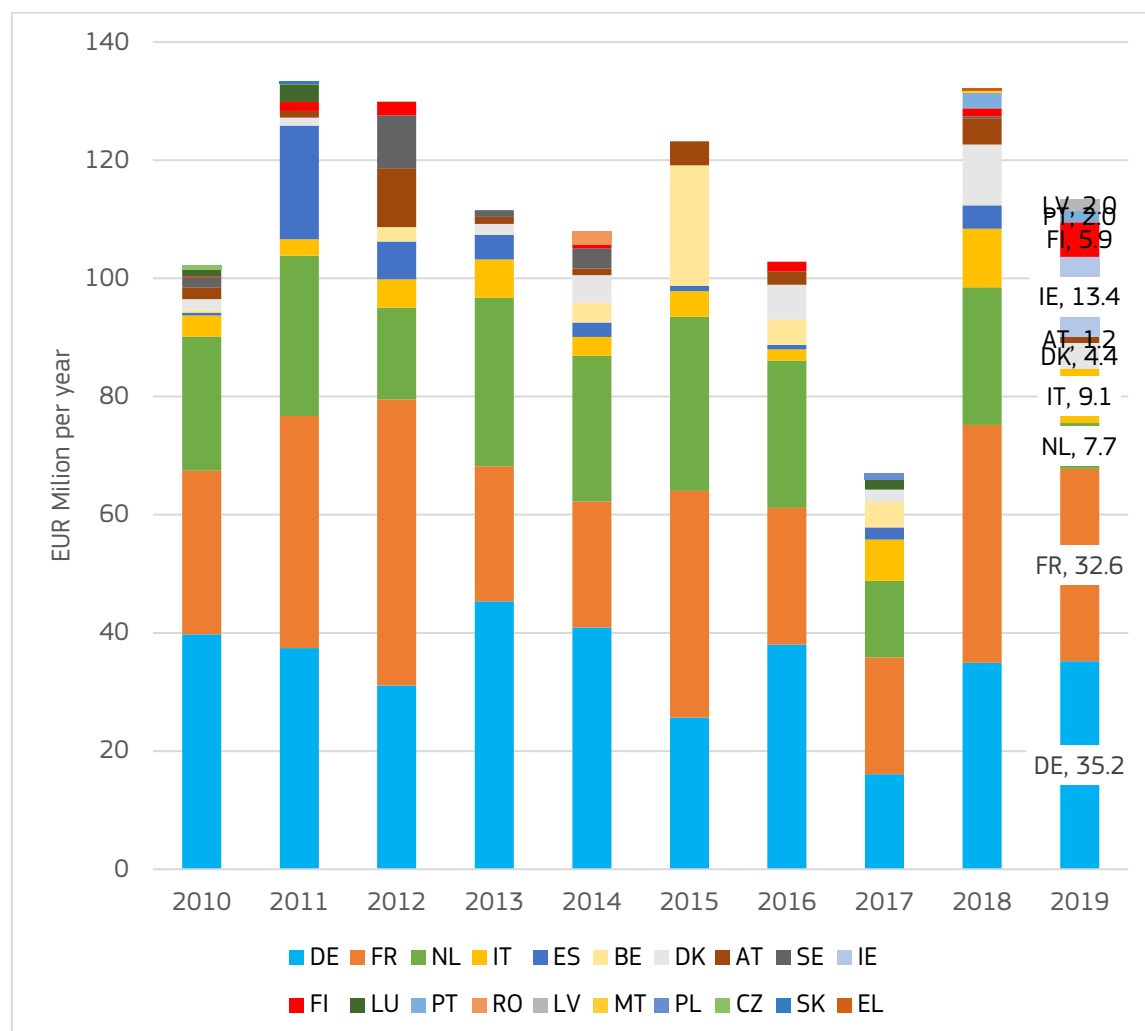
Our analysis indicates that since 2012, the US has been the top investor in private R&D. The EU ranks second with a relatively stable level of funding for private RD&I, aside from a decrease in 2017 (Figure 12a). Within the EU, over the period of time analysed, Germany, France, the Netherlands, Italy and Spain are the top five countries with the largest private R&D investment in CCUS (Figure 12b).

Figure 11. 2010-2019 private R&D investment (EUR million/year) in CCUS a) globally and b) in the EU by MS.

a)



b)



Source: JRC

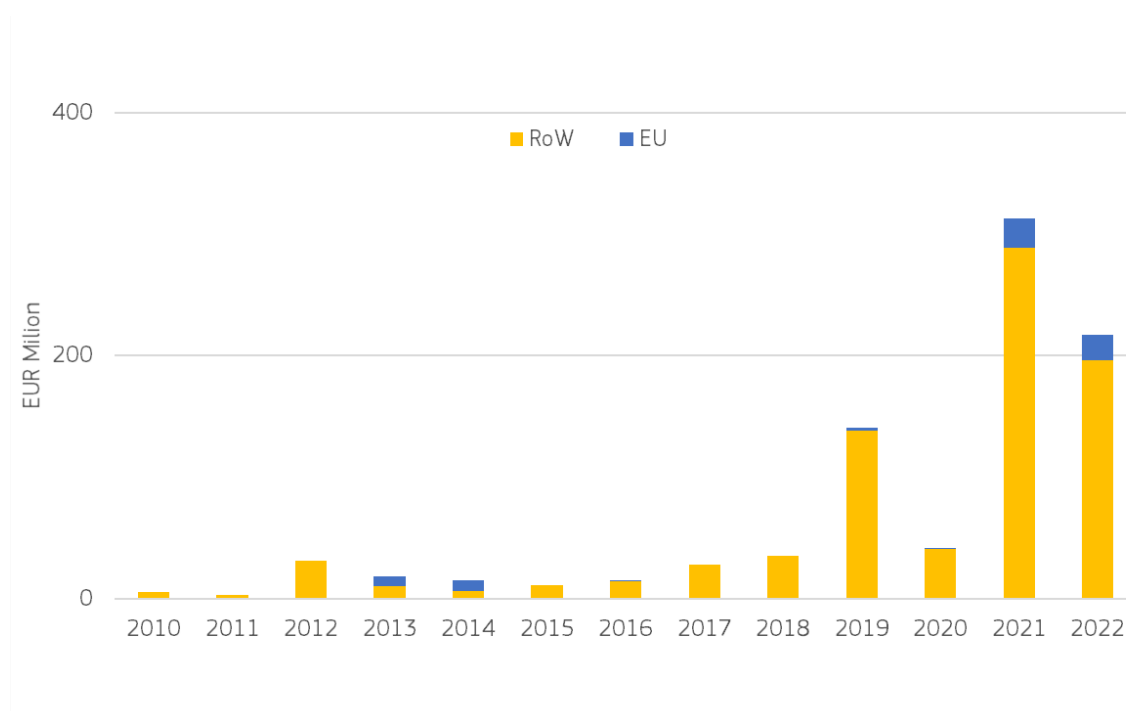
In addition to public and corporate RD&I financing, venture capital (VC) is crucial for technology development as it provides additional equity funding to innovative start-ups and project developers and supports their growth.

In 2022, global VC investment has again more than doubled compared to 2021, reaching a new all-time high of EUR 1.5 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 investment. Similarly, over the period 2017-22, the US has been the leader, capturing 41% of all VC investment in CCUS. Ranked second is Switzerland, which has captured a growing share of investment (24%) through the largest deal announced in DAC, via the sole company Climeworks. This is followed by the UK (12.6%) and Canada (10.3%). Germany ranks fifth and is by far the leading EU country with 8.2% of global investment. This is the direct result of a large deal that SUNFIRE secured for expanding markets for green hydrogen derived from renewable sources like wind and solar and applies CO₂ capture for renewable syngas production.

Over 40% of VC companies were founded after 2020, with a majority in the US and only a few in the UK and EU. These companies account for approximately 10% of global VC investment from 2017-2022.

From 2017 to 2022, global early stage⁸ investment amounted to EUR 775 million. On the one hand, early-stage investment outside the EU (Figure 13) displays 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 remains stable in 2022 and the EU improves its competitive position, capturing 6% of investment over the 2017-2022 period. We note also that the identified grant funding per EU VC company is less than half of the amount secured by those elsewhere in the world.

Figure 12. Early-stage VC investment by region, 2010-2022 (EUR million)



Source: JRC based on Pitchbook

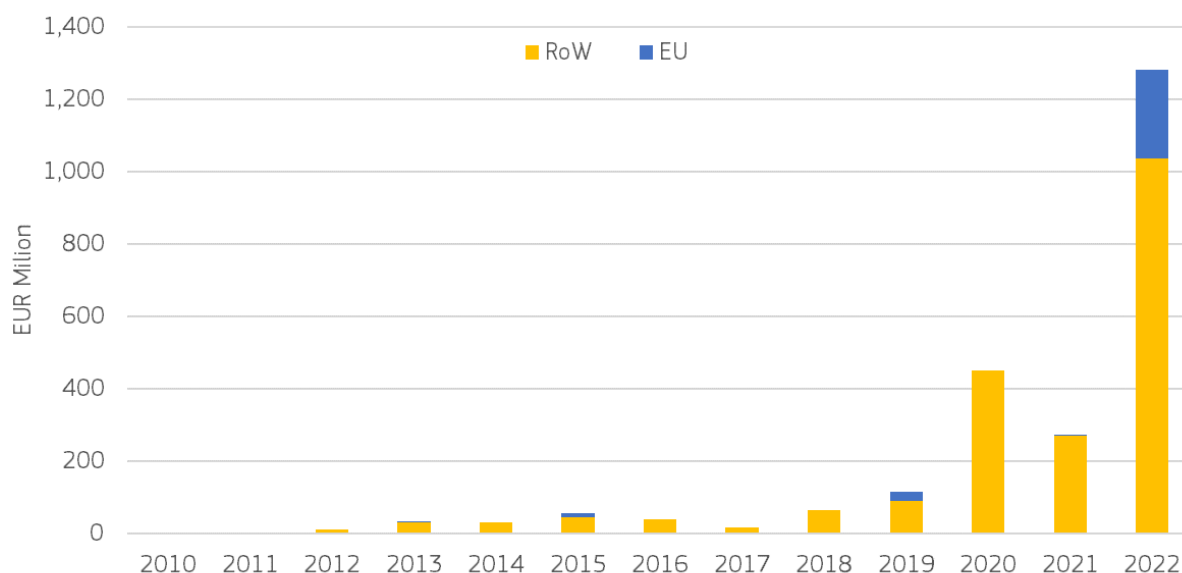
Global later-stage⁹ VC investment amounted to EUR 2.2 billion from 2017 to 2022. Over this period, the EU captured 13% of later stage VC investment, boosting its competitiveness. We note that in 2022, the global later

⁸ The early-stage indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed, Early stage VC investment as well as public grants.

⁹ 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.

stage investment increased five-fold compared to 2021, supported by a larger number of deals in both the EU and the ROW (Figure 14).

Figure 13. Later-stage VC investment by region, 2010-2022 (EUR million)



Source: JRC based on Pitchbook

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 (PATSTAT¹⁰) and follows a method developed by the JRC¹¹. Patents on CCUS are identified using class Y (specifically subclass Y02C and Y02P) of the Cooperative Patent Classification (CPC) System, a partnership between the 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. 2019 is the last year for which complete data are available, but our analysis also includes partial data from 2020.

From 2018 to 2020, the EU had 198 inventions in total¹², with 66% being high-value¹³ - the highest percentage compared to the other regions and the rest of the world (ROW) (Figure 15). Despite increased inventive activity in China (644 total inventions), the high-value inventions account for only 4%. The US, EU and Japan have the most high-value inventions between 2009 and 2020 (Figure 16). Among EU Member States, France has the highest number of high-value inventions, followed by Germany and the Netherlands (Figure 17).

Figure 18 shows the companies that have been leading in high-value inventions from 2018 to 2020, globally (a) and in the EU (b). L'air Liquide (FR) is the leading company in both global and EU top companies. Linde (DE)

¹⁰ EPO - PATSTAT. Worldwide Patent Statistical Database

¹¹ 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

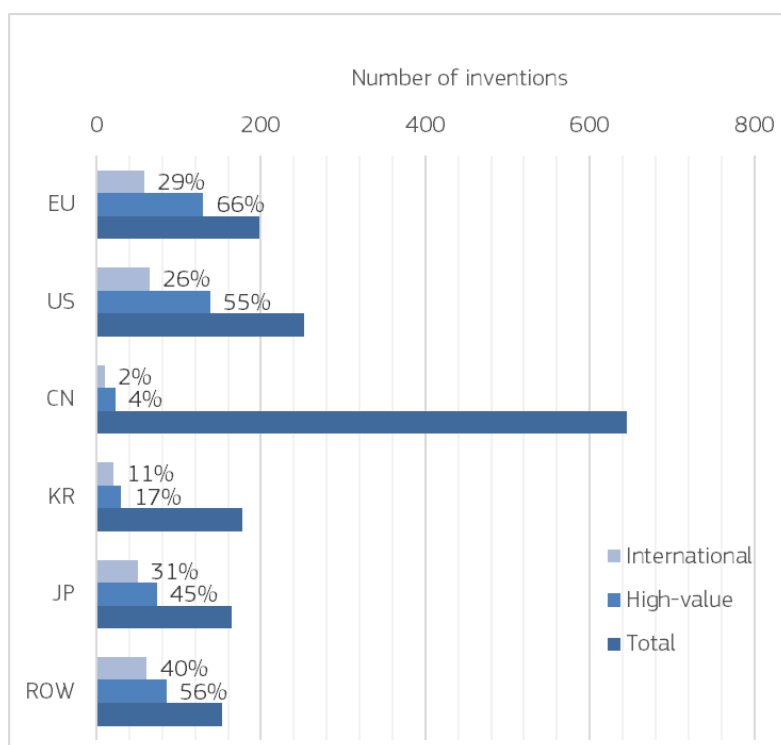
Pasimeni, F. (2019). SQL query to increase data accuracy and completeness in PATSTAT. World Patent Information, 57, 1-7. <https://doi.org/10.1016/j.wpi.2019.02.001>

¹² The total includes international, national, high-value patents etc.

¹³ High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.

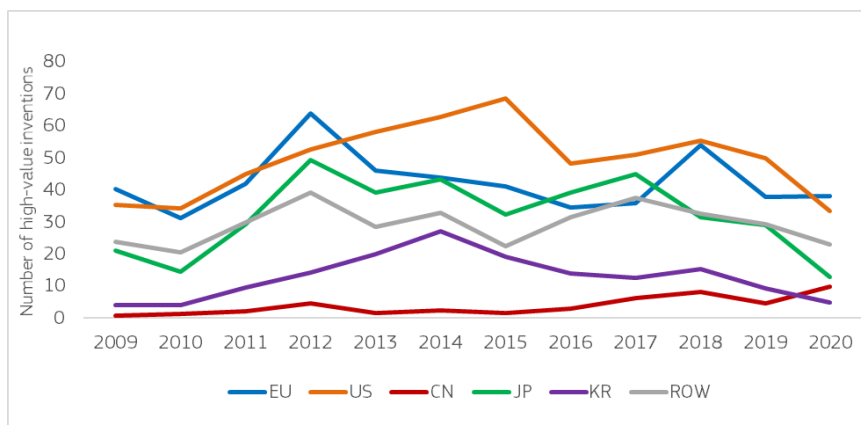
ranks second in the EU and sixth in the world in the top 10 companies based on the number of high-value inventions.

Figure 14. Number of inventions and share of high-value and international activity (2018-2020)



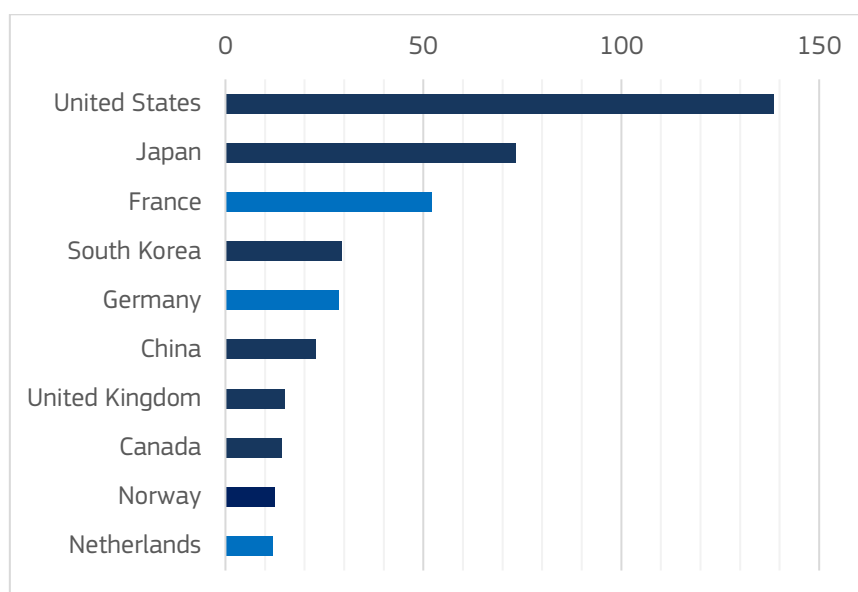
Source: JRC based on EPO Patstat

Figure 15. Number of high-value inventions and international activity (2009-2020)



Source: JRC based on EPO Patstat

Figure 16. High-value inventions – Top 10 countries (2018-2020)

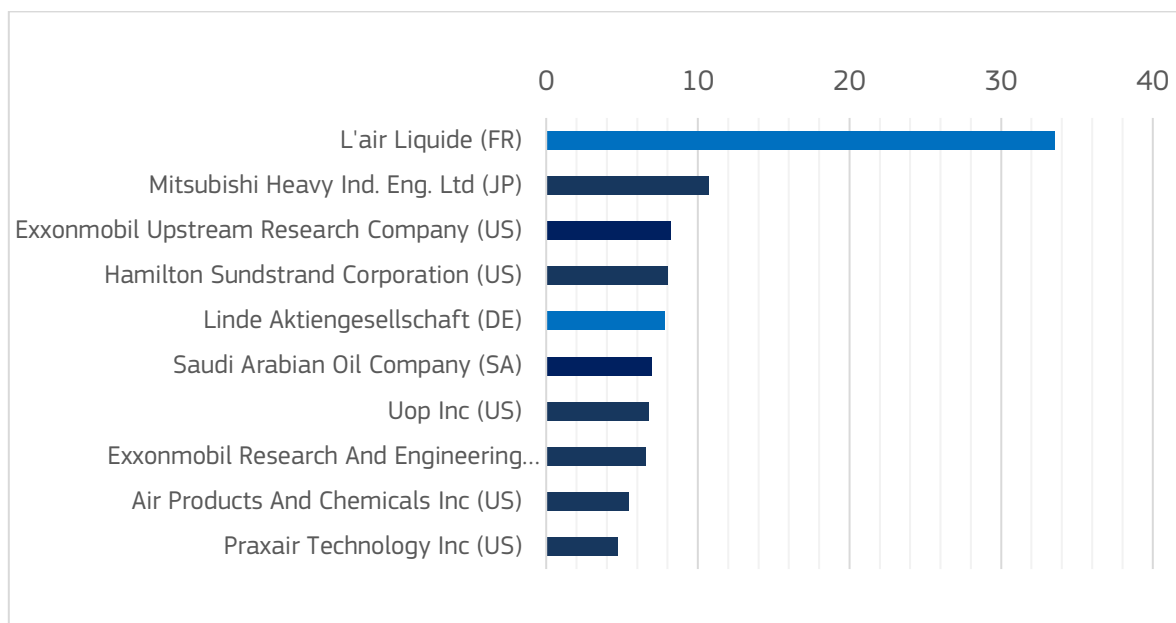


Source: JRC based on EPO Patstat

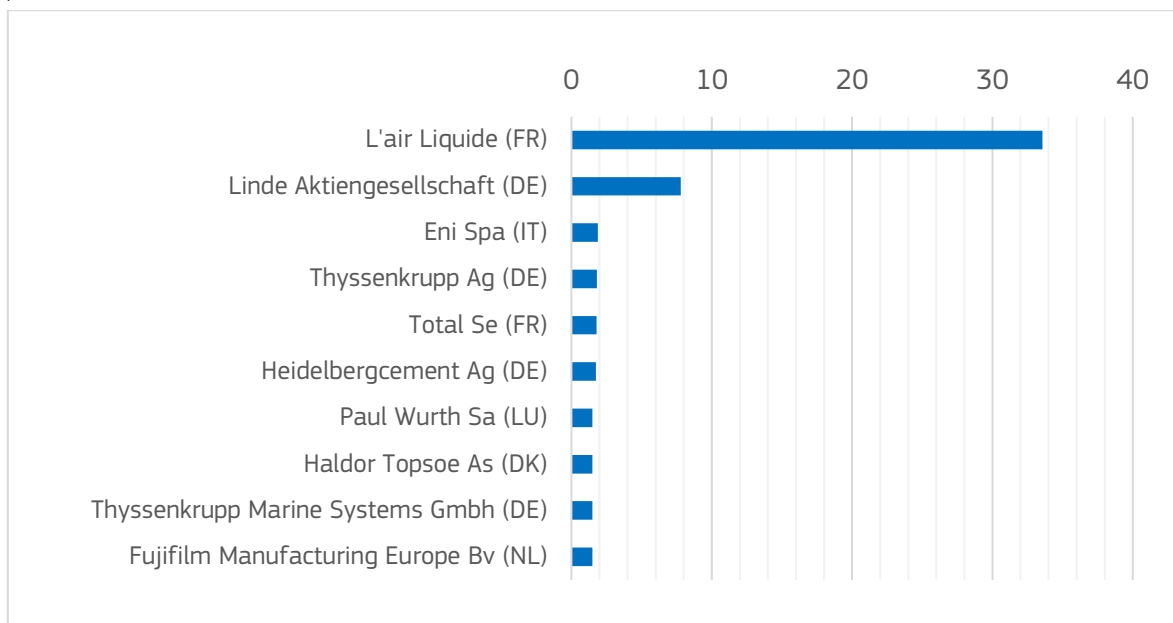
Note: Dark blue shows non-EU countries, light blue shows EU countries.

Figure 17. High-value inventions (2018-2020), a) global top 10 companies and b) EU top 10 companies

a)



b)

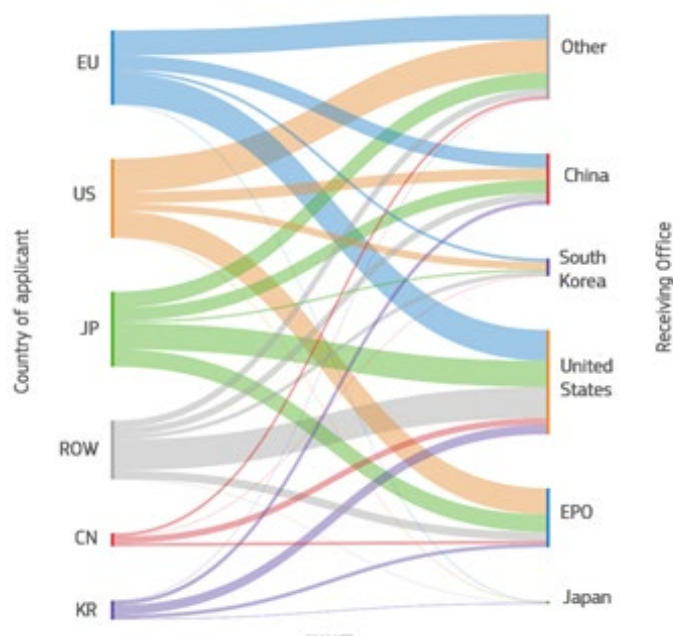


Source: JRC based on EPO Patstat

Note: Dark blue shows non-EU organisations, light blue shows EU organisations.

The EPO (European Patent office) and the US and Japan offices are the top patent offices for filing. US applicants file with European as well as Chinese offices. Japanese applicants seek protection by filing mainly with the USTPO, the EPO and the Chinese Patent Office. European applicants seek to protect their inventions by filing with the US, Chinese, and other offices (Figure 19).

Figure 18. International flows of high-value inventions between major economies (2018-2020)



Source: JRC based on EPO Patstat

Note: EU represents the 27 Member States; EPO is the European Patent Office.

2.7 Scientific publication trends

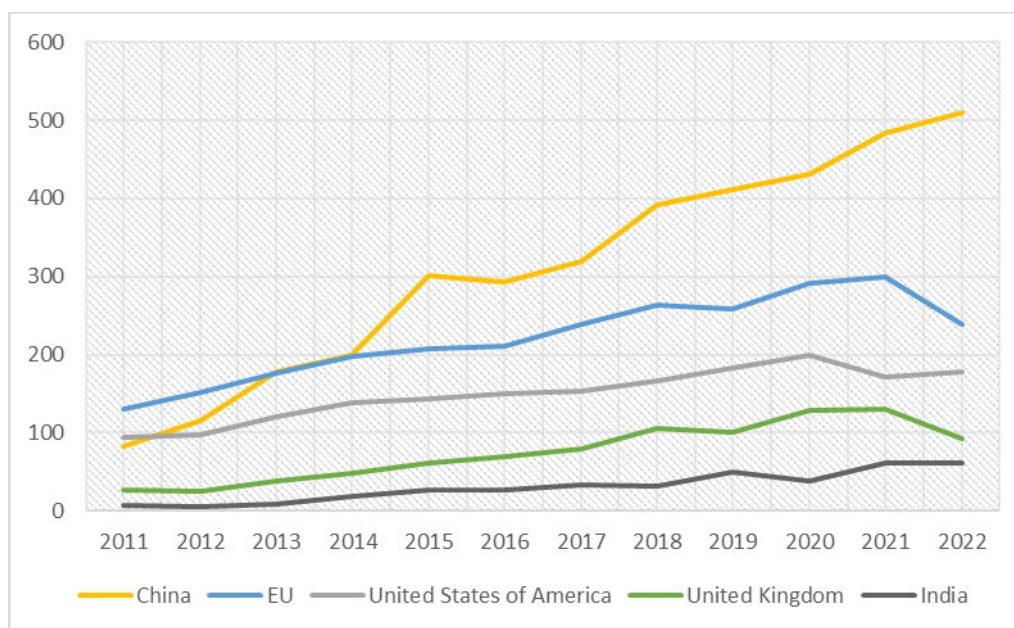
Given the potential that is attributed to CCUS in helping countries to achieve ambitious net-zero climate goals, there is growing research interest in various related fields. Bibliometric analysis is a useful tool to search through published information on a specific topic and is widely applied to evaluate academic activity quantitatively (Sarkodie and Strezov, 2019). Bibliometric analysis can be used not only to explore the characteristics, structure, and development of academic literature but also to identify quickly the research trends in a field. In general, a bibliometric analysis contains the analysis of spatial and temporal trends, disciplines and journals, institutions, authors, citations, and keywords (Wei, Mi and Huang, 2015).

To identify bibliometric trends in this study, we used the JRC Tools for Innovation Monitoring (TIM) Scopus database.¹⁴ The keywords used to create the datasets were based on the technology classification presented in Table 1.

Publications dealing with CO₂ capture have been steadily increasing over the last eleven years. The EU led the way on the number of peer-reviewed articles per year until 2013, but China has since taken over (Figure 20a). Within the EU, Spain, Italy, Germany, France and the Netherlands have been the top five countries in peer-reviewed scientific publications (Figure 20b).

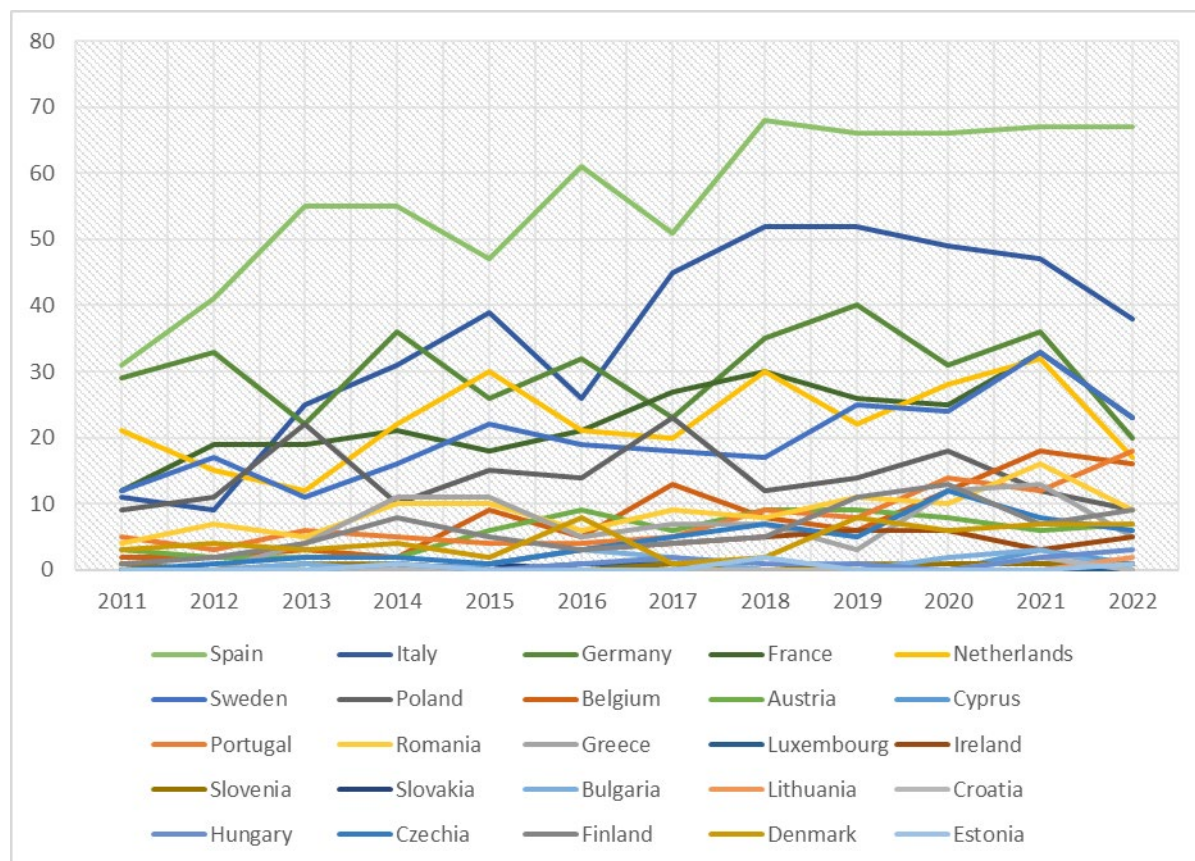
Figure 19. Number of peer-reviewed articles in CO₂ capture per year 2011-2021 a) in the top 5 countries of the world b) within EU countries

a)



¹⁴ TIM is a series of analytics tools that enables to support policymaking in the European Institutions in the field of innovation and technological development. It is available at: www.timanalytics.eu

b)



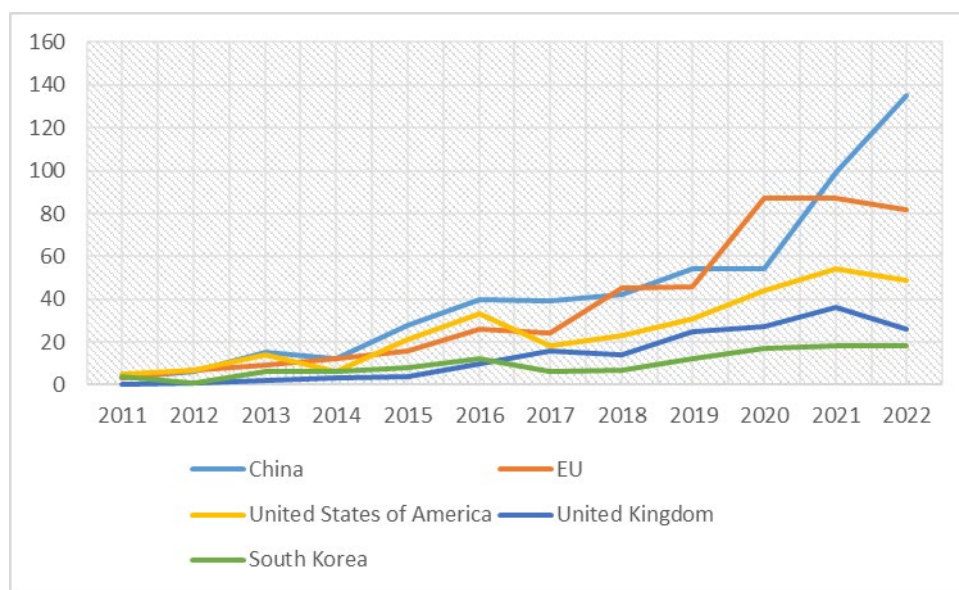
Source: JRC TIM

Regarding CO₂ capture-specific technologies, adsorption and absorption dominate, with China having the lead since 2012 and 2015, respectively. In 2022, publications from China in adsorption reached 320. Far fewer articles are published on high temperature looping and membranes. In recent years, the EU and China have been alternating in the leading position publishing on high temperature looping. In 2022, China had 33 articles published and the EU 26. On membranes, China had 29 and the EU 9.

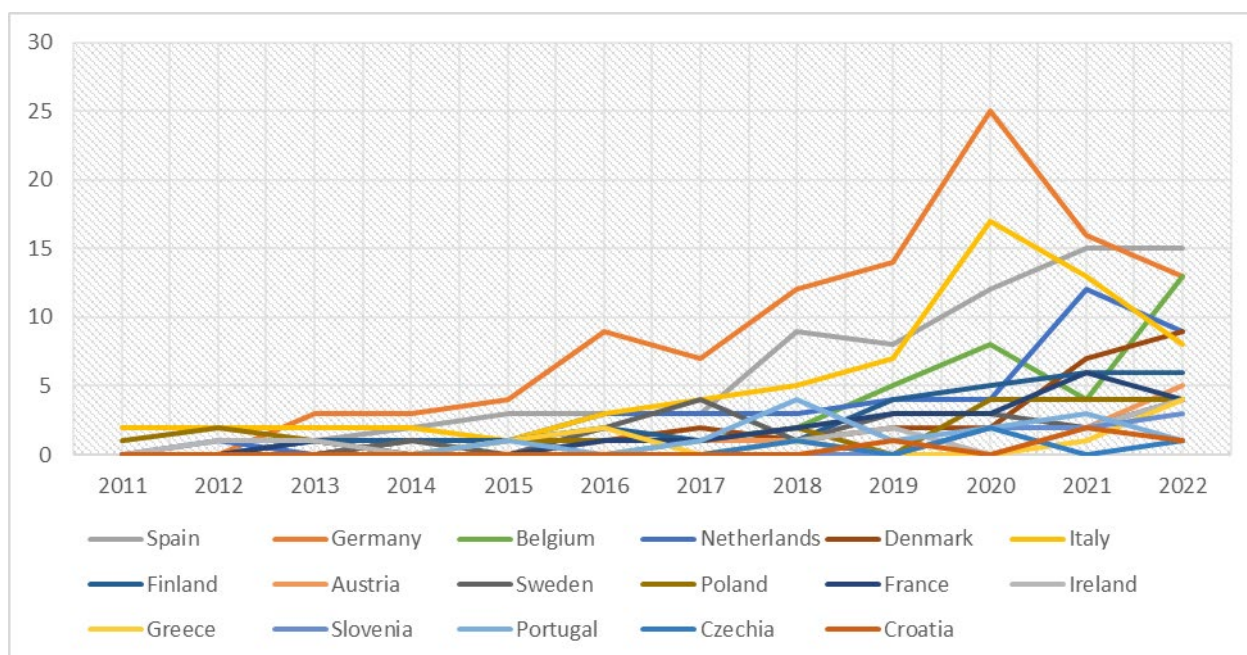
China produced the greatest number of publications on CO₂ utilisation until 2018. Since then, it has taken turns with the EU (Figure 21a). In 2022, China had 135 articles published and the EU 82. Among Member States, Germany led from 2013 to 2021, followed by Spain and Italy. In 2022, Spain surpassed Germany (Figure 21b).

Figure 20. Number of peer-reviewed articles in CO₂ utilisation per year 2011-2021 a) in the top 5 countries of the world, b) within EU countries

a)



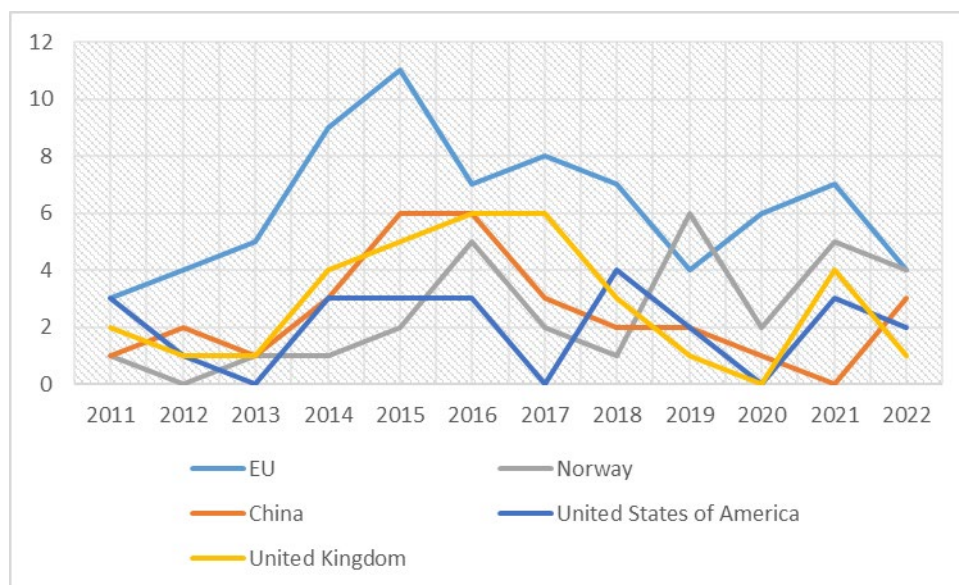
b)



Source: JRC TIM

On CO₂ transport, the EU and Norway are leading in peer-reviewed articles, with France having the highest number of published papers. In 2022, France published four articles on the topic, followed by the Netherlands with three articles (Figure 22).

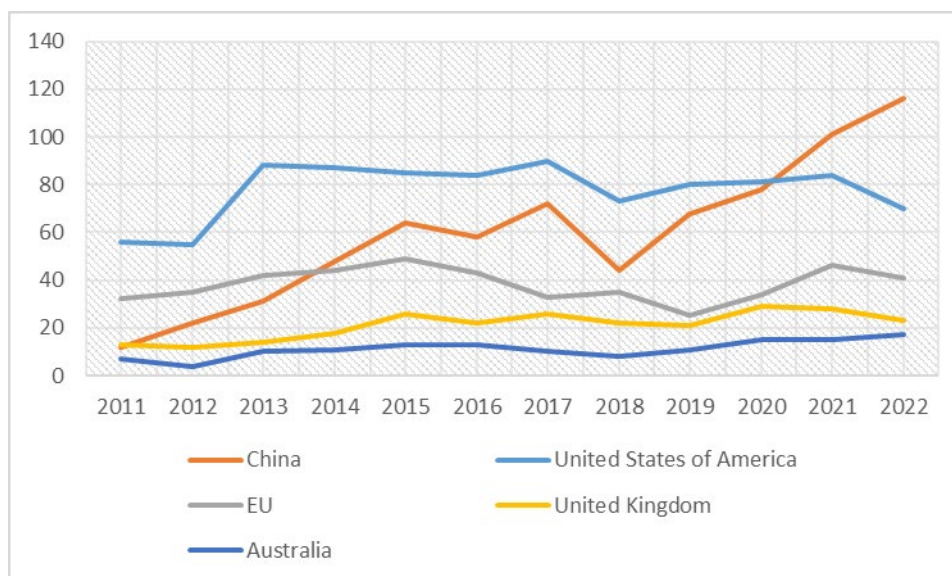
Figure 21. Number of peer-reviewed articles per year 2010-2022 in CO₂ transport in the top 5 countries of the world



Source: JRC TIM

On CO₂ storage, the USA was the country with the highest number of publications until 2020 when China surpassed it. In 2022, China had 116 relevant publications, while the USA had 70, respectively. The EU remains far behind with only 41 CO₂ storage peer-reviewed articles published in 2022 (Figure 23). France, Spain, Germany, Italy and Sweden are the countries with the highest numbers within the EU with 12, 7, 5, 4 and 4 articles, respectively.

Figure 22. Number of peer-reviewed articles per year 2011-2021 in CO₂ storage in the top 5 countries of the world



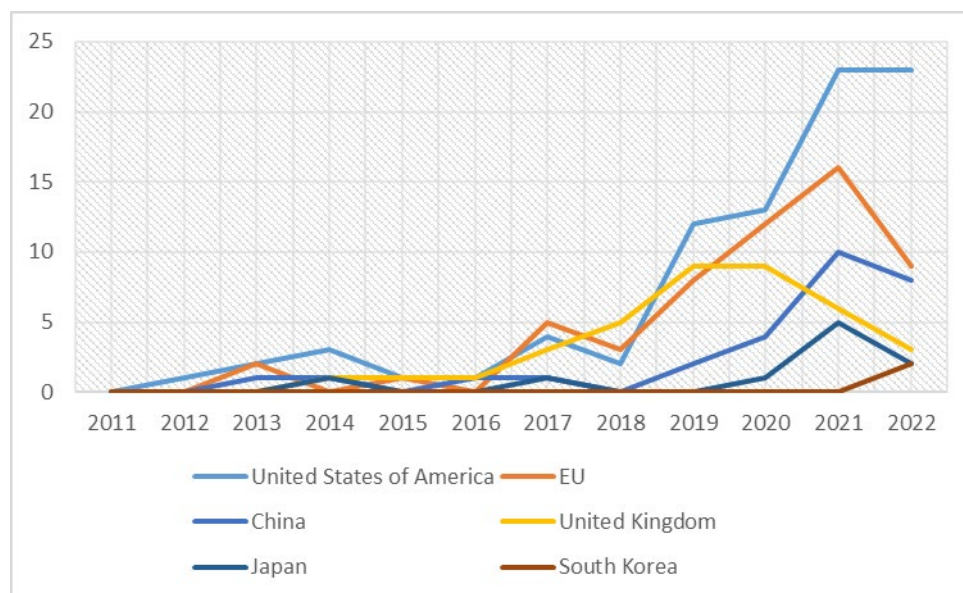
Source: JRC TIM

Peer-reviewed publications in technological carbon dioxide removal solutions such as bioenergy with carbon capture and storage (BECCS) as well as DAC have increased substantially since 2017. This may be due to the fact that carbon dioxide removals have gained significant policy support – the European Climate Law requires that greenhouse gas (GHG) emissions and removals are balanced within the European Union at the latest by 2050 with the aim to achieve negative emissions thereafter.

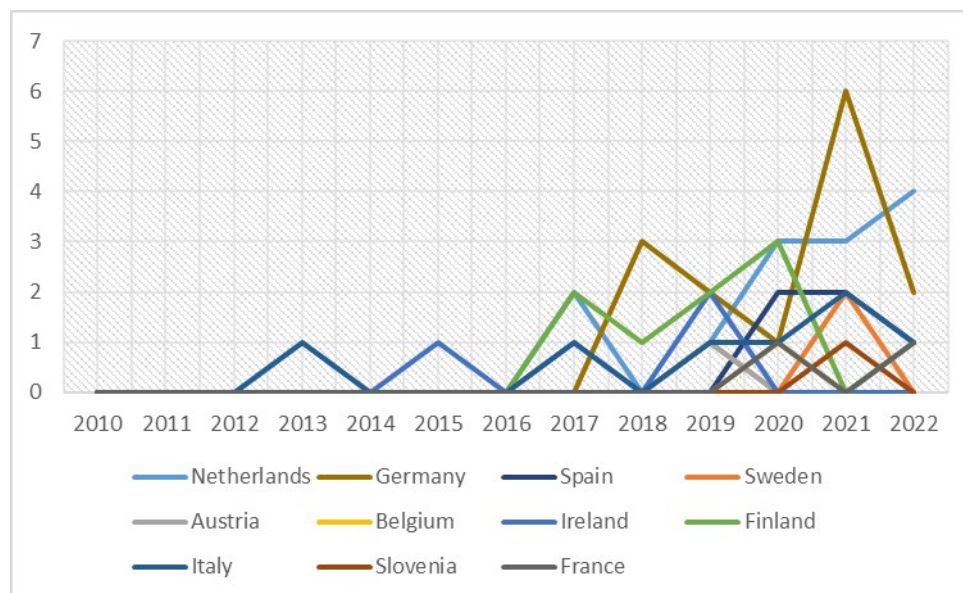
In 2022, the USA, EU, UK, China, Japan and South Korea had the highest number of DAC peer-reviewed publications (Figure 24a). In the EU, the Netherlands (4), Germany (2), Austria (1), France (1), Finland (1), Italy (1) and Spain (1) were the countries with the most published DAC peer-reviewed articles in 2022 (Figure 24b).

Figure 23. Number of peer-reviewed articles per year 2011-2021 in DAC a) in the top 5 countries of the world and b) within EU countries

a)



b)



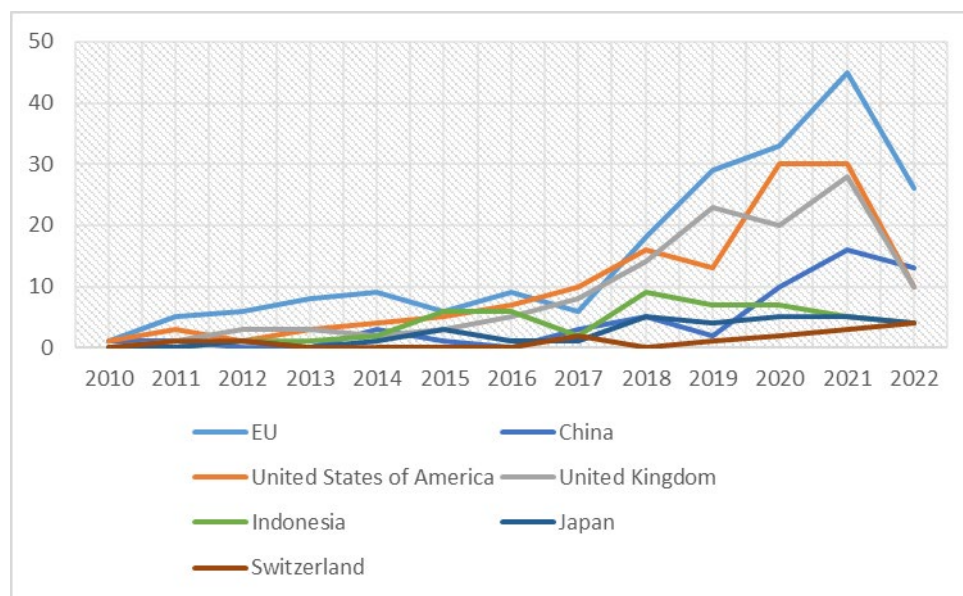
Source: JRC TIM

For BECCS, in 2022, the top five countries hosting institutions publishing peer-reviewed articles are the EU, US, UK, China, Indonesia, Japan and Switzerland (Figure 25a). We note that the US and UK as well as Indonesia, Japan and Switzerland have the same number of published peer-reviewed articles. Sweden (8), the Netherlands

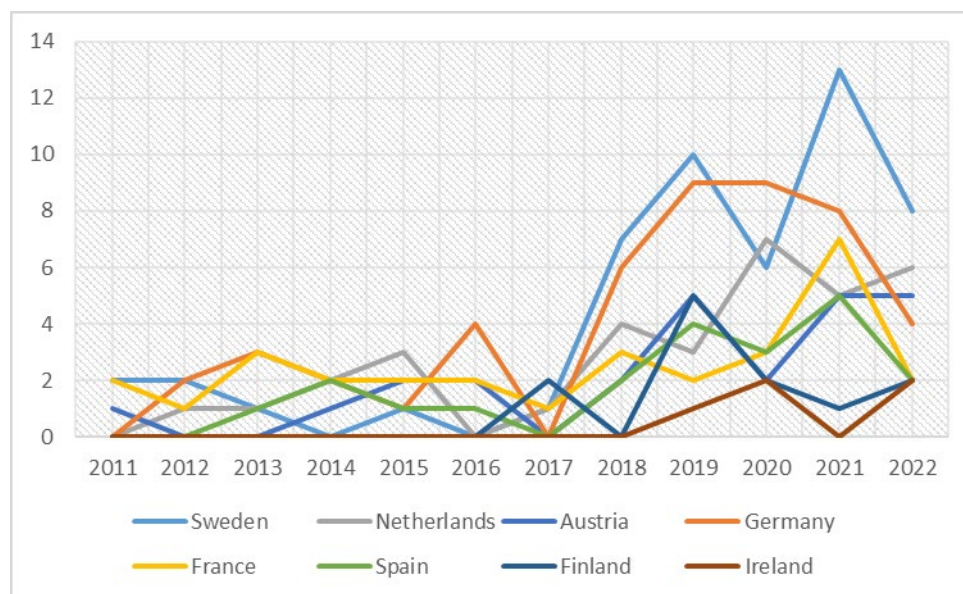
(6) and Austria (5) are followed by Germany (4) and Finland, France, Spain and Ireland with two articles each (Figure 25b).

Figure 24. Number of peer-reviewed articles per year 2011-2021 in bioenergy with CCS (BECCS) a) in the top five countries of the world and b) within EU countries

a)



b)



Source: JRC TIM

Citation impact is a measure of how many times an academic paper in a journal, book or author is cited by other paper, books or authors. Citation counts are used as a means to measure the impact or influence of academic work. Nowadays, citation impact indicators play a prominent role in the evaluation of scientific research (Waltman, 2016). In our analysis, we have gathered data from 2010-2022 and refined which of the papers published have been highly cited¹⁵.

¹⁵ Publication with normalized citation impact above 2,25.

Citations on research published from EU organisations rank the second highest in the world, following China which ranks first. We identified 569 highly cited articles in CO₂ capture which represent 20% of all highly cited articles published on that topic. These come mostly from Spain (174), Germany (92), Italy (74), the Netherlands (69) and Sweden (65). The most highly cited articles from the EU refer to absorption (116) and adsorption technologies (171). For absorption, these originate primarily from France (22), Italy (22), Spain (21), Germany (15), and the Netherlands (14). For adsorption, the top five countries with the most highly cited articles are from Spain (56), the Netherlands (22), Italy and Germany (19) and France (14).

The same trend is observed for CO₂ utilisation, where the 105 highly cited EU-originating papers represent 20% of the global highly cited papers, second after China. These papers come mostly from Germany (32), Netherlands (15), Spain (13), Italy and Belgium (11).

Highly cited papers on CO₂ transport related research are primarily originating from the EU (11), representing 31% of the highly cited articles in the world. Netherlands and Germany (3), Sweden and Austria (2), Italy (1), are the top 5 EU countries in highly cited papers in the domain. On CO₂ storage, the US is the leader with 163 highly cited papers, followed by China (93). The EU ranks third with 64 highly cited papers, representing 14% from the highly cited articles in this topic worldwide.

On BECCS, EU originating research comes first on highly cited articles (58) with a 29% share, followed by the UK with 43 highly cited articles representing a 22% share. These articles originate mainly from Germany (19), Sweden (15), the Netherlands (12), Austria (9), France (8) and Spain (7). When it comes to DAC, EU originating research represents 25% with 22 highly cited articles, ranking second after the US which hold a 31% share and 28 highly cited papers. The EU originating articles come mainly from Germany (7), Finland (6), the Netherlands (4), Ireland (3) and Italy (2).

With regard to participation in co-operation and networks, EU originating articles on CO₂ capture are products of collaboration mostly with the UK and Switzerland. Spain, France and the UK tend to produce more joint articles in CO₂ capture. When it comes down to specific technologies, the trend is similar for absorption but for adsorption, collaborations are more prominent within the EU, China and the rest of the world. In high temperature looping technology and membrane related publications, the EU is mostly collaborating with the USA. Within Europe, the UK, Greece and France appear to collaborate more prominently on absorption-relevant research articles. Equally, Italy, Spain and Denmark is another prominent network of collaboration on absorption-relevant topics as well as Norway, Sweden and Finland. On adsorption, collaborations are identified within the UK, Spain and Poland. Another important network appears between Italy, Norway and Sweden. Spain appears to collaborate with the UK and Switzerland on high temperature looping. Poland, Norway, France and Belgium are also important collaboration networks on this technology. Italy, the UK and Czech Republic and Germany, Spain and Netherlands are the most prominent collaboration networks on membranes.

On CO₂ transport and storage and CO₂ utilisation the EU mostly collaborates with the UK and the rest of the world with China. Within Europe, Germany is collaborating quite prominently with the Netherlands on CO₂ transport research. Similarly the UK with Sweden, Austria and Finland. Norway collaborates with the majority of the active countries in the field. On CO₂ storage related publications, prominent networks in Europe include the UK and Germany, the Netherlands and Norway, Denmark, Belgium and Spain, Switzerland and Ireland. CO₂ utilisation related research publications are identified in networks between the UK, Spain, France, Switzerland and Belgium, Germany and Denmark and Italy, the Netherlands and Norway.

On BECCS topics, the EU is collaborating mostly with the US and the UK. Collaborations in DAC, follow a similar trend with CO₂ capture, i.e. the EU is mostly collaborating with the UK and Switzerland. The UK is collaborating with the majority of the countries active in DAC. Germany, Finland and Belgium and the Netherlands, Spain, Switzerland and France are also prominent collaborating networks in DAC. On BECCS, the UK is mostly collaborating with Germany. Sweden, Norway, Finland and Austria are another group of countries forming a collaboration network in BECCS. Lastly, Spain is collaborating with Switzerland.

2.8 Assessment of R&I project developments

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

H2020 IMPACTS9 – Starting on May 2019 (finished April 2022), this project aimed to support the realisation of the SET Plan Implementation Plan on CCS and CCU.¹⁶

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.

The full list of H2020 funded projects is given in the Annex 4.

CO₂ capture and utilisation in H2020

The levelised cost of electricity (LCOE) (EUR/MWh), cost of capture (EUR/t CO₂), cost of CO₂ avoided (EUR/t CO₂), capture rate (%), energy for solvent regeneration or obtained O₂, operational hours (h) or efficiency penalty (%) have all been used as key performance indicators (KPIs) for projects.

Technology readiness level (TRL) is a common metric that has been widely used to indicate the maturity level of particular technologies. However, it is not always clearly indicated by project developers and research consortia. Making TRL reporting a prerequisite for future programmes could provide a uniform basis in analysing the results and impact of supported projects.

In terms of separation technology, sorbent facilitated capture via CO₂ adsorption has been a main focus of H2020 projects.

Projects focusing on Chemical Looping Combustion CLC received important support in framework programmes (FP) programmes. The decreased support identified within H2020 can be justified as the technology moved up to TRL 7. Calcium looping (CaL) focused projects were present within FP6 and FP7 achieving a TRL 6.

Completed H2020 projects aimed at TRL 6 for oxyfuel, chilled ammonia, membrane, sorbent and CaL in industrial processes. While there have not been breakthroughs with regard to increases in TRL, these projects have facilitated the approach of carbon capture to industry.

With regard to certain technological options and based on specific targets indicated by projects on their TRL evolution it is expected that:

- ✓ Calcium looping (CaL) and Chemical Looping Combustion (CLC) moved up to TRL 6-7.
- ✓ Process improvements bring membrane application to TRL 8 and up to TRL 9 for ceramic and polymeric membranes.
- ✓ Adsorption process using solid sorbents move up to TRL 8.

With regard to CO₂ utilisation, chemicals and fuels have been the dominant areas of study. While numerous H2020 projects are ongoing, seven projects that can be classified in this category are completed. Two of the projects mark “successful testing”. Out of the five new projects added on CO₂ utilisation, two are focusing on chemicals (C4U and SELECT CO₂) and three are focusing on fuels (EcoFuel, LAURELIN, 4AirCRAFT).

CO₂ transport, storage and monitoring in H2020

Most of the projects that have been identified within H2020 with a focus on CO₂ storage have been completed.

CARBFIX 2, completed at the time of writing this report, aimed at upscaling and optimising subsurface, in situ carbon mineralisation as an economically viable industrial option. This project was a continuation of FP7-funded CARBFIX. The project is known for the particularity to make possible and efficient the CO₂ storage in basalts.

VIRTUALSEIS – Virtual seismology: monitoring the Earth’s subsurface with underground virtual earthquakes and virtual seismometers. With this technique it is expected to monitor fluid flow in aquifers. This can be useful for CO₂ storage reservoirs. The project should be completed in 2023. The total costs for this project will be EUR 2.5 million, covered in total by EU funds.

¹⁶ 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](#)).

One new project, DISCO2 STORE, started in February 2021 and will run for four years. This project will investigate mechanical discontinuities to provide a better interpretation of their effects, as well as tools that will ensure safety in CO₂ geological sequestration operations.

Another new project, PilotSTRATEGY is investigating geological CO₂ storage sites in industrial regions of Southern and Eastern Europe. The research focuses on deep saline aquifers and will run until 2026.

Innovation Fund

The Innovation Fund supports the commercial demonstration and deployment of innovative low-carbon technologies, encompassing CCS and CCU technologies as a core focus point.

In November 2021, the list of projects to develop large-scale innovation was announced. Out of the seven projects, four are aiming to develop CCS:

- SHARC: this project will demonstrate two ways of producing clean hydrogen at a refinery in Porvoo, through renewable energy and by capturing CO₂ and permanently storing it in the North Sea.
- K6 Program: the project will capture unavoidable emissions in a cement plant and in part store the CO₂ geologically in the North Sea and in part integrate it into concrete.
- Kairos@C: To reduce the emissions in the production of hydrogen and chemicals, this project will develop a complete carbon capture, transport and storage value chain in the Port of Antwerp.
- HYBRIT: this project will create a full-scale bioenergy carbon capture and storage facility at its existing biomass combined heat and power plant in Stockholm.

In July 2022, The European Commission announced that it will further invest EUR 1.8 billion towards seventeen large scale innovative clean technology projects, including carbon capture and storage. Seven of the seventeen approved projects include a CCS or CCU component. The selected CCS and CCU projects are located in Bulgaria, Iceland, Poland, France, Sweden and Germany. The projects focus on low-carbon cement production, carbon mineral storage site development and sustainable aviation fuel production.

The renewed interest in CCS and CCU in industry and power reinvigorates the positive momentum seen at a European and national level, with funding through the Connecting Europe Facility for Energy (CEF) programme to European CCS and CCU projects (Porthos, Antwerp CO₂, Acorn Sapling, Ervia).

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.

The 10 CCUS SET-Plan targets for 2030 are to be reached by (SET-Plan Working Group CCUS, 2021):

- 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.

3 Value chain analysis

The carbon capture use and storage (CCUS) value chain include several stages, each playing a vital role in successfully implementing the CCUS technologies.

The first stage of the CCUS value chain is capture¹⁷, which involves the extraction of CO₂ emissions from various sources. Different capture technologies employ solvents, sorbents, or membranes to absorb, adsorb or separate the CO₂ from other gases selectively. The equipment needed in post-combustion carbon capture systems has not been mass produced, and the industry has not reached the 'learning-by-doing' point yet. Large plants need to be built to reduce costs – mass production of this equipment will make the production processes more efficient and the cost per unit lower, and there will be learnings from operating these plants

The second stage of the value chain is transport, which involves the safe and efficient movement of captured CO₂ from the capture sites to the storage or utilisation locations. This often requires the development of a robust infrastructure, primarily pipelines, for long-distance transport, but ships and trucks can be considered for small volumes over short distances.

The third stage of the value chain is storage, where the captured CO₂ is stored in geological formations and not utilised for other purposes.

Alternatively, a third stage of the value chain can be **utilisation**. CO₂ utilisation involves converting the captured CO₂ into valuable products, for example those used as feedstock for producing chemicals, polymers, and construction materials or EOR in mature oil fields. CO₂ utilisation presents the opportunity of an additional stream of revenue, improving the overall economics of CCUS projects.

The CCUS industry does not yet have specialised supply chains (BNEF, 2022).

3.1 Turnover

Although the number of projects in the CCUS pipeline is increasing, the utilisation of this technology cannot yet be classified as a widely accepted and popular practice in business operations. Market analysis reports that the global CCUS market was worth nearly EUR 2.7 billion¹⁸ (USD 2.83 billion) in 2020 and is further projected to reach EUR 5.6 billion (USD 5.9 billion) by the year 2027.

In 2021, the USA achieved the highest revenue in the CCUS value chain, reaching EUR 1.945 billion. This is significantly higher than any other country and is possibly due to the extensive activity in CO₂ Enhanced Oil Recovery (EOR) in the country (Table 4).

¹⁷ Intergovernmental Panel on Climate Change. IPCC Special Report on Carbon Dioxide Capture and Storage. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_wholereport.pdf

¹⁸ Exchange rate 1 USD = 0.94899 EUR (source: oanda. Accessed 20/5/2022).

Table 4. Overall revenue in the CCUS value chain by major countries, 2021.

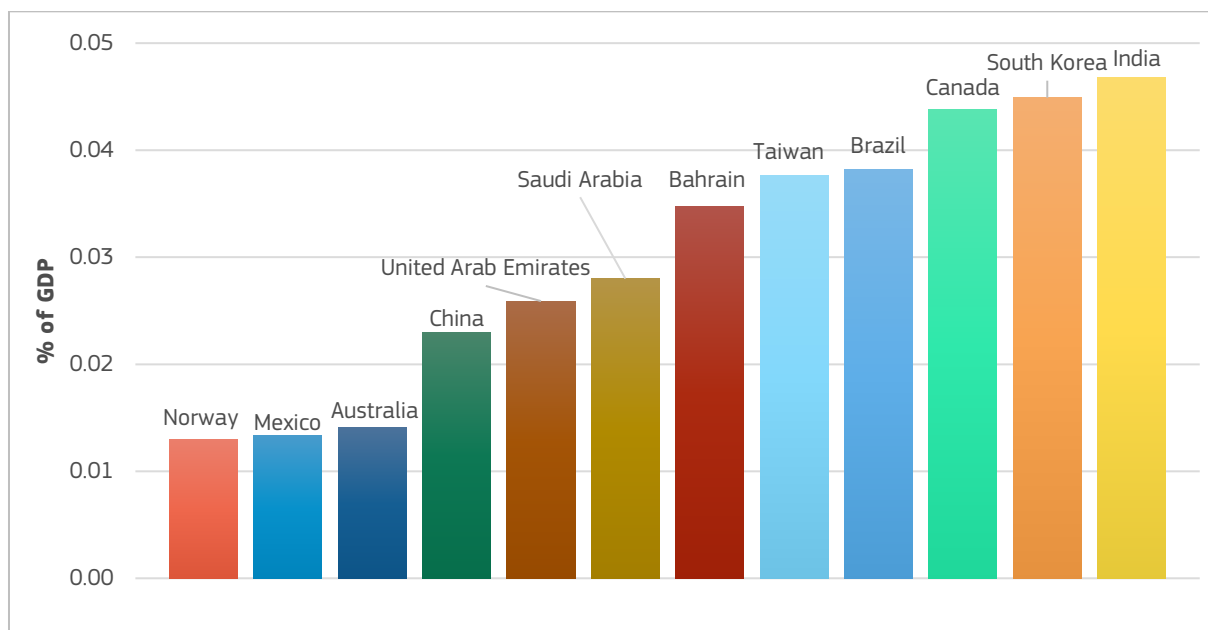
Country	EUR Million
USA	1 945
Australia	158
Norway	152
Malaysia	126
Indonesia	123
Russia	95
Europe	92
China	76
Saudi Arabia	47
UAE	47
Brazil	38
UK	27
Canada	23

Source: Secondary Research, Primary Interviews and Polaris Market Research Analysis

3.2 Gross value added

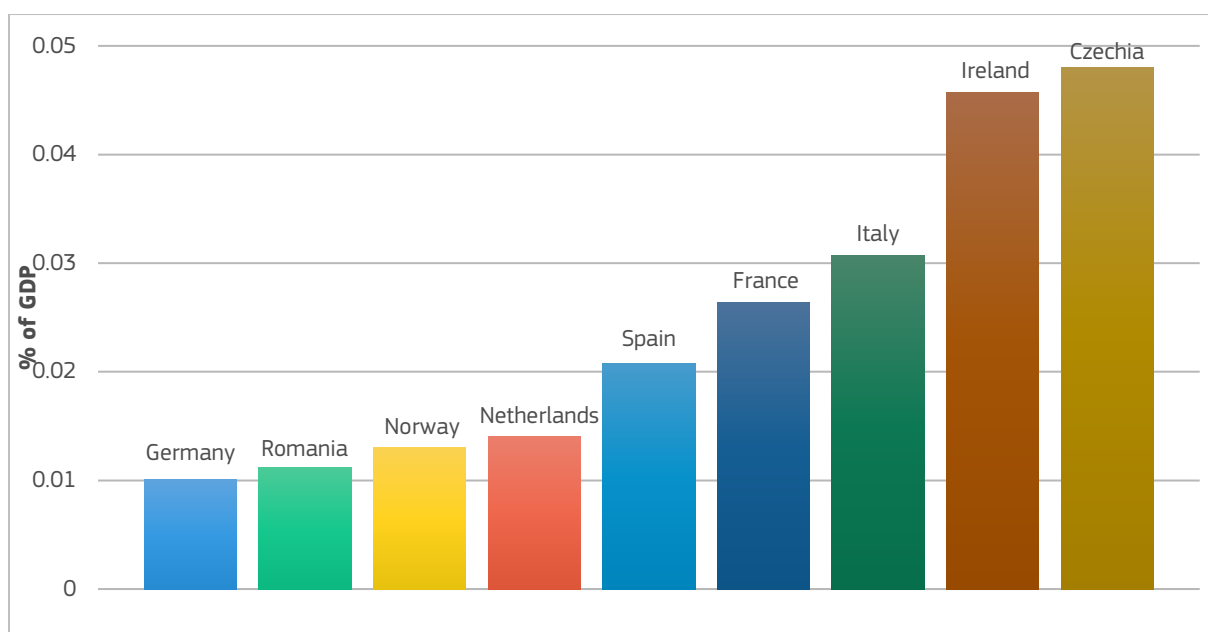
Figure 26 and Figure 27 show the value added by non-EU and by EU country. The data indicates that in 2021 there is value added in countries such as Taiwan, Malaysia and Bahrain and Czechia and Romania. We note that countries with no existing or planned CCUS projects can still have economic activities that are pertinent to CCUS (see section 3.4) and that the data are amended on a yearly base. In 2019, Japan and the UK report value added from CCUS activities.

Figure 25. Value added by non-EU country (% of GDP), 2021



Source: JRC with data from Polaris Market Research Analysis.

Figure 26. Value added by EU country (% of GDP), 2021



Source: JRC with data from Polaris Market Research Analysis.

3.3 Environmental and socio-economic sustainability

The purpose of CCUS is to reduce CO₂ emissions by capturing and permanently storing CO₂. Thus, it is important that far more CO₂ is stored than that which is emitted as a result of the construction, operation and decommissioning of the CCUS chain. The EU Taxonomy¹⁹ includes CCUS, stating that ‘CCS can be eligible in any

¹⁹ The EU taxonomy is a classification system, establishing a list of environmentally sustainable economic activities. Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

sector/activity if it enables that primary activity to operate in compliance with the threshold – for example, steel, cement or electricity production’.

So far, this topic was not a priority when addressing CCUS. Priority was given to other issues such as for example the technical and economic feasibility.

The studies that have addressed this issue base their results primarily on literature reviews. Although CCS can have a large role in the abatement of CO₂ emissions in the industrial sector, the amount of studies addressing the environmental impacts of deploying CCS in the industry is rather limited. Thus, most studies focus on the power sector.

In 2018, Gassnova, the Norwegian State Enterprise for carbon capture and storage, commissioned an analysis to better understand the CO₂ footprint of the Norwegian carbon capture and storage demonstration project, now renamed to Longship project. The study found that the Longship project has a very low CO₂ footprint compared to CCS projects studied elsewhere. This appears to be the result of using thermal energy available at the capture plants, low grid emission factor in Norway and a concerted effort to use combustion fuels with a low emission factor at both capture plants and in transport options (Helgesen et al., 2021).

Life cycle assessment (LCA) is a widely recognised and used tool for evaluating the potential environmental impact of products, processes and services. CCU's beneficial or negative impacts should be assessed from a system perspective and with regard to how it can provide societal benefits. A recent study provides guidelines for carbon capture and utilisation (European Commission-Directorate General for Energy et al., 2022). For the power generation sector, Van der Giesen et al. found that post-combustion capture at 90% capture rate reduces the system-wide lifecycle GHG intensity of coal-based electricity by 73%, from 0.85 to 0.23 kg CO₂-eq/kWh (van der Giesen et al., 2017).

Colsten et al. performed an assessment of existing LCA literature to obtain insights into potential environmental impacts over the complete life cycle of fossil fuel fired power plants with CCS (Corsten et al., 2013). As Table 5 indicates, despite the sometimes large ranges, for most categories the environmental impact of NGCCs with CCS, in absolute terms, is smaller than for PCs with CCS. This trend would also be expected for GWP because of the lower emission factor of natural gas and comparable percentages of CO₂ captured using MEA in PCs and NGCCs. However, the ranges reported in the literature for GWP are comparable for both coal- and natural gas-fired power plants with CCS.

Table 5. Ranges in absolute values found in literature for various environmental impact categories (Corsten et al., 2013)²⁰.

Impact category	Unit (per kWh)	PC + CCS MEA			Coal oxyfuel + CCS			NGCC + CCS MEA			IGCC + CCS solvents		
		min	max	n	min	max	n	min	max	n	min	max	n
CED	MJ	9.6	14.3	7	10.4	11	2	7.7	8.4	5	9.5	9.5	2
GWP	gCO ₂ eq	79	275	17	25	176	8	76	245	14	110	170	6
EP	gP04eq	0.06	0.30	11	0.01	0.09	3	0.017	0.134	8	0.035	0.035	1
AP	gSO ₂ eq	0.34	2.1	11	0.13	1.2	3	0.07	0.81	10	0.33	0.33	1
HTP	g1,4DBeq	21	165	7	17	42.8	2	0.134	57.5	3	18.4	18.4	1
POP	gC ₂ H ₄ eq	-0.37	0.152	10	0.005	0.047	3	0.0049	0.13	10	0.007	0.007	1
PM10	gPM10eq	0.013	0.43	8	0.012	0.025	4	0.005	0.23	4	0.004	0.004	1
FAETP	g1,4DBeq	0.48	13.4	4	0.62	0.62	1	0.013 ¹	0.52	2			

²⁰ Some values not included in the range, see (Corsten et al., 2013). min: lowest value reported in the reviewed literature; max: largest value reported in the reviewed literature; n: number of data points. Abbreviations: PC: Pulverised coal-fired power plant, NGCC: Natural gas-fired combined cycle, IGCC: Integrated gasification combined cycle, CED: Cumulative energy demand, GWP: Global warming potential, EP: Eutrophication potential, AP: Acidification potential, HTP: Human toxicity potential, POP: Photochemical oxidation potential, FAETP: Fresh water aquatic ecotoxicity potential, TETP: Terrestrial ecotoxicity potential, LCA: Life cycle assessment, MEA: Monoethanolamine, PM: Particulate matter, GHG: Greenhouse gas

Impact category	Unit (per kWh)	PC + CCS MEA			Coal oxyfuel + CCS			NGCC + CCS MEA			IGCC + CCS solvents		
		min	max	n	min	max	n	min	max	n	min	max	n
TETP	g1,4DBeq	0.13	0.51	3	0.16	0.16	1	0.002 ¹	0.045	2			

With regard to water use, early studies (Zhai, 2010) that are widely referenced and cited in CCS discussions indicated that an installation of a post-combustion capture system would nearly double the water consumption for thermal power generation using recirculating cooling. More recent estimates (DOE/NETL, 2015b) however, showed an increase of less than 50% for coal-fired power generation. This decrease resulted from the use of a more advanced CO₂ capture technology that has better performance, and thus, lower cooling requirements. The type of cooling system used in a facility influences the increases in water withdrawal and consumption. As such, different CO₂ capture systems and approaches have different impacts, with significant variability among reported values. The same conclusion on cooling was reached by a 2020 study (Rosa et al., 2020). They also found that in cases where water scarcity does not already exist, the addition of CCS will not generally induce scarcity. It should be noted that 43% of the current installed global coal-fired power capacity is located within regions that now experience water scarcity for at least one month a year. Over 30% of global capacity faces scarcity for five or more months a year. In these regions, implementation of CCS technologies worsens the water stress (Rosa et al., 2020). However, Europe was not among the regions with power plant capacity facing year-round water scarcity.

The implications of carbon capture and storage on demand for materials have not been studied in detail (Gielen, 2021). This is an area of research in need of attention.

When it comes to carbon dioxide removal technologies, land use and hardware distribution are commonly raised concerns, but research suggests that DAC units have minimal land requirements compared to other approaches, such as Bioenergy with Carbon Capture and Storage (BECCS) (Kapetaki, 2019). A similar finding also applies to water use (Smith et al., 2016).

Deutz and Bardow find that DAC combined with storage already has the potential for negative emissions today. However, a substantial contribution to climate change mitigation requires the rapid and massive deployment of DAC. According to their analysis, this scale-up will not be limited by material and energy requirements (Deutz and Bardow, 2021).

Close attention should be paid to the quality and credibility of carbon removals, as they are at risk of uncontrolled re-emissions, uncertain estimates or carbon leaks elsewhere. On November 2022, the European Commission proposed a first EU-wide voluntary certification framework for carbon removals. Certified ways to remove carbon under the EU's framework are carbon farming (restoring forests, soils, and management of wetlands and peatlands), industrial technologies (BECCS or DACCS (direct air carbon capture and storage)) and storing in long-lasting products and materials (wood-based or carbonate-bonded construction materials).

When it comes to circularity, technologies that convert CO₂ into fuels, chemicals and building materials can play a key role in a circular carbon economy. Carbon is very important for today's chemical and polymer industries for energy as well as material purposes. While options exist to substitute carbon for energy-related purposes, the material use of carbon is more challenging. The utilisation of CO₂ as a source for carbon used as a material has been reported as a promising option on this front (Kaiser and Bringezu, 2020).

Regarding other environmental issues, one of the biggest perceived risks stemming from CCS operation has been the potential for leakages of CO₂²¹ during the operation and post-closure phases. Health and safety can also be a concern with regard to the large chemical inventories and usage expected on the capture plant site, for example with the use of solvents (UK Environment Agency, 2002). Thus, designing high-performing solvents and creating environmentally friendly solvent processes for CO₂ capture are areas for potentially useful research (Mission Innovation, 2017). To date, no major incidents have been reported with regard to the operation of CCUS projects. However, the estimated values for CO₂ pipelines failure rates are in the same range of those reported for hydrocarbon pipelines (Vitali et al., 2022).

²¹ about 1% of captured CO₂ at Petra Nova was not sequestered (<https://www.osti.gov/servlets/purl/1608572>).

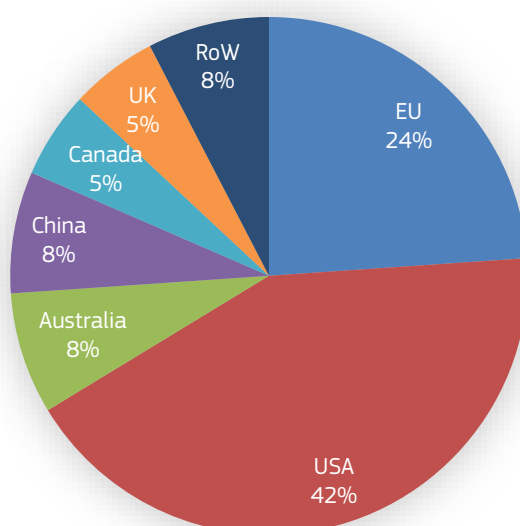
Finally, as regards the social aspect, CCUS projects have suffered to date from severe criticism and a lack of public acceptance. There have been failures to deliver whole projects due to a lack of public acceptance, such as in Barendrecht, the Netherlands. CCUS projects are complex, with many types of stakeholder and engagement activities. Experience so far has made clear that projects must make the required provisions for timely and efficient public outreach campaigns (Kapetaki et al., 2017).

3.4 Role of EU companies

Market research identified 186 key companies worldwide with activity in CCUS. In reality, we are expecting these to be much more dependent on the boundary set for the value chain. In May 2021, the UK government published a roadmap to maximise the UK's potential in CCUS which also included a mapping of companies involved in the CCUS supply chain (UK BEIS, 2021). This mapping identified 17 719 companies involved in all aspects of the supply chain from technology providers to services, to legal and different various aspects. This mapping reveals the need for a similar exercise for the EU, i.e. identifying the supply chain so as to evaluate the value chain in CCUS. Notwithstanding the limitation imposed by the restrained data available when it comes to identifying companies active in the CCUS supply chain, there may be an opportunity for an indicative assessment.

Out of the 186 companies identified, 45 (24%) are European or are active in the field through their European subsidiaries. The US is leading the way, with 42% of the key companies identified either American or US-based.

Figure 27. Key companies identified with activity in CCUS by country



Source: JRC with data from Polaris Market Research Analysis.

In the EU, companies have been mostly involved in project development. While in the mid 2000s it was primarily utilities that were involved in CCUS, the focus has now shifted to industry. HeidelbergCement is the company primarily active in 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. The Innovation Fund beneficiaries also reveal an interest in BECCS, with one BECCS project developed by Stockholm Exergi. 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 CO₂ use.²² ThyssenKrupp is active in CO₂ use and its pilot plant is synthesising methanol from blast furnace and basic oxygen furnace gas. It also aims 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 its steel plant site in IJmuiden, the Netherlands, since 2010. To scale up the

²² ArcelorMittal.

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 (Somers, 2021).

In North America the landscape is very different. There, most CCUS development takes place in 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 (Global CCS Institute, 2022b) provided a technology compendium intended to showcase commercially-available CCS technologies worldwide. In terms of CO₂ capture, 16 companies were listed as major technology providers. Five of these can be classified as EU companies (Air Liquide (FR), Axens (FR), Leilac Group (CALIX) (EU), Saipem (IT), Shell (NL)). On CO₂ transport, the publication identified five companies, of which two are in the EU (MAN Energy Solutions and Svanehøj). On CO₂ storage, none of the companies listed are in the EU. In the full value chain, two companies (Linde (DE) and Schlumberger (FR)) are EU companies. These lists show that the EU is relatively well positioned in CO₂ capture technologies. However, when it comes to transport, storage and the full value chain, the EU is far behind the US and Canada.

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

Venture capital analysis shows that the EU is lagging behind on this front. Out of the 92 companies identified, only eight 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

Market research indicates that currently, there are approximately 6 400 people employed in the CCUS chain worldwide (Table 6). These jobs spread from research to consultancy and from people employed in funding bodies (e.g. governments) to technology providers. As companies and organisations do not always update publically available information, especially on employment, these numbers can only be indicative.

Table 6. Employment in the CCUS chain in major countries, 2021.

Country	No of jobs
USA	4 000
Australia	400
Norway	350
Malaysia	300
Indonesia	275
Russia	250
EU	200
China	175
UAE	150
Saudi Arabia	100
Brazil	100
UK	65
Canada	50

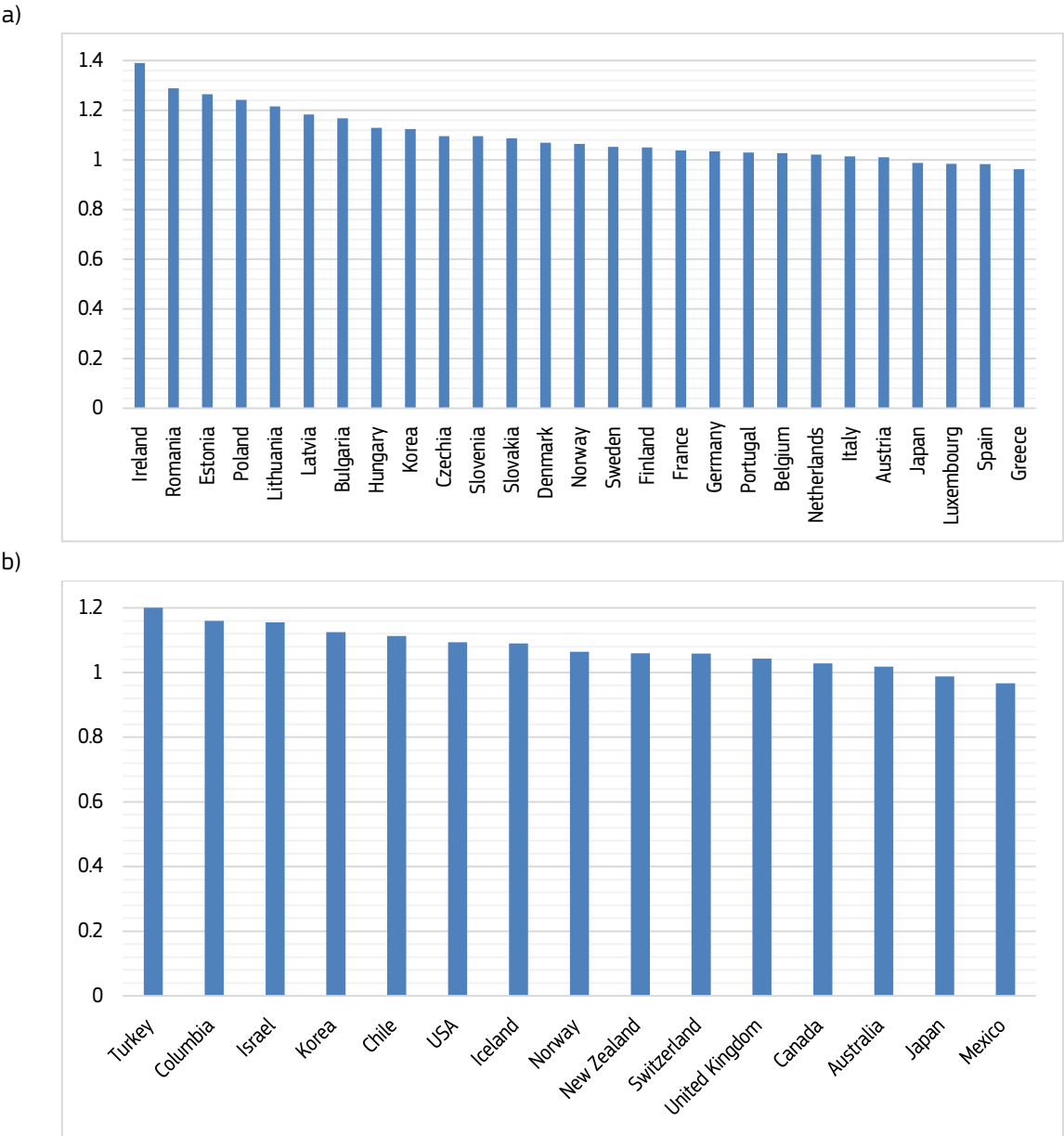
Source: Secondary Research, Primary Interviews and Polaris Market Research Analysis.

Market research estimates that within the EU Member States, Ireland has the highest labour productivity ratio²³ when it comes to CCUS, followed by Romania, Estonia, Poland and Lithuania (Figure 29a). Turkey, Columbia,

²³ The real gross domestic product (GDP) per hour worked in the CCUS sector.

Israel, Korea and Chile are the top five countries with the highest labour productivity ratio outside the EU (Figure 21b).

Figure 28. Labour productivity estimate by a) EU Member State and b) worldwide, 2021.



Source: JRC with data from Polaris Market Research Analysis.

The Global CCS Institute estimates that CCUS deployment could create up to 1.4 million jobs globally by 2040, with a significant proportion in Europe. The report also highlights the need for a skilled workforce trained in various aspects of CCUS, including capture, transportation, and storage. The global CCS industry must grow by more than a factor of 100 by the year 2050, to achieve the Paris Agreement climate targets. This means building 70 to 100 facilities a year, up to 100 000 construction jobs and ongoing jobs for 30 000 to 40 000 operators and maintainers (Global CCS Institute, 2021b).

According to (Serin *et al.*, 2021), CCUS investment can generate a substantial number of jobs in the short, medium and long term. Studies that explicitly quantify these aspects suggest more jobs will lie in the construction than in the operation phase of CCUS projects. At least 1 200 direct construction jobs could be

created at each new large-scale capture facility, rising to 4 000 or more depending on location, application and size (IEA, 2020b). As well as creating new jobs, CCUS is crucial for helping retain existing jobs in energy-intensive industries.

The Longship CCS project (including Northern Lights) in Norway is expected to generate as many as 4 000 jobs during the investment and construction phase, and 170 permanent jobs. For the UK, another advanced country in CCUS project planning and development, the Grantham Institute study estimates that by 2030 up to 31 000 jobs could be created and up to 51 000 can be potentially preserved in energy-intensive industries.

3.6 Energy intensity and labour productivity

Most carbon capture technologies aim to prevent at least 90% of the CO₂ in flue gases from reaching the atmosphere. As the technology approaches 100% efficiency, it gets more expensive and takes more energy to capture additional CO₂. From an engineering perspective, it is easier to capture carbon from a gas with a higher concentration of CO₂ because more molecules of carbon dioxide are flowing past the scrubbers. This is one of the reasons why DAC is so costly.

The energy or efficiency penalty caused by the operation of carbon capture in a plant has been a central research topic in the last decade. Depending on the source of heat used to meet the steam requirements in the capture unit, retrofitting a coal power plant can cause a drop in plant thermal efficiency of 11.3-22.9% (Supekar and Skerlos, 2015). Carbon capture reduces the net electricity output by 24% in a typical coal plant and 14% in a typical natural gas plant (Herzog, 2018). Carbon capture has been implemented at two coal power plants, Boundary Dam in Canada and Petra Nova in the USA.²⁴ The Boundary Dam project reported that it is able to generate 115–120 MW of power using a 161 MW turbine with an 11 MW existing parasitic loss, 15 MW requirement for compression, 9 MW for CO₂ and SO₂ capture and 14 MW for the amine and heat regeneration (IEAGHG, 2015). To capture 1 Gt of CO₂ using solar-powered DAC, around 2 000 terawatt hours (TWh) of electricity per year are required, which represents almost 10% of the current global electricity consumption (IRENA, 2021).

3.7 EU production data

Absorption by amine solvents is the most industrially mature process for large scale CCUS projects currently in operation (Castro et al., 2022). However, uses of amine solvents also extend to feedstock for detergent, emulsifier, polishes, pharmaceuticals, corrosion inhibitors and chemical intermediates (Frauenkron *et al.*, 2002). Therefore, Prodcom²⁵ codes²⁶ used to track EU production can offer only limited insight into the CCS technology trends.

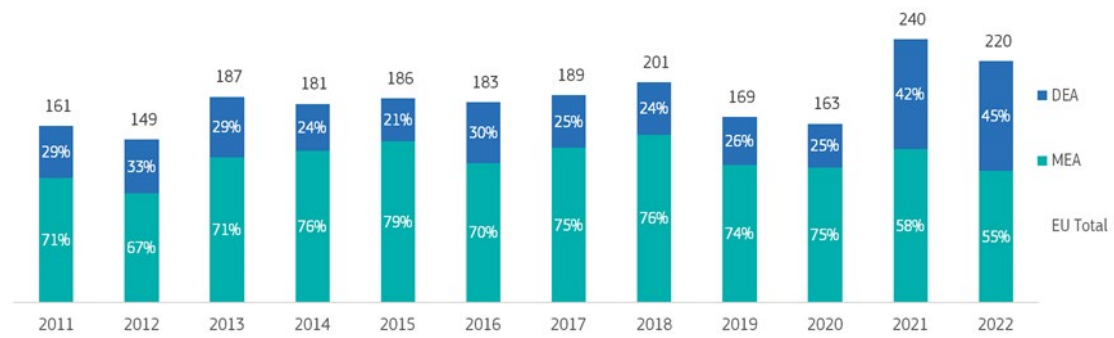
Figure 30 displays the EU production values per amine solvent from 2011 to 2022. Over the last decade, the total production value increased by 17% with an average value of EUR 192 million and an annual compound growth of 2%. In 2022, production shrank by 8% in total value compared to the previous year, with DEA production value more than doubling in 2021 and remaining consistent in 2022. MEA production value fluctuated around EUR 130 million over the years. Member States keep their production data confidential. Sweden and Denmark are the top EU producers amongst those Member States who disclose their data, but combined they hold less than 2% of the total EU production value.

²⁴ Petra Nova suspended operation in 2020 on the grounds of low oil prices amid the coronavirus pandemic.

²⁵ 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)

²⁶ Prodcom codes monitored were 20144233 Monoethanolamine and its salts (MEA) and 20144235 Diethanolamine and its salts (DEA). No codes for Methyldiethanolamine (MDEA) were identified.

Figure 29. EU production value per commodity [EUR million]



Source: JRC based on PRODCOM data.

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 at country and corporate level, yet the pace of announcements must increase further to be on track for net-zero.

The EU market share in the CCUS industry remains difficult to assess. This is due to 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 than transport and storage topics, while the number of EU projects involving the use of CO₂ is the smallest. The most significant market players for various segments of the CCUS value chain are identified in Section 3.4.

The US has been the leader in the carbon capture market from the beginning and will maintain its market share in 2030. This is due to the fact that the US has been providing, and continues to provide, excellent financial support for CCUS through the technology's most famous incentive: the 45Q tax credit. The US, UK and Canada will lead in capture capacity deployment, and are establishing frameworks to build capacity rapidly, at scale. China is still far behind in capacity announcements and incentives to deploy the technology (BNEF, 2022a).

In the decade ahead, the emergence of clusters of emitters paired with transport and storage developers, known as CCUS hubs, is the way to accelerate economies of scale. Currently, there are no commissioned CCUS hubs today in the world, but this is expected to change rapidly.

In the EU, industrial port cities will be major CCUS hubs. Offshore storage will be prioritised over onshore, due to limited land availability and policy barriers. In the Port of Rotterdam (The Netherlands), the Porthos hub will capture CO₂ from refining and chemical emitters, including Air Liquide, Air Products, ExxonMobil and Shell, for storage in depleted gas fields in the North Sea (BNEF, 2022b).

In continental Europe, Norway's Longship project should start operation in 2024, with an annual capacity of 1.5 million tonnes per annum. The main constituents of the hub are Heidelberg Cement's factory Norcem, Hafslund Oslo Celsio's waste facility and the Northern Lights Project, which will transport and store CO₂ offshore in the North Sea. However, carbon capture at the Hafslund Oslo Celsio are temporarily halted by high costs exceeded the foreseen budget. The Northern Lights project is a model for public-private collaboration on a CCS hub. Equinor, Total, and Shell partnered to transport and store CO₂ and are also in discussion with other EU facilities who may want to feed their emissions into the open-access infrastructure. The Coda terminal in Iceland is a partnership between the EU, Iceland and Norway. The project aims to capture and store 3 Mtpa by 2031, using transportation provided by five ships. It is unique as it is one of the first cross-border transport and storage hubs (BNEF, 2022b).

In the US, major pipeline infrastructure determines where hubs can be formed. Summit Carbon Solutions (SCS) is operating a fully integrated business model that provides capture, transport and storage services to 32 ethanol plants across the Midwest to store 9 Mtpa. With the 1 billion tonne CO₂ storage hub under development in North Dakota, the company is considering expanding to local cement and steel industries. Valero, Navigator and Blackrock aim to develop a 1 300 mile pipeline to transport 5 Mtpa of CO₂ to a storage site by 2024, which is estimated to scale to 15 Mtpa (BNEF, 2022b). The project will capture CO₂ from 33 bio-refineries across five Midwest states. Bayou Bend is an offshore CCS hub representing a joint venture between Chevron, Talos and Equinor²⁷, targeting local petrochemical producers, power plants and refineries. It aims to store the CO₂ along the Gulf Coast in south east Texas.

²⁷ [Norway's Equinor acquires a stake in U.S. Bayou Bend CCS project | Reuters](#)

4.2 Trade (Import/export) and trade balance

Amine solvents have been used as a proxy for CCUS trade as CO₂ capture with amine scrubbing is the technology used in the majority of commercial CCUS projects in operation. International trade is monitored using the six-digit codes of the Harmonised System (HS) classification²⁸, based on Eurostat's Comext²⁹ and the United Nations' Comtrade³⁰ databases. Our analysis considered the following HS codes: 292211 (Monoethanolamine and its salts, MEA), 292212 (Diethanolamine and its salts, DEA), 292213 (Triethanolamine and its salts, TEA). In 2017, the code for TEA was discontinued and two new codes were created: 292215 and 292217 for Triethanolamine (TEA) and Methyldiethanolamine and ethyldiethanolamine (MDEA_EDEA), respectively. We note that the amine solvents depicted by the HS codes above 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.

Figure 31 shows that the extra-EU imports and exports of amine solvents remained at a fairly similar level until 2016. In 2017 and 2020, the EU had a trade surplus of EUR 15 million and registered a trade deficit of around EUR 30 million in 2019 and 2022. Trade values in 2022 marked a step increase of 53% for imports and 44% for exports compared to 2021.

Figure 30. Extra-EU trade of amine solvents as proxy for CCUS, EUR million.



Source: JRC based on COMEXT data

During 2020–2022, imports from the Single Market (intra-EU) represented nearly 70% of total EU imports. Belgium, Germany, Spain, Italy and France were the top importers of amine solvents in the EU. The EU imported mainly MEA (53%) and TEA (37%). The extra-EU imports came mostly from Saudi Arabia (47%) and the US (32%).

During the same period, the majority of extra-EU exports were DEA (56%), MEA (18%) and TEA (17%). The US was the largest extra-EU exporter from the EU with 61%, followed by the UK, China, Türkiye and Switzerland. Belgium, Germany, France, Sweden and Netherlands were the top EU exporters.

Furthermore, the US and Saudi Arabia were the top global exporters of amine solvents, while China, India and the US were the top global importers. We note that trade in these countries is mainly related to the oil and gas industry.

²⁸ World Customs Organization (WCO), HS Nomenclature 2022 Edition <https://www.wcoomd.org/en/topics/nomenclature/instrument-and-tools/hs-nomenclature-2022-edition.aspx>

²⁹ <https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/focus-on-comext>

³⁰ <https://comtradeplus.un.org/>

Canada and the US are the fastest growing non-EU markets, scoring the highest on the two-year average of net import change³¹ from 2019 to 2021³². (Table 7). The EU captured the majority of amine solvents imports in the US (69%) and the UK (81%) and more than one-fifth in South Korea and Türkiye.

Table 7. EU share of biggest global importers and growing non-EU markets.

Country	Total import (2019-2021) [EUR Million]	% import from the EU	Growing non-EU markets
Canada	153	0%	27
United States	148	69%	23
United Kingdom	117	81%	14
South Africa	22	13%	14
China	421	12%	13
United Arab Emirates	97	3%	9
Indonesia	38	4%	5
Japan	65	5%	3
Malaysia	20	6%	3
Türkiye	33	26%	2
Singapore	61	3%	2
South Korea	67	22%	1

Source: JRC analysis

4.3 Resource 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. In what follows we will present an overview of these topics.

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 CCUS projects in operation. However, other materials such as membranes (polymeric, ceramic, etc.) and adsorbents can be and are also used for carbon capture. At present, the main commercially available adsorbents are activated carbons, zeolites, hollow fibres and alumina (Lee and Park, 2015). 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 CO₂ shipping and piping infrastructure rely heavily on steel. Ships used for transportation resemble hydrogen vessels and utilise similar kinds of materials, although various grades of steel, membrane lines, and insulation. The amount of steel, its grade and how it is lined depend on the pressure under which the CO₂ is transported. The construction of CO₂ pipelines requires tubular steel, whose availability is unlikely to limit deployment (IEA, 2023).

The bulk materials required for CO₂ 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 (IEA, 2023). (Parker, Meyer and Meadows, 2009) listed materials that are used for CO₂ injection wells (Table 8). The availability of well construction materials and components is unlikely to be a constraint on the development 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. CO₂ storage sites require monitoring equipment.

³¹ Calculated as $net\ import\ change = [(import_{2020} - import_{2019}) + (import_{2021} - import_{2020})]/2$

³² Latest data for the year 2022 may be incomplete for Comtrade, because it does not provide estimates for the missing values as Comext does.

Table 8. Typical construction materials for CO₂ 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: (Parker, Meyer and Meadows, 2009)

In addition to injection wells, pipelines and ships, steel will be required for the construction of 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 apart from chromium, strategic materials, such as manganese, silicon, copper, cobalt, nickel and critical materials such as aluminium, phosphorous and vanadium. Due to the changing geopolitical context and competing demand from other technologies, skyrocketing prices and shortages in the supply chain could be expected. Prevention and mitigation strategies have to be considered in order to overcome these situations (Carrara et al., 2023)³³.

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 years³⁴, shortages have been reported 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, 76% for silicon, 62% for vanadium and 56% for aluminium) (Carrara et al., 2023). Chromium, an essential alloy is sourced from South Africa (56%). However, Europe is one of the world's leading suppliers of natural zeolites.³⁵ Furthermore, the captured CO₂ can be used to produce high value chemicals and building materials, which could provide additional streams of revenue of benefit to EU companies.

Biomass is another relevant material, used for bioenergy with carbon capture and storage (BECCS). Biomass sources include: wood and wood processing waste, agriculture crops and waste materials (corn, soybeans, sugar cane, switchgrass, woody plants, algae, and crop and food processing residues), biogenic material in municipal solid waste, animal manure and human sewage. Today biomass feedstock supply is dominated by forest management schemes and agriculture (Consoli, 2019). According to our previous work, there is considerable potential for biomass in the EU (Kapetaki *et al.*, 2020), but the supply chain would need to be developed. Major scale-up of purpose-grown bioenergy is challenging due to its far-reaching linkages to issues beyond the energy

³³ Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, Á., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D., Christou, M., Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/386650, JRC132889

³⁴ Bloomberg, 2022; Financial Times, 2021; S&P Global Market Intelligence, 2020.

³⁵ Chemeurope.com

sector, including competition with land for food production and forestry, water use, impacts on ecosystems, and land use change (IPCC 2022).

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 (Luis, 2016). The 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 (Material Economics, 2019), 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 CCS needs, raising concerns if demand spikes suddenly (Forecast report, 2023). Another aspect to consider is that increased MEA production leads to negative environmental consequences due to CO₂ emissions and energy demands.

Research has concentrated on improving the technical and economic efficiency of this solvent. The CO₂-absorbing capacity of MEA is concentration dependent, ranging from 447 to 581 g CO₂/kg MEA (Huertas *et al.*, 2015). On the CO₂ capture process itself, the energy required to regenerate the solvent is very high (U.S. Department of Energy, 2019). Today's amine processes will require 0.29 kWe/kgCO₂ including compression for 90% capture (Herzog, 2018).

The large-scale deployment of DACCS requires a considerable amount of energy, depending on the type of technology, water, and make-up sorbents, while its land footprint is small compared to BECCS (Chatterjee and Huang 2020, Smith et al. 2016). 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 current market supply (Realmonte et al. 2019) (IPCC, 2022). Liquid solvent DACCS systems need substantial amounts of water (Fasihi et al. 2019), although much less than BECCS systems (Smith et al. 2016), which could negatively affect SDG 6 (clean water and sanitation).

On technology autonomy and/or dependence, our analysis in section 3.4 shows that the EU is relatively well positioned on CO₂ capture technologies. However, when it comes to transport, storage and the full value chain, the EU is far behind the US and Canada.

5 Conclusions

This work touches on a variety of topics, all related to carbon capture storage and utilisation. The primary conclusions are detailed below, drawing attention to some future options for development

- The number of commercial facilities in the pipeline has seen unprecedented growth, but the pace must further increase to be on track for net-zero.
- CCUS costs are high and remain an added cost, without tax credits, public funding or loans. The costs vary widely depending on the method used to capture carbon, the type of industry, the location and the regulatory framework in place. Significant cost reductions can be achieved through the use of emerging technologies, exploiting economies of scale, and sharing infrastructure.
- The US (23%), Canada (18%) and Japan (13%) attracted the highest amount of public R&D funding and investment over the last decade. The EU ranked fifth with a 10% share, and within it, Germany, France and the Netherlands were the front-runners. The US attracted by far the most VC investment, reinforcing its leading position in the CCUS industry from the very beginning, while the EU managed to secure 18% of global VC investment.
- The US filed the most high-value inventions between 2009 and 2020, followed by the EU and Japan. Among the EU Member States, France has the highest number of high-value inventions, followed by Germany and the Netherlands. These countries are also in the top five regarding the number of peer-reviewed publications related to various aspects of the CCUS value chain.
- The US has been the world leader in CCUS from the beginning, accounting for almost half of large-scale commercial projects. The US also generates the most revenue in the CCUS value chain and employs the most personnel, based on 2021 data. The EU is largely unrepresented globally.
- CCUS does not have specialised supply chains yet. Large plants need to be built, the equipment required in capture processes needs to be mass-produced and the infrastructure required for transport and storage needs to be developed. Currently, there do not appear to be any significant materials supply chain risks for the deployment of CCUS.
- A skilled workforce is needed along all segments of the CCUS value chain, for construction as well as operation and maintenance. A growing CCUS industry provides opportunities for jobs across various industries.
- Safety, health, potential impacts on the environment and public acceptance remain topics of concern.

Different roadmaps identify CCUS as among the technologies necessary to facilitate the transition towards net-zero in the industrial and energy sector. However, several **legal, financial and social barriers** to the full deployment of CO₂ infrastructure persist. Despite EU support to CCUS technology through the CCUS Directive, there are **gaps and shortcomings in the existing regulation**. Most Member States have transposed the CCS Directive, but have not yet developed a regulatory framework to govern the permitting process for CCS. Today there are no rules guaranteeing open access to transport and storage infrastructure, other than non-discrimination for access to storage overcapacity established under the CCS Directive. Additionally, capture projects may be placed at a disadvantage because the transport and storage provider might have an effective natural monopoly as the only option for emitters. Moreover, there are no basic CO₂ quality standards for infrastructure access, given the dispersed and diverse nature of emitters, and the variations in capture technologies, CO₂ purity and transport. Furthermore, infrastructure planning is not coordinated or planned at EU level. In the Netherlands, there are no regulatory barriers to deploying CCUS directly. However, major construction projects (such as Porthos) experience delays due to regulations on nitrogen emissions and the impact of soil extraction (EC, 2023).

The main **financial barrier** regards certainty about the return on investment. Funding is currently restricted to a limited group of projects, the majority of which tend to be in demonstration stage. The absence of a low risk environment for investors is another barrier to the development of a commercial CCS market in Europe. Most European projects have failed to date because government support was not strong enough to provide the subsidies needed. As CCS projects develop, there is a need for insurance to reduce the financial burden. As it currently stands, there is no commercial insurance available and the CCS Directive requirements are relatively unclear, with the topic being handled differently by different national governments (EC, 2023).

A third important barrier to the deployment of CCUS is **societal acceptance**. The most frequently mentioned risk perceptions in the literature relate to negative health impacts, especially for people living near CO₂ storage and transport infrastructure. Local administrators, NGOs, academia, and other economic stakeholders play a central role in increasing awareness of CCUS and facilitating informed debate, providing transparency regarding projects, together with an acknowledgement of the uncertainties, and encouraging collaboration with local communities.

The main challenges for the development of CCUS do not involve technology or technical implementation. However, ongoing research tackles specific bottlenecks in the process that can accelerate progress.

In terms of **CO₂ capture**, research should focus on developing new capture technologies and making existing ones more efficient and cost-effective. Specifically, areas for research include improving or developing new solvents that last longer and release the bound CO₂ at lower temperatures, ultimately reducing capture costs. Environmental friendliness should also be addressed. For sorbents and membranes, advancement in materials and process integration is a key topic that requires further research. Technological advancements to enable high capture rates and low energy requirements – novel absorber designs, modularisation and cost-effective materials – should be supported. Flexibility, compactness and potential for heat integration and process intensification are also important. In addition to CO₂ separation, understanding the potential of carbon capture in H₂ production will have to be pursued, i.e. H₂ production based on fossil (or biomass) fuels.

Concerning **CO₂ transport and storage**, developments in digitalisation, including advanced modelling, sensing and real-time monitoring technologies should be used to accelerate site appraisals and improve CO₂ tracking. Technical areas of research for transport include CO₂ composition, impurities and fluctuating flows in the pipelines.

For **CO₂ utilisation**, new routes to create carbon-based materials from CO₂ should be looked at. The scientific community is advocating for research in photoelectrochemical conversion of CO₂ into selective gaseous (methane, ethane) and liquid products (formate, methanol, ethanol) under solar light irradiation, especially for liquid products at ambient temperature and pressure. To use CO₂ as a raw material, advancements in technology readiness level are required. Life cycle assessment analyses are needed to evaluate the environmental impact of CO₂ utilisation compared to conventional methods. Increasing the efficiency of CO₂ utilisation pathways will require intensified research on improved catalysts. Another avenue could be to directly utilise the flue gas, avoiding the separation, dehydration, purification and transport steps. This would offer the potential to apply CO₂ conversion to industrial processes directly, resulting in drastic cost reductions and revenue generation.

Machine learning and artificial intelligence can help design and optimise effective CCUS strategies by shortening the time-consuming exploratory investigations. This can target the discovery of energy-efficient solvents for CO₂ capture, reducing the cost of capturing CO₂ from point sources, subsurface modelling for designing geological CO₂ storage sites and novel financial models to understand the impact of the rate of innovation on different decarbonisation scenarios. Quantitative models based on techno-economic, environmental and social aspects should be employed to guide decision-making, both for setting a clearer target mitigation potential using CCUS conformed to carbon neutrality, and for the integration of CCUS with the entire carbon-neutral technology system.

Several materials and components used along the CCUS value chain were identified in Section 4. Currently, considering the most commercially advanced capture process, the availability of materials and components is unlikely to limit the deployment of the CCUS. However, an in-depth supply chain analysis and materials demand forecast needs to be carried out. This should also consider emerging capture technologies that will most likely prove to be superior, in terms of efficiency and cost, to the amine solvent-based processes.

In recent years, carbon dioxide removal technologies have gained substantial interest. On November 2022, the European Commission proposed a first EU-wide voluntary certification framework for carbon removals. Certified ways to remove carbon under the EU's framework are carbon farming (restoring forests, soils, and management of wetlands and peatlands), industrial technologies (BECCS or DACCS) and storing in long-lasting products and materials (wood-based or carbonate-bonded construction materials). However, several barriers still need to be examined in future endeavours. These hurdles include the ability of the technology to be replicated on a larger scale, the cost implications, and the land and energy requirements.

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List of abbreviations and definitions

ASU – Air Separation Unit
BECCS – Bioenergy with CCS
CAPEX – Capital Expenditure
COP – Conference of the Parties
CCS – Carbon Capture and Storage
CCUS – Carbon Capture, Use and Storage
CEF – Connecting Europe Facility
CLC – Chemical Looping Combustion
DAC – Direct Air Capture
DACCS - Direct Air Carbon Capture and Storage
IEA – International Energy Agency
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
JRC – Joint Research Centre
LCA – Life Cycle Analysis
LCOE – Levelised Cost of Electricity
Mtpa – Million tonnes per annum
MS – Member State
OPEX – Operational Expenditure
PSA – Pressure Swing Adsorption
RTIL – Room Temperature Ionic Liquid Membranes
TRL – Technology Readiness level
TSA – Temperature Swing Adsorption
SET - Strategic Energy Technologies
SETIS - Information System
SEWGS - Sorption Enhanced Water Gas Shift
VSA – Vacuum Swing Adsorption
CSLF – Carbon Sequestration Leadership Forum
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, 2021
	Installed capacity & energy production	JRC based on Global CCS institute, 2022
	Technology costs	JRC based on Global CCS Institute, 2021
	Public and private RD&I funding	JRC based on Pitchbook, 2019
	Patenting trends	JRC based on EPO Patstat, 2020
	Scientific publication trends	JRC based on TIM, 2023
	Assessment of R&I project developments	JRC based on CORDIS, 2022
Value chain analysis	Turnover	JRC based on Polaris Market Research, 2021
	Gross Value Added	JRC based on Polaris Market Research, 2021
	Environmental and socio-economic sustainability	Scientific literature, European Commission
	EU companies and roles	JRC based on Polaris Market Research 2021, Global CCS Institute, Pitchbook, Patstat
	Employment	JRC based on Polaris Market Research, 2021, Global CCS Institute, 2021
	Energy intensity and labour productivity	Scientific literature, IEAGHG, IRENA
	EU industrial production	JRC based on PRODCOM, 2022
Global markets and EU positioning	Global market growth and relevant short-to-medium term projections	COWI
	EU market share vs third countries share, including EU market leaders and global market leaders	BNEF
	EU trade (imports, exports) and trade balance	JRC based on COMEXT, 2022
	Resource efficiency and dependencies (in relation EU competitiveness)	Scientific literature, EC Reports, IPCC 2022

Annex 2 Sustainability assessment framework

Parameter/Indicator
Environmental
<i>LCA standards, PEFCR or best practice, LCI databases</i>
<i>GHG emissions</i>
<i>Energy balance</i>
<i>Ecosystem and biodiversity impact</i>
<i>Water use</i>
<i>Air quality</i>
<i>Land use</i>
<i>Soil health</i>
<i>Hazardous materials</i>
Economic
<i>LCC standards or best practices</i>
<i>Cost of energy</i>
<i>Critical raw materials</i>
<i>Resource efficiency and recycling</i>
<i>Industry viability and expansion potential</i>
<i>Trade impacts</i>
<i>Market demand</i>
<i>Technology lock-in/innovation lock-out</i>
<i>Tech-specific permitting requirements</i>
<i>Sustainability certification schemes</i>
Social
<i>S-LCA standard or best practice</i>
<i>Health</i>
<i>Public acceptance</i>
<i>Education opportunities and needs</i>
<i>Employment and conditions</i>
<i>Contribution to GDP</i>
<i>Rural development impact</i>
<i>Industrial transition impact</i>
<i>Affordable energy access (SDG7)</i>
<i>Safety and (cyber)security</i>
<i>Energy security</i>
<i>Food security</i>
<i>Responsible material sourcing</i>

Annex 3 Energy system models and scenarios: POTEnCIA and POLES

This annex provides an overview of the energy system models and scenarios used in CETO to support the technology development assessment and the strategic overview on clean energy technologies.

A3.1 POTEnCIA model overview

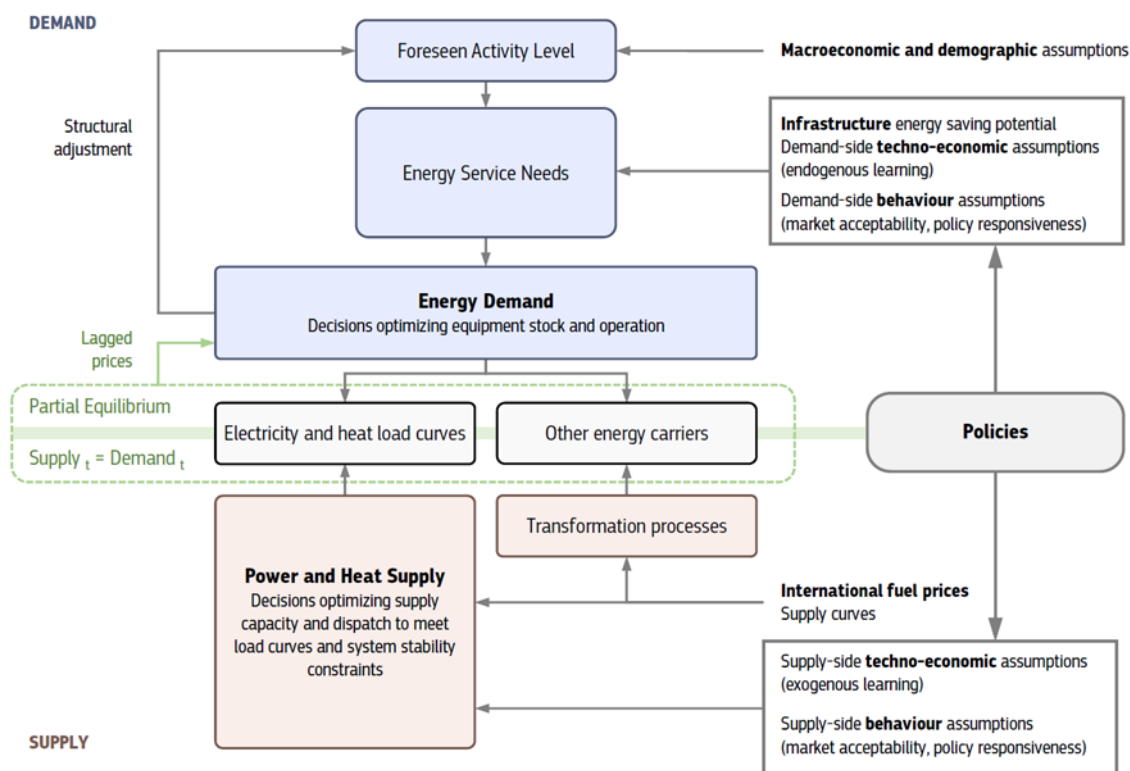
The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) is an energy system simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed 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 A3-1; detailed in the [POTEnCIA model description](#) and in the [POTEnCIA Central Scenario report](#)) 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 maximise its benefit or minimise its cost under constraints such as available technologies and fuels, behavioural preferences, and climate policies. This core modelling approach is tailored to each sector, for instance to represent different planning horizons and expectations about future technologies under imperfect foresight. In particular, power dispatch modelling uses a high time resolution with full-year hourly dispatch to suitably depict the increasing need for flexibility from storage and demand response, and the changing role of thermal generation in a power system dominated by variable renewable energy sources. Within this sector modelling framework, investment decisions of the representative agents are simulated with discrete-choice modelling. The model then finds an overall equilibrium across different sectors using price signals for resources such as traditional and renewable energy carriers while accounting for efficiency and environmental costs.

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 CO₂ 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](#)). JRC-IDEES has been developed in parallel to POTEnCIA, and an updated release is planned in 2024 to ensure the transparency of POTEnCIA's base-year conditions and to support further research by external stakeholders.

Figure A3-1. The POTEnCIA model at a glance



Source: Adapted from the [POTEnCIA Central scenario report](#)

A3.2 POTEnCIA CETO climate neutrality scenario overview

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 EU27 GHG emissions by 55% by 2030 versus 1990, and reaches the EU27's climate neutrality by 2050 under general assumptions summarised in Table A3-1. To suitably model technology projections under these overarching GHG targets, the scenario includes a representation 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 deployment of bioenergy and renewable power generation technologies to 2030 is consistent with the EU's Renewable Energy Directive target (42.5% share of renewables in gross final energy consumption by 2030). Similarly, the adoption of alternative powertrains and fuels in transport is also promoted by a representation of updated CO₂ emission standards in road transport and by targets of the ReFuelEU Aviation and FuelEU Maritime proposals.

Table A3-1. General assumptions of the POTEnCIA CETO Climate Neutrality Scenario

General scenario assumptions	Modelled scenario and policy assumptions
GDP growth by Member State	GDP projections based on EU Reference Scenario 2020, with updates to 2024 from DG ECFIN Autumn Forecast 2022
Population by Member State	Population projections based on EU Reference Scenario 2020, with updates to 2032 from EUROPOP 2019
International energy markets	Natural gas import projections consistent with REPowerEU targets for supply diversification and demand reduction. International fuel price projections to 2050 aligned with REPowerEU

Source: JRC

A3.3 POLES-JRC model

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. POLES-JRC is hosted at the JRC and is particularly adapted to assess climate and energy policies.

POLES-JRC covers the entire energy system, from primary supply (fossil fuels, renewables etc.) to transformation (power, biofuels, hydrogen) and final sectoral demand (Figure A3-2). International markets and prices of energy fuels are simulated endogenously. Its high level of regional detail (66 countries & regions covering the world with full energy balances, including all OECD and G20 countries) and sectoral description allows assessing a wide range of energy and climate policies in all regions within a consistent global framework: access to energy resources, taxation policy, energy efficiency, technological preferences, etc. POLES-JRC operates on a yearly basis up to 2050 and is updated yearly with recent data and model updates.

The POLES-JRC model is used to assess the impact of European and international energy and climate policies on energy markets and GHG emissions, by DG CLIMA in the context of international climate policy negotiations and by DG ENER in the context of the EU Energy Union.

POLES-JRC has also been applied for the analyses of various Impact Assessments in the field of climate change and energy, among them: the *"Proposal for a revised energy efficiency Directive"* (COM(2016)0761 final) and *"The Paris Protocol – A blueprint for tackling global climate change beyond 2020"* (COM(2015) 81 final/2).

Moreover, POLES-JRC provided the global context to the *EU Long-Term Strategy* (COM(2018) 773) and formed the energy/GHG basis for the baseline to the CGE model JRC-GEM-E3.

POLES-JRC forms part of the *Integrated Assessment Modelling Consortium* (IAMC) and participates in inter-model comparison exercises with scenarios that feed into the IPCC Assessment Reports process.

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://ec.europa.eu/jrc/en/geco>

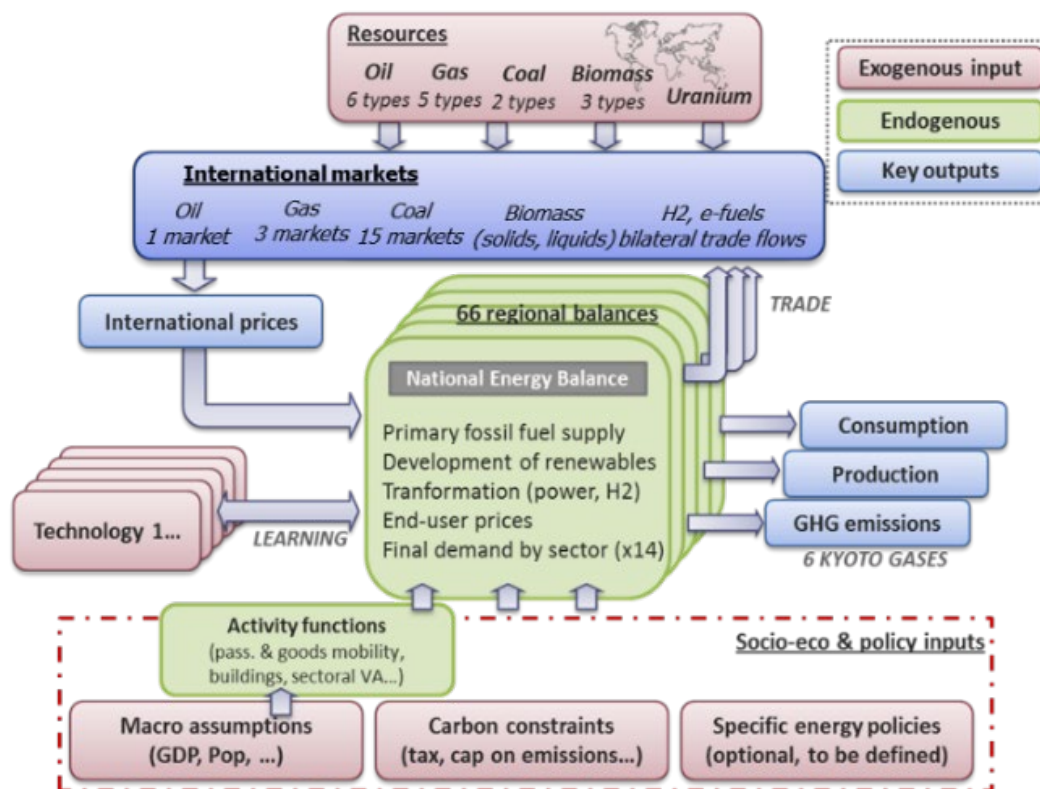
A3.3.1 Power system

POLES-JRC considers 37 power generating technologies, covering existing technologies as well as emerging technologies. Each technology is characterised by its installed capacity, cost parameters (overnight investment cost, variable & fixed operating and maintenance cost), learning rate and other techno-economic parameters (e.g. efficiencies). The cost evolution over time is taken into account by technology learning driven by accumulated capacity.

For renewable technologies maximum resource potentials are taken into account. Similarly, the deployment of carbon capture and storage (CCS) technologies is linked to region-specific geological storage potential. In addition to these technical and economic characteristics, non-cost factors are applied to capture the historical relative attractiveness of each technology, in terms of investment and of operational dispatch.

With regard to the clean energy technologies covered by CETO, the model includes power generation using photovoltaics (utility and residential), concentrated solar power (CSP), on-shore and off-shore wind, ocean energy, biomass gasification and steam turbines fuelled by biomass, geothermal energy as well as hydropower. CCS-equipped combustion power technologies are considered as well. Moreover, electricity storage technologies such as pumped hydropower storage and batteries are also included

Figure A3-2. Schematic representation of the POLES-JRC model architecture



Source: JRC

A3.3.2 Electricity demand

The total electricity demand is computed by adding the electricity demand from each sector (i.e. residential, services, transport, industry and agriculture). The evolution over time of the sectoral electricity demand is driven by the activity of each sector and competition between prices for electricity and other fuels.

POLES-JRC uses a set of representative days with an hourly time-step in order to capture load variations as well as to take into account the intermittency of solar and wind generation. The usage of representative days also allows to capture hourly profiles by sector and end-uses.

With a view to other CETO technologies influencing electricity consumption, the model includes heat pumps in the residential and service sector, batteries for electric vehicles and electrolyzers.

A3.3.3 Power system operation and planning

The power system operation assigns the generation by technology to each hour of each representative day. The supplying technologies and storage technologies must meet the overall demand.

The capacity planning considers the existing structure of the power mix (vintage technology), the expected evolution of the demand, and the production cost of technologies.

A3.3.4 Hydrogen

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

Hydrogen can be used as fuel in all sectors. Moreover, hydrogen is used to produce fertilisers as well as to produce fuels used in the transport sector (i.e. gaseous and liquid synfuels and ammonia). POLES-JRC models global hydrogen trade and considers various means of hydrogen transport (pipeline, ship, truck, refuelling station).

A3.3.5 Bioenergy

POLES-JRC receives information on land use and agriculture through a soft-coupling with the GLOBIOM model³⁶. This approach allows to model bioenergy demand and supply of biomass adequately by taking into account biomass potential, production cost and carbon value. Moreover, the emissions from land use and forestry (CO₂) as well as agriculture (CH₄ and N₂O) are derived from GLOBIOM.

Power generating technologies using biomass are biomass gasification (with and without CCS) and biomass fuelled steam turbines.

Hydrogen can be produced from biomass via gasification and pyrolysis. Moreover, the production of 1st and 2nd generation biofuels for gasoline and diesel is considered.

A3.3.6 Carbon Capture Utilization and Storage (CCUS)

POLES-JRC takes into account CCUS technologies for:

- 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 coal and biomass pyrolysis;
- DAC where the CO₂ is stored or used to produce synfuels (gaseous or liquid);
- CO₂ storage in geological sites.

A3.3.7 Model documentation and publications

A detailed documentation of the POLES-JRC model and publications can be found at:

- <https://publications.jrc.ec.europa.eu/repository/handle/JRC113757>
- <https://ec.europa.eu/jrc/en/poles>

A3.4 POLES-JRC CETO global 2°C scenario

The global scenario data presented in this CETO technology report refers to a 2°C scenario modelled with the POLES-JRC model. The 2°C scenario assumes a global GHG trajectory consistent with a likely chance of meeting the long-term goal of limiting the temperature rise over pre-industrial period to 2°C in 2100.

The 2°C scenario was designed with a global carbon budget over 2023-2100 (cumulated net CO₂ emissions) of approximately 1150 Gt CO₂, resulting in a 50% probability of not exceeding the 2.0°C temperature limit in 2100. A single global carbon price for all regions is used in this scenario, starting immediately (2023) and strongly increasing. The 2°C scenario is therefore a stylised representation of an economically-efficient pathway to the temperature targets, as the uniform global carbon price ensures that emissions are reduced where abatement

³⁶ Global Biosphere Management Model (GLOBIOM) model description. International Institute for Applied Statistical Analysis, Laxenburg, Austria. <http://www.globiom.org>

costs are lowest. This scenario does not consider financial transfers between countries to implement mitigation measures.

The POLES-JRC model has been updated with the latest technologies costs from recent literature. Most of the historic data used in the 2°C scenario refers to data used in the [GECO 2022 scenarios](#) (energy balances, energy prices, capacities).

Annex 4

List of projects identified

Table A4-1. Projects identified exploring different CCUS aspects

Project Acronym	Status	EU contribution (EUR)	Total (EUR)
CHEERS	Ongoing	9 727 105	16 818 668
IMPACTS9	Ended 30/4/2022	1 100 299	1 100 299
STRATEGY CCUS	Ended 31/7/2022	2 959 534	3 069 474

Table A4-2. Projects funded under the H2020 ACT running until 2022.

Project Acronym	Capture	Transport	Storage/ Monitoring	Use	Other*	Funding (EUR)
ALIGN	✓	✓	✓	✓	✓	14 000 000
AC2OCEM	✓			✓	✓	3 000 000
ACTOM			✓	✓	✓	1 500 000
ANICA	✓			✓	✓	2 400 000
DIGIMON				✓	✓	5 000 000
FUNMIN				✓	✓	700 000

Project Acronym	Capture	Transport	Storage/ Monitoring	Use	Other*	Funding (EUR)
LAUNCH	✓			✓	✓	5 100 000
MemCCSea	✓			✓	✓	1 700 000
NEWEST-CCUS	✓			✓	✓	2 200 000
PrISMa	✓			✓	✓	2 100 000
REX-CO ₂			✓	✓	✓	2 500 000
SENSE			✓	✓	✓	2 700 000
SUCCEED			✓	✓	✓	2 500 000

*Includes activities such as developing materials (for example sorbents, membranes) relevant to CCUS, developing business case, knowledge networks, dissemination, knowledge sharing, raising public awareness etc.

ACT was completed on 30/9/2021. However, 13 projects were offered funding from ACT in autumn 2021. A brief overview of the projects is available [here](#). Links to the projects will be available when all contractual documents are signed.

Table A2-3. H2020 projects identified in the field of carbon capture and utilisation with EU funding contribution higher than 250 kEUR.

Project acronym	CO ₂ use	Solvent	Sorbent	Membrane	HTL	Other	EU Contribution (EUR)	Total Cost (EUR)
ACCSESS		✓					14 983 874	18 427 187
BIOCONCO ₂	✓						6 999 886	6 999 886
C2Fuel	✓						3 999 840	4 130 291
C4U			✓				12 499 083	13 845 497
CARMOF*			✓				5 993 228	7 440 050
CAT CO ₂ NVERS	✓						6 641 111	6 641 111
CHEERS					✓		9 727 105	16 818 668
CLEANKER					✓		8 972 201	9 237 851
CO ₂ Fokus	✓						3 994 950	3 994 950
CO ₂ LIFE	✓						1 302 710	1 302 710
CO ₂ MPRISE	✓						702 000	702 000
CO ₂ SMOS	✓						6 918 240	6 918 240
ConsenCUS	✓						12 862 332	13 905 273
COSMOS			✓				1 500 000	1 500 000
COZMOS	✓						3 997 164	4 752 387
DeCO-HVP	✓						1 499 994	1 499 994

Project acronym	CO ₂ use	Solvent	Sorbent	Membrane	HTL	Other	EU Contribution (EUR)	Total Cost (EUR)
DMX Demonstration in Dunkirk		✓					14 739 370	19 239 369
eCOCO ₂	✓						3 949 979	4 447 979
EcoFuel	✓						4 858 548	4 858 548
ENGICOIN*	✓						6 986 910	6 986 910
GasFermTEC	✓						2 496 875	2 496 875
GECO*	✓						15 599 843	18 220 331
GENESIS				✓			9 563 904	9 563 904
GICO	✓		✓				3 928 258	3 928 258
HybridSolarFuels*			✓				1 498 750	1 498 750
ICO ₂ CHEM*	✓						5 948 589	5 948 589
KEROGREEN*	✓						4 951 959	4 951 959
LAURELIN	✓						4 448 839	4 853 054
LEILAC2						✓	11 932 231	20 770 635
LOTER.CO ₂ M*	✓						4 264 453	4 264 453
MOF4AIR			✓				9 947 143	11 094 138
OCEAN*	✓						5 523 650	5 523 650

Project acronym	CO₂ use	Solvent	Sorbent	Membrane	HTL	Other	EU Contribution (EUR)	Total Cost (EUR)
REALISE	✓	✓					6 444 164	7 131 753
RECODE*	✓						7 904 415	7 904 415
SELECT CO ₂	✓						3 772 265	3 971 833
STEELANOL	✓						10 192 516	14 560 737
TAKE-OFF	✓						4 998 788	5 340 539
UltimateMembranes				✓			1 875 000	1 875 000
VIVALDI	✓						6 969 836	6 969 836
4AirCRAFT	✓						2 239 592	2 897 154

*These projects are expected to be completed by the time this report is published

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