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CARBON CAPTURE UTILISATION AND STORAGE IN THE EUROPEAN UNION

STATUS REPORT ON TECHNOLOGY DEVELOPMENT, TRENDS, VALUE CHAINS AND MARKETS

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Contents

Foreword

This report is an output of the Clean Energy Technology Observatory (CETO). CETO's objective is to provide an evidence-based analysis feeding the policy making process and hence increasing the effectiveness of R&I policies for clean energy technologies and solutions. It monitors EU research and innovation activities on clean energy technologies needed for the delivery of the European Green Deal; and assesses the competitiveness of the EU clean energy sector and its positioning in the global energy market.

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Executive summary

2021 has seen unprecedented advances in carbon capture, utilisation and storage (CCUS) technologies. This report focuses on CCUS in power generation and industry. It is an output of the Clean Energy Technology Observatory (CETO), a joint initiative of the Joint Research Centre (JRC) and the Directorates-General for Research & Innovation and Energy.

Policy context

Carbon capture, utilisation and storage 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. The European Green Deal included CCUS in the technologies necessary for a transition to climate neutrality. 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. Therefore, CCUS remains relevant in a policy context and is the focus of this report.

Key conclusions

- CO_2 capture, transport and storage technology components are commercially available for most industries.
- The number of commercial facilities in the pipeline has increased, but more are needed to achieve ambitious targets.
- CCUS costs are still considerable, but expected to fall as/if/when capacity increases.
- There is a need for thorough (supply) value chain identification and mapping.
- Demand for materials required in the CCUS value chain is another field in need of study.
- The EU is in a good position when it comes to publications, patents, and private and public research & innovation (R&I), but is lagging behind other parts of the world in terms of venture capital companies.

Main findings

Among EU Member States, France has the highest share of public investments in CCUS research and development. Next come Germany (24%) and the Netherlands (11%), closely followed by Poland (10%). Worldwide, the US (26%) and Canada (20%) are leading the way in CCUS investments, with Japan close behind at 14% and the EU at 11%. Private R&D investments in the EU have been the second highest, following the USA, until 2017. In 2018, the EU overtook the USA in private R&D investments. Within the EU, Germany, France, the Netherlands, Italy and Spain are the top 5 countries in private R&D investment in CCUS. Our analysis shows that the USA is the leader in early-stage venture capital investments, with investments soaring to EUR 277 million between 2016 and 2021. Among EU countries, Sweden ranked the highest in CCUS venture capital, with EUR 4.5 million between 2016 and 2021. As for later-stage private investments, our analysis shows that the USA is still well in the lead, with nearly EUR 274 million in venture capital between 2016 and 2021. Among EU countries, Germany was in the lead in later-stage venture capital between 2016 and 2021, achieving venture capital volumes almost double what they were in 2010-2015. The EU, the US and Japan had the highest numbers of high-value inventions between 2009 and 2019. Among 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 5 for the number of peer review publications on the different parts of the CCUS chain, together with Belgium, Italy, Finland, Spain and Sweden.

In 2021, the USA had 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 USA's extensive activity in CO_2 enhanced oil recovery (EOR) (the respective value for Europe has been estimated at EUR 92 billion). Czechia, Ireland, Italy, France, Spain and the Netherlands are the countries with the highest estimated value added as a percentage of their gross domestic product.

Related and future Joint Research Centre work

CETO's objective is to provide an evidence-based analysis feeding the policymaking process, thus increasing the effectiveness of R&I policies for clean energy technologies and solutions. CETO is the successor of the Low Carbon Energy Observatory (LCEO) that ran from April 2015 to 2020.

Quick guide

Chapter 2 presents the state of the art of the technology, as well as future developments and trends. Chapter 3 focuses on the technology's value chain. Chapter 4 discusses the position of the EU regarding CCUS technology. Finally, Chapter 5 discusses some key points and conclusions.

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

Strengths	**Weaknesses**
• Two long-running projects in Norway and many more in the pipeline • CO_2 capture, transport and storage technology components are commercially available for most industries • Many European companies with project experience and knowledge • EU is in a good position when it comes to publications, patents, private and public R&I	• Low capture rates and high energy requirements, which should be addressed via appropriate technological advancements • Lack of clarity on the environmental impact and integrity of CO_2 capture and use • Associated cost • Lack of a clear business case • Perceived project risks and lack of investor confidence • Lack of thorough value (supply) chain identification and mapping • Lack of mapping for associated critical materials required in CCUS
Opportunities	**Threats**
• According to modelling results, facilities with CCS can decrease CO_2 emissions at an affordable cost • A sufficiently high carbon price in the EU Emissions Trading System may promote business and technology developments • Cost reduction can be achieved through increased project capacity • Large potential CO_2 storage capacity in Europe, especially in the North Sea • Models can be advanced to take into account lifecycle techno-economic, environmental and social considerations, to guide well-rounded decision making	• Lack of established CO_2 infrastructure • Lack of public acceptance • Not enough commercial facilities to achieve ambitious targets • Potential disruptions in the supply chain due to economic/geopolitical circumstances

1 Introduction

CCUS has been acknowledged in the context of the European Energy Union as a fundamental research and development priority to achieve 2050 climate objectives in a cost-effective way (European Commission, 2015). The European Green Deal included carbon capture, storage and utilisation 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).

2021 has seen unprecedented advances for CCUS technologies. In this report, the sectors covered include power generation and industry. For the current analysis, given that industrial applications are also considered, the, so far, usual classification (pre-, post-, oxy- combustion) may not be representative. In industrial processes, CO_2 may not come from fuel combustion but from the process itself such as for example, in calcination of calcium carbonate to give calcium oxide. As such, CO_2 capture is defined by the separation technology involved.

CO_2 utilisation processes include the chemical transformation of CO_2 into another product with commercial value. Enhanced oil recovery (EOR), and other uses, as in the food industry or as supercritical solvent, where CO_2 is subjected to physical and long-term chemical changes, have not been considered in this report. The overview covers all applications, related to the synthesis of fuels, chemicals and materials. Regarding CO_2 storage the focus is both on offshore and onshore aquifers, but also on considering alternative ways such as storage in basalts. On transport, both shipping and pipelines are considered.

The review of each topic is organised following main blocks: (i) Literature review and technology analysis to depict the state-of-the-art of CCS and CO_2 use technologies. (ii) Technology assessment based upon technology readiness level (TRL) evolution according to literature and to European R&D projects.

The review of the technology status is based on different relevant sources such as subject matter books and scientific articles published in peer-reviewed journals; the SETIS webpage and associated SET Plan actions; the Carbon Sequestration Leadership Forum (CSLF); online information from the International Energy Agency (IEA), the Global CCS Institute and the Global Status of CCS series, among others.

In the patenting activities section the data are sourced 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 for up to 2019.

In the *Impact and Trends of EU-supported Research and Innovation* paragraph, the main sources are CORDIS and internal databases for identifying the EU co-funded projects.[1] Aside 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 in 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 maybe inconclusive. Projects that do not consider the separation of CO_2 directly or its immediate re use, such as for example specific catalyst development with chemical functionalisation, artificial photosynthesis and technologies aiming to advance CO_2 reduction have been excluded from the analysis. Technologies that are focusing on the molecular level are also excluded.

On the technology readiness assessment from European R&D projects, the focus is on CCS and CO_2 utilisation projects granted H2020 (2014-2020) funding. Technologies that refer to standalone techniques, envisioned to be part of CO_2 capture or utilisation chain have not been considered (for example, the study of integrated platforms for photocatalytic water splitting and CO_2 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 CO_2 utilisation technologies, processes for the synthesis of fuels, chemicals or materials are also examined. TRL levels for CO_2 storage, transport and monitoring follow the classification given by (European Commission and EC, 2014) and (DOE/NETL, 2015). Finally, to determine the TRL of a sub-technology we assume that there should exist at least one project at the specific TRL assigned.

[1] The keywords used were: carbon capture, carbon dioxide, CO_2 capture, carbon utilisation and use, carbon use, surplus, CO_2 storage, CO_2 transport, CO_2 monitoring and CCS.

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 organisation 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 properly cited where relevant.

2 Technology State of the art and future developments and 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.

Commercial uses of CO_2 also exist and CO_2 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, are at different TRL level.

From the source to the sink of CO_2 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 a safe storage, avoiding any leakage of CO_2 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.

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*[1] 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

Source: JRC analysis

Table 2. Other research areas.

Area
Materials and corrosion
Storage (natural analogues)
CO_2 storage in other geological sites, eg. basalts
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.

Source: JRC analysis

2.1 Technology readiness level (TRL)

2.1.1 Carbon capture and utilisation technology

Until now, CO_2 capture configurations were described with definitions mainly referring to their relation with 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 to (iii) cryogenic air separation (air separation unit – ASU) to obtain pure oxygen. These technologies are currently available but research and development on necessary improvements is ongoing. Second generation technologies include those in research and development (R&D) phase that will be ready for demonstration at a later stage, while third generation technologies are at an early stage of development, even at a conceptual stage. Different demonstration timeframes have been suggested over the years. However, some technologies have not evolved in their TRL in the last 10 years, perhaps indicating some fundamental challenge to further development (e.g., functional material reactivity and/or stability, need of extreme operating conditions, limitations in gas-liquid/solid contact area, etc.). The technology readiness levels of different technologies are shown in Table 3.

According to the Global CCS Institute, there are 27 commercial CCUS facilities operating worldwide, out of which 4 are in Europe (Hungary, Iceland and Norway) (Global CCS Institute, 2021a). The projects operate in natural gas processing and direct air capture. The only project in power generation (CarbFix) is in Iceland and includes a carbon capture and injection solution where CO_2 dissolved in water is injected into the subsurface. There it reacts with favourable rock formations to form solid carbonate minerals via natural processes in about 2 years. In the initial pilot tests CO_2 was sourced from a pilot gas separation station at the Hellisheidi geothermal plant.

Table 3. TRL assessment and key technology vendors of the CO_2 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)	5-7	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
Solid looping	Calcium Looping (CaL)	6-7	Carbon Engineering
	Chemical Looping Combustion (CLP)	5-6	Alstom
Inherent CO_2 capture	Allam-Fetvedt Cycle	6-7	8 Rivers Capital
	Calix Advanced Calciner	5-6	Calix

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

In addition to CO_2 capture from point sources, direct air capture is one set of technologies extract CO_2 directly from the atmosphere. Today, two technology approaches are being used to capture CO_2 from the air: liquid and solid systems. Liquid systems pass air through chemical solutions (e.g. a hydroxide solution), which removes the CO_2. The system reintegrates the chemicals back into the process by applying high-temperature heat while returning the rest of the air to the environment. Solid system technology makes use of solid sorbent filters that chemically bind with CO_2. When the filters are heated and placed under a vacuum, they release the concentrated CO_2, which is then captured for storage or use (IEA, 2021a). Permanent CO_2 storage is a necessary prerequisite for this technology to achieve negative CO_2 emissions.

Figure 1 shows a scheme of technology readiness through the CCUS value chain presented by the International Energy Agency which includes CO_2 use processes.

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

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

In October 2021, the CCUS SET-Plan community published the CCUS Roadmap 2030. This Roadmap aims to identify and stress the actions that will be necessary for the large-scale development and deployment of CCS and CCU in the 2020s, build on the work done within the CCUS SET-Plan, and provide an overview of the status of the technologies today. The Roadmaps suggests to target for 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, of which at least two pilots to test climate positive solutions such as Bio-CCS and direct air capture (DAC) (SET-Plan Working Group CCUS, 2021).

2.1.2 CO_2 transport and storage

Currently, CO_2 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 CO_2 at the very large scale associated with CCS has not yet been achieved using ships or rail. The TRL for CO_2 shipping ranges from 3 to 9. (Global CCS Institute, 2021b). Pipelines are the mode of transporting CO_2 at significant scale, primarily in the United States. In Europe, CO_2 pipelines are operating in Netherlands and Norway. In Norway, an offshore 153-kilometre long CO_2 pipeline is operating for the Snøhvit CO_2 storage facility.

CO_2 storage in saline formations has a TRL 9. CO_2 storage in saline formations has been occurring in the North Sea since 1996 when the Sleipner CCS project started operating. Since then over 20 Mt of CO_2 have been injected for storage. CO_2 storage through Enhanced Oil Recovery (CO_2-EOR) has been in operation for nearly 50 years (National Petroleum Council, 2019). Currently, there are over 40 CO_2-EOR operations with most of them operating in the USA (Bui. M et al., 2018). While CO_2-EOR operations aim to maximize oil recovery, CO_2 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 the storage of CO_2: 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).

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

Source: (IEA, 2020a)

2.2 Installed Capacity

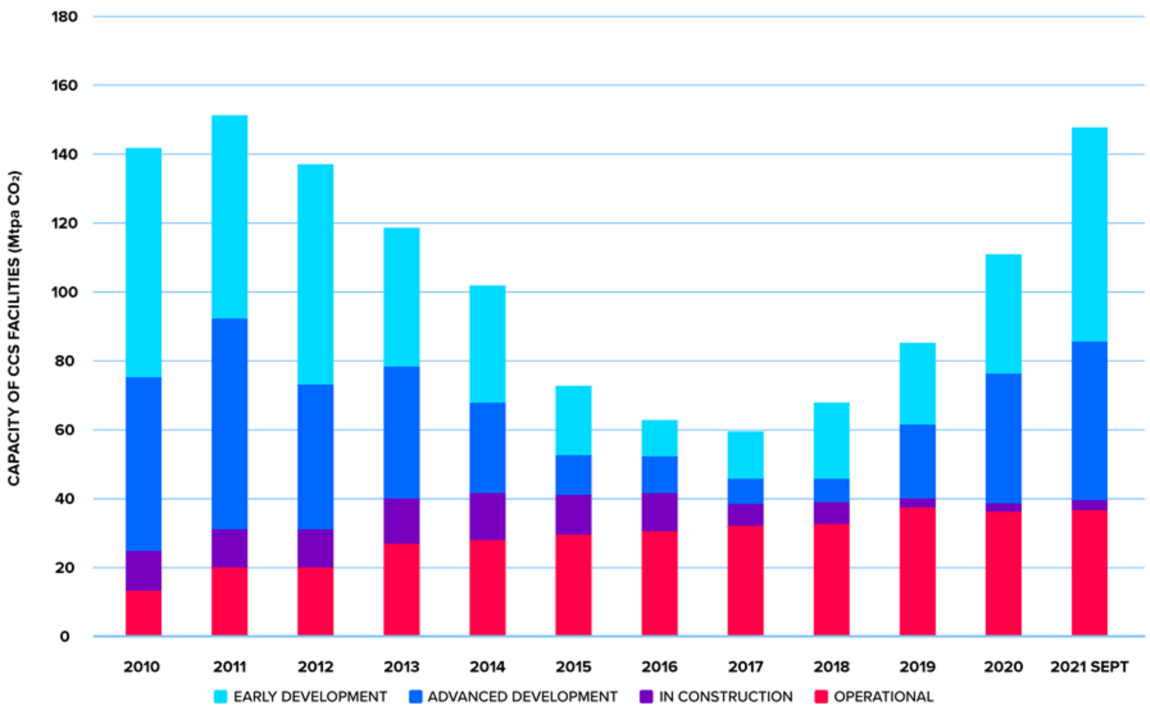
According to the Global CCS Institute, the CCS project pipeline is growing more robustly than ever. As of June 2021, the capacity of projects in development grew to 111 Mtpa CO_2 in September 2021 – a 48 per cent increase from 2020 (Global CCS Institute, 2021c). These facilities cover a wide range of 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 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 CO_2 infrastructure such as the PORTHOS, ATHOS and ARAMIS projects in the Netherlands and Antwerp@C in Belgium as well as projects included in the projects of common interest lists for 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 the last years. The Global CCS Institute lists 6 projects in hydrogen production in the EU (in Italy, the Netherlands and Sweden), albeit different stages of development. It remains to be seen whether this trend will continue and develop further. Direct Air Capture (DAC) has also received a lot of attention besides the typical CO_2 separation technologies. Since its foundation in 2009, the Swiss company Climeworks has deployed 15 DAC facilities throughout Europe (Climeworks, 2021). The first commercial plant is operating since 2017 and in 2021 another commercial CCS facility, ORCA, entered operation in Iceland. While CCS developments stagnated in power generation in the last decade, one project, the Italian Adriatic Blue – ENI Power CCS, has emerged to be in early development.

Globally, there are 27 operating CCUS projects with a capture capacity of nearly 37 Mt of CO_2 per year (Global CCS Institute, 2021c). Of these, nearly 3 Mt of CO_2 per year are captured and stored in Europe, specifically in Norway, in the Sleipner and Snohvit projects.

While in Europe this trend has not changed, globally, almost 40% of this capacity has been achieved in the last ten years as shown in Figure 2.

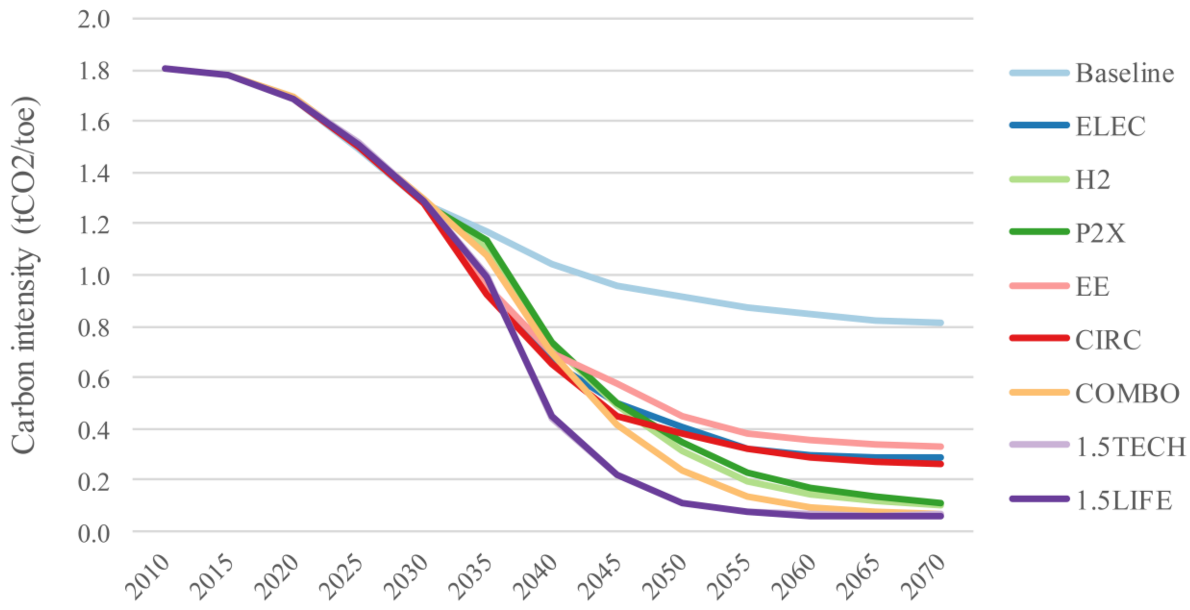
Figure 2. Pipeline of commercial CCS facilities from 2010 to September 2021 by capture capacity (Global CCS Institute, 2021c)



Source: (Global CCS Institute, 2021c)

The latest scenarios released by the European Commission as part of the Fit-For-55 package are focusing in 2030. Toward 2050, according to the European Commission's Long Strategic Vision, 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 progressively get out of the power mix, with about 20 GW only left in all scenarios except for 1.5TECH scenario, where 38 GW capacity is still present. 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. On 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



Source: (European Commission, 2018b)

The role of carbon removal technologies such as DAC and BECCS is somehow 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 $MtCO_2$ and more than 500 $MtCO_2$ 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 CO_2/year are projected to be captured using direct air capture (DAC) by 2050, and already 85 Mt CO_2/year by 2030 (IEA, 2021a). Projections from the scenarios within the EU long-term strategy (LTS) to reach carbon neutrality by 2050, allocate 210 $MtCO_2$ and 123 $MtCO_2$ 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 $MtCO_2$/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 tons of CO_2 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.

2.3 Technology Cost – Present and Potential Future Trends

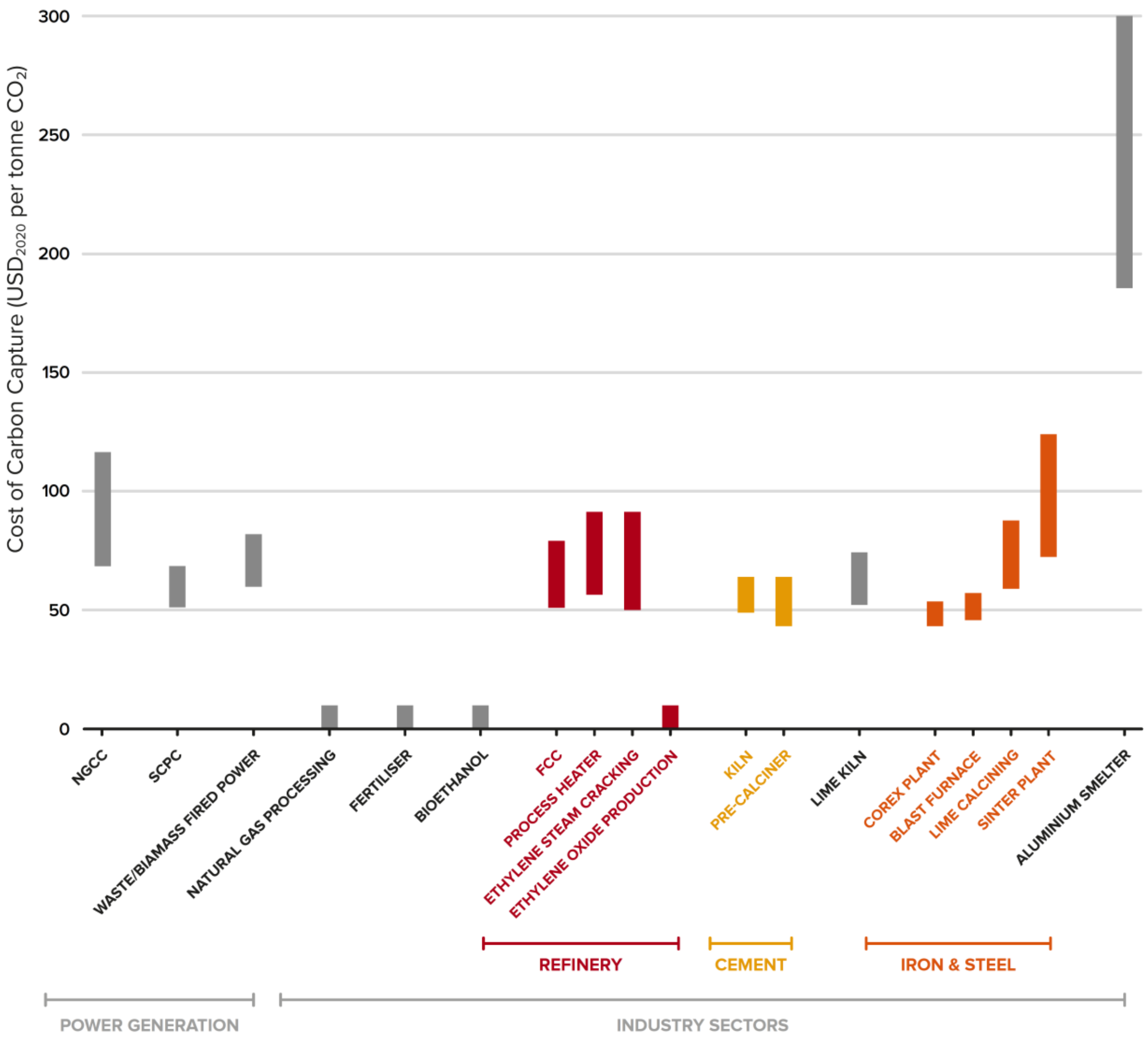
The cost of each CCS component varies from project to project. Technology is a vital consideration in CCS cost, but it is not the only factor affecting it. Cost variation is primarily due to differences in the size and location of the CCS facility and the characteristics of the CO_2 source.

Looking specifically at carbon capture, costs vary significantly based on the sector and the technology (IRENA, 2021). The cost of capturing CO_2 can vary from a range of EUR[2] 13-22/t CO_2 for industrial processes producing "pure" or highly concentrated CO_2 streams (such as ethanol production or natural gas processing) to EUR 35-105/t CO_2 for processes with "dilute" gas streams, such as cement production and power generation. The large range in costs is also due to that while some CO_2 capture technologies are commercially available, others are

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

still in development and hence, prohibitively expensive (IEA, 2021c). Figure 4 indicates the cost of carbon capture for the major sectors in which it can be applied.

Figure 4. Cost of carbon capture by industry



Source: (Global CCS Institute, 2021b)

Regarding the cost of transport and storage, this can also vary greatly on a case-by-case basis, depending mainly on CO_2 volumes, transport distances and storage conditions. In the United States, for example, the cost of onshore pipeline transport is between EUR 1.8-12 (USD 2-14)/t CO_2. The cost of onshore storage also shows a wide range. In Europe, ZEP estimated the typical costs for a short onshore pipeline (180 km) and a small volume of CO_2 (2.5 Mtpa) to be just over EUR 5/t CO_2, reducing to approximately EUR 1.5/t CO_2 for a large system (20 Mtpa). Offshore pipelines are more expensive. For transport with ships, the cost is less dependent on distance. For a large transport volume of CO_2 (20 Mtpa) costs are estimated to approximately EUR 11/t CO_2 for 180 km; EUR 12/t CO_2 for 500 km and nearly EUR 16/t CO_2 for very long distances (1 500 km), including liquefaction. For a smaller volume of CO_2 (2.5 Mtpa), costs for 500 km are just below €15/tonne, including liquefaction (ZEP, 2011a).

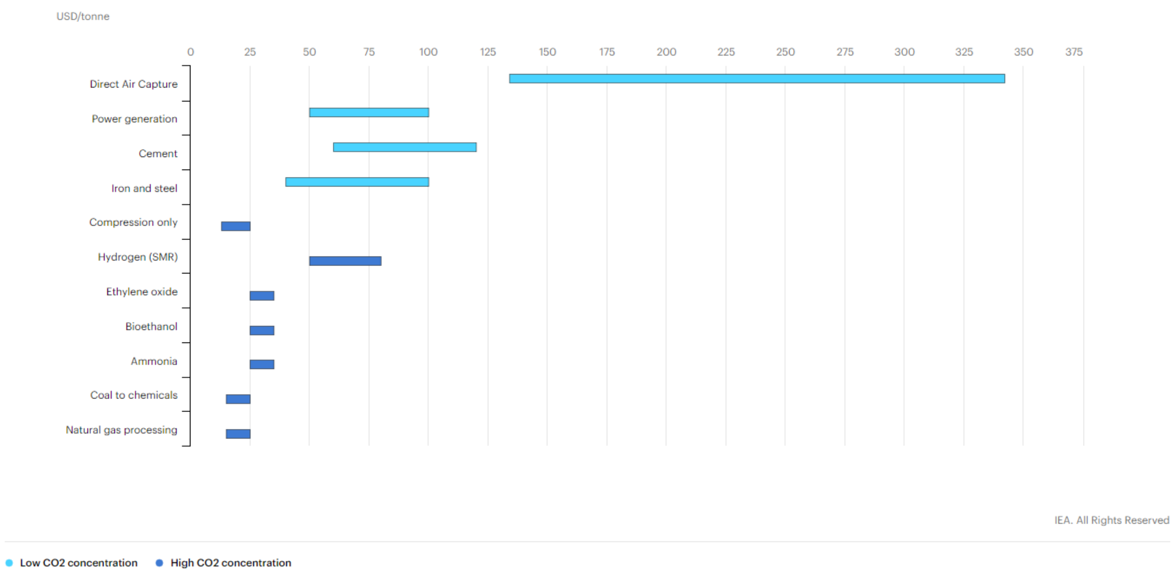
Regarding CO_2 storage, the cost range is large spanning from EUR 1 to 20/t of CO_2. On the assumption that the cheaper available storage sites will be developed first, ZEP suggested that storage costs for the early commercial phase will be at the level of EUR 2-12/t as defined for onshore saline aquifers. However, onshore CO_2 storage has been largely prohibitive in Europe, thus, a more realistic assumption is to consider CO_2 storage cost in the offshore (for example in depleted oil gas reservoirs) which is in the range of EUR 2 to 20/t of CO_2 (ZEP, 2011a).

In the US, projects have managed to create revenue by selling CO_2 to be injected into (and permanently stored in) oilfields to enhance production (enhanced oil recovery).

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 costed EUR 868 million (CAD[3] 1.24 billion), of which EUR 420 million (CAD 600 million) was for CCS and the rest for modernizing the plant (National Coal Council, 2015). However, published results from this project expect cost reductions as high as 67% for a next 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 5 shows values for CO_2 capture by sector and initial CO_2 concentration. This ranges from EUR 44-88 (USD 50-100) t/CO_2 for the power generation sector.

Figure 5.Levelised cost of CO_2 capture by sector and initial CO_2 concentration, 2019



Source: IEA (2021) Is carbon capture too expensive?, https://www.iea.org/commentaries/is-carbon-capture-too-expensive. All rights reserved.

The cost of CO_2 capture from sources such as in coal-fired power generation has been reducing over the past decade and is projected to decrease 50% by 2025 compared to 2010 (Global CCS Institute, 2021b). However, the levelised cost is sensitive to fuel price (for example coal, gas). The current rise of coal and gas price (2021) would obviously have an impact on the cost estimations.

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 (USD_{2020} 105) per tCO_2 (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 (USD_{2020} 70)/tCO_2 (Petra Nova Parish Holding LLC, 2017).

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

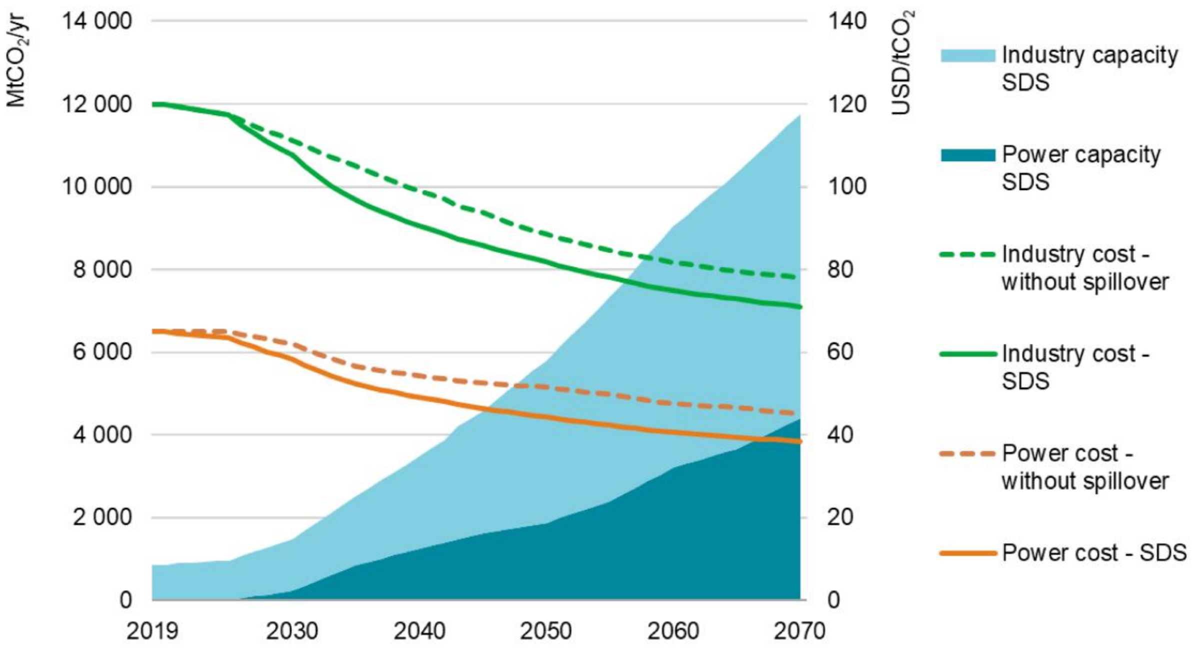
The IEA expects capture costs in power generation to be reduced by the adoption of various emerging technologies. For instance, electrochemical separation is projected to lower the LCOE with CO_2 capture by 30%; chemical absorption with advanced solvents and configurations, membrane separation, pressure 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-

[3] 1 CAD= 0.69992 EUR (Source: oanda.com. Accessed on 13/01/2022. Available at: https://www.oanda.com/).

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 CO_2 (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).

For transport and storage, the main route for reducing costs is by exploiting economies of scale (IEA, 2020a). Clustering some of the projects would also allow for the development of sufficient regional transport and storage infrastructure to make additional projects that much are more viable (Helle and Koefoed, 2018). Wood and Mackenzie also forecast cost reductions of around 20% by 2050, as the industry scales up and technology improves (Wood Mackenzie, 2021).

Figure 6.Cumulative capacity and capture cost learning curve for CO2 chemical absorption in coal-fired power generation and small industrial furnaces in the Sustainable Development Scenario, 2019-2070 [4]



Source: IEA (2020), CCUS in clean energy transitions. All rights reserved. (IEA, 2020b)

In 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 R&I funding

Government, or public, R&D investment can have a significant positive effect on the development and deployment of a technology, creates a positive environment for private initiatives, and affects among others the number of relevant publications and patent applications. As such, it is an important indicator of the level of development and competitiveness in a given technological area. The following information is based on JRC analysis with data from the IEA (IEA, 2021b).

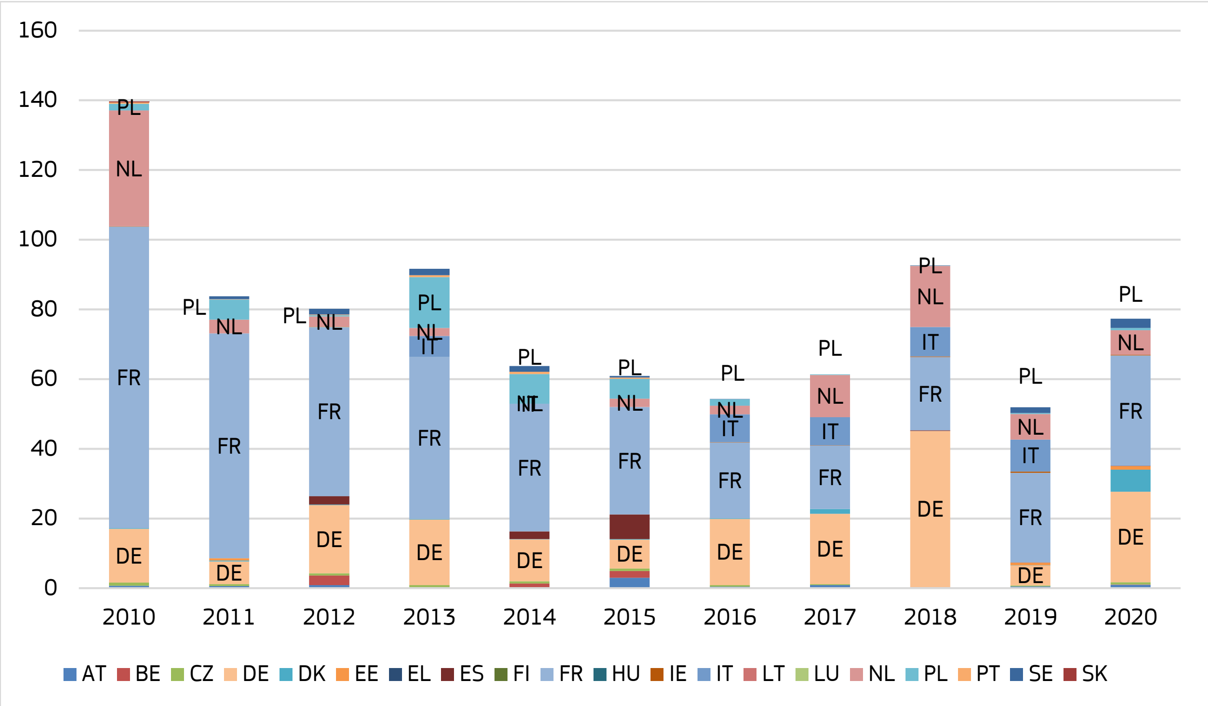
In 2010 the public investment in CCUS R&D reached a 10-year maximum from 2010 to 2019 (Figure 7). Increased investments in the EU can be seen again in 2013 and 2018. The majority of the investments were classified generically without specifying any CCS chain part. From the ones that specified this, the majority of

[4] Note: SDS = Sustainable Development Scenario. Solid line for technology costs represents the cost trajectory in the Sustainable Development Scenario while the "without spillover" case is a counterfactual that shows the slower price decline that would be observed if the technology could not benefit from experience gathered in different applications.

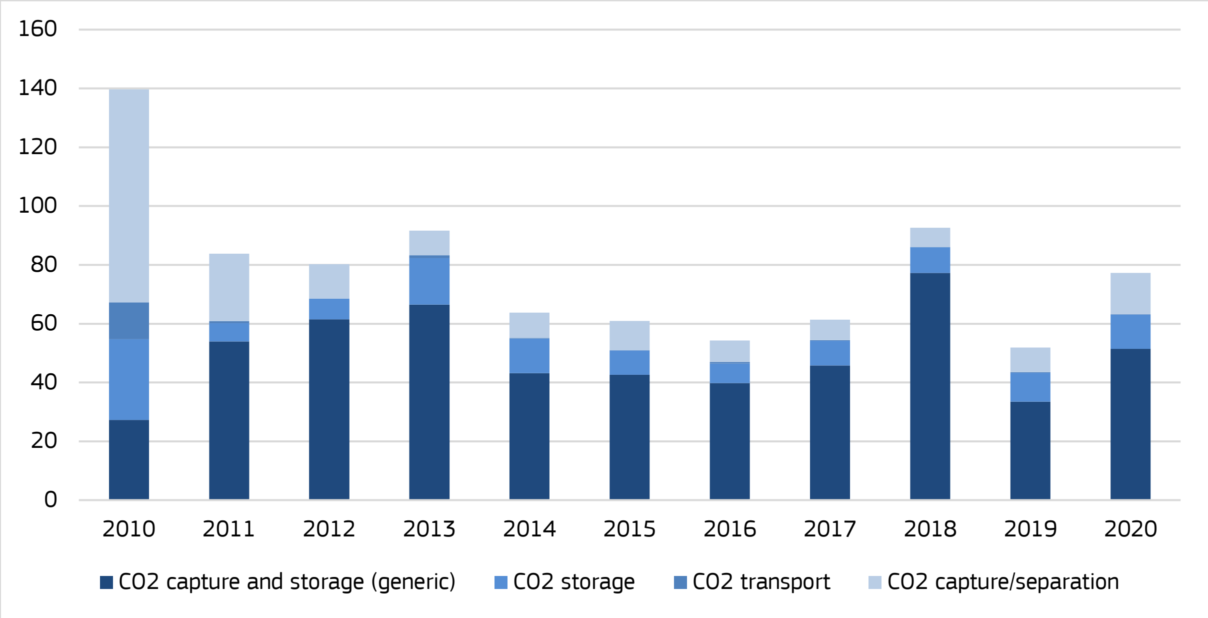
the investments were channelled toward CO_2 capture/separation (EUR 98.02 million), followed by CO_2 storage (EUR 73.35 million) and CO_2 transport (EUR 8.11 million). On an EU level for projects starting in 2019, and for H2020 specifically, France (i.e. French entities) is the MS with the highest share of grants in CCUS R&D. This is in agreement with the highest public R&D investment for the same year. The next entities awarded with the highest share cumulatively in H2020 are located in Belgium, Spain, the Netherlands and Italy. However, with regards to public investments, following France are the NL, Germany, Sweden and Estonia. These investments focus in the area of carbon capture and utilisation, mostly for the production of chemicals.

Figure 7. a) Public R&D investments (EUR million) in CCUS in the EU by year and by MS; b) Public R&D investments (EUR million) in CCUS in the EU by year by CCUS component.

a)



b)

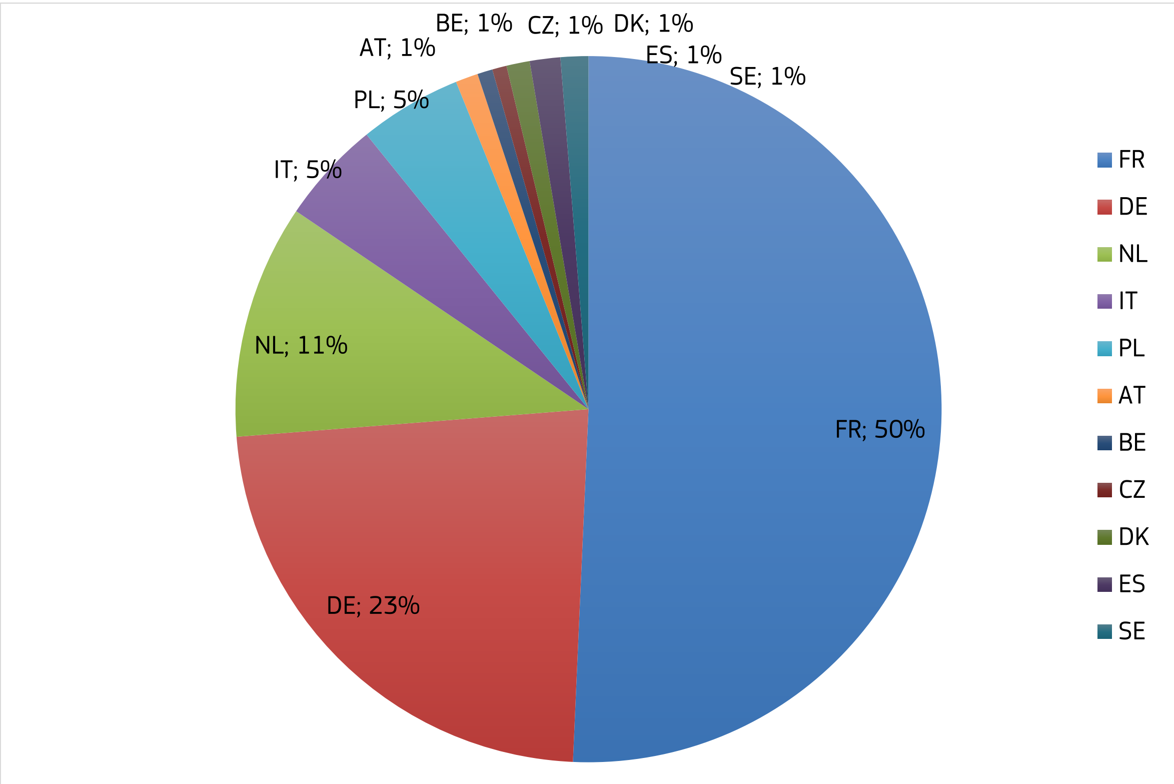


Source: JRC based on IEA

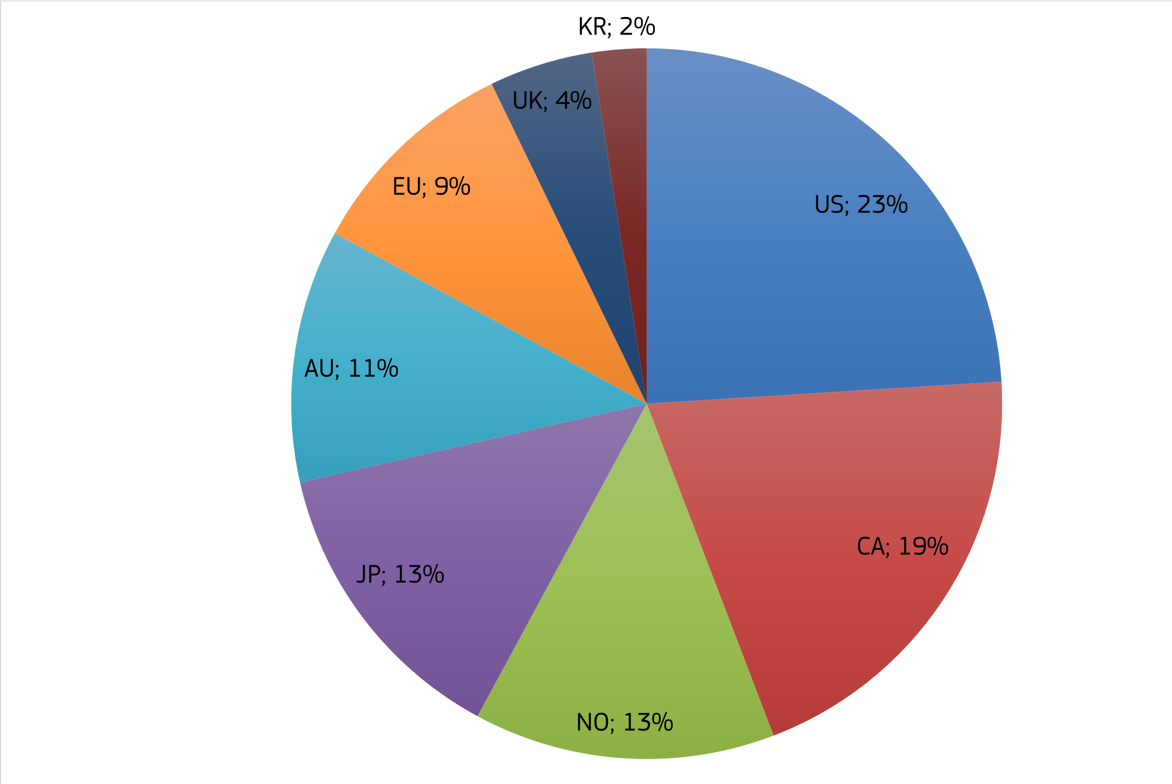
Between 2010-2019, Figure 8 shows that among EU MS, France was the country with the highest share of public investments made in CCUS research and development. Next was Germany (24%) and the NL (11%), closely followed by Poland (10%). Worldwide, the US (26%) and Canada (20%) are leading the way in CCUS investments. Japan follows closely with Europe at 14% and 11%, respectively.

Figure 8. 2010-2020 public R&D investments (EUR million) in CCUS in the a) 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

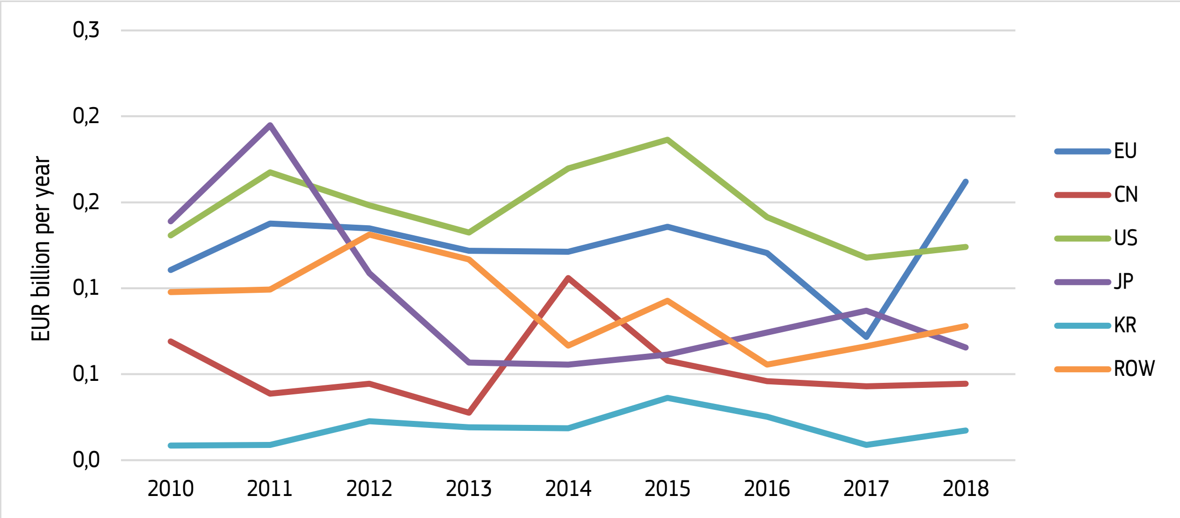
2.5 Private R&D funding

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

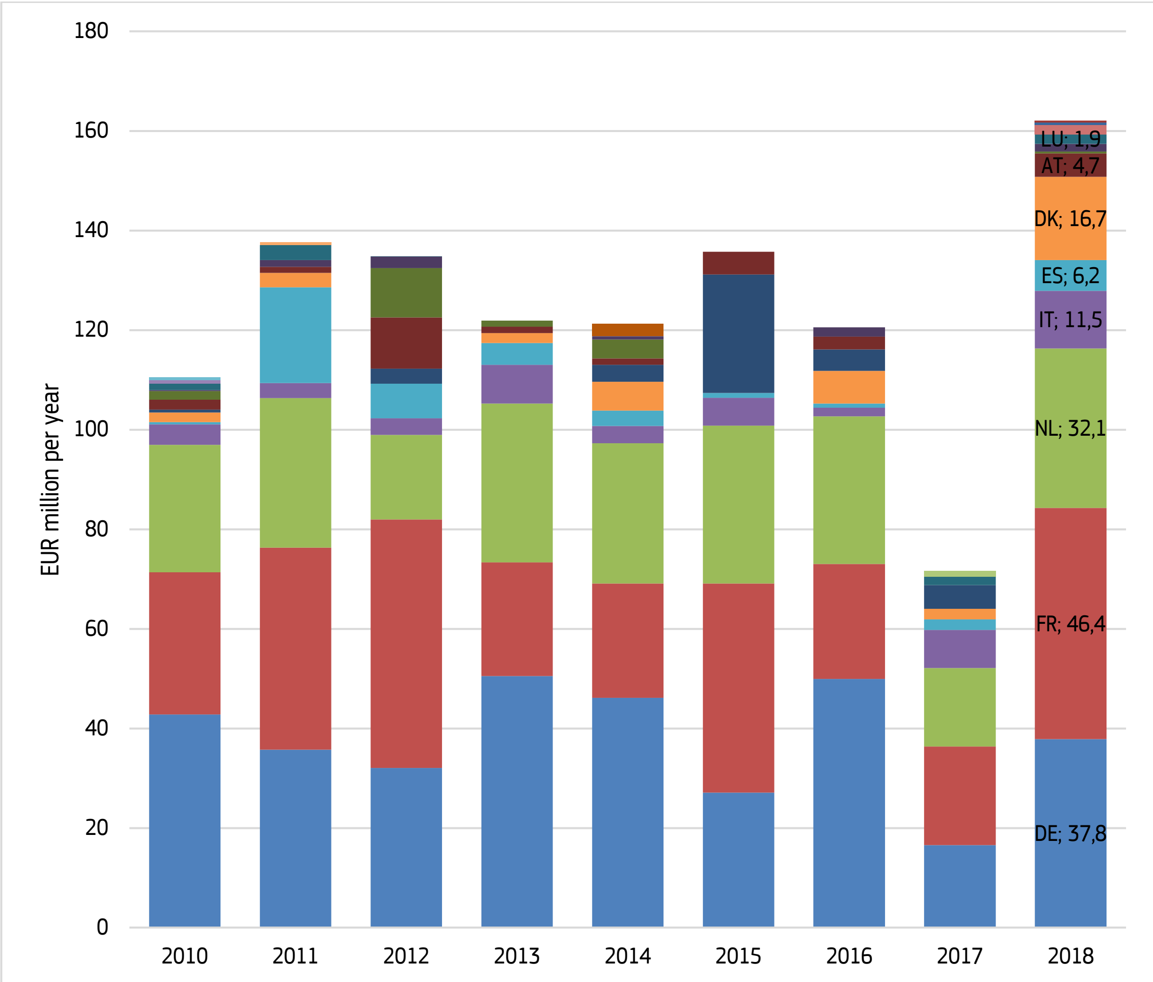
Our analysis indicates that private R&D funding has been relatively stable in the EU. R&D investments in the EU have been the second highest, following the USA, until 2017, when investments in the EU were the highest (Figure 9a). Within the EU, Germany, France, the Netherlands, Italy and Spain are the top 5 countries in private R&D investment in CCUS (Figure 9b).

Figure 9. 2010-2018 private R&D investments (EUR million/year) in CCUS in the a) EU by MS and b) globally.

a)



b)

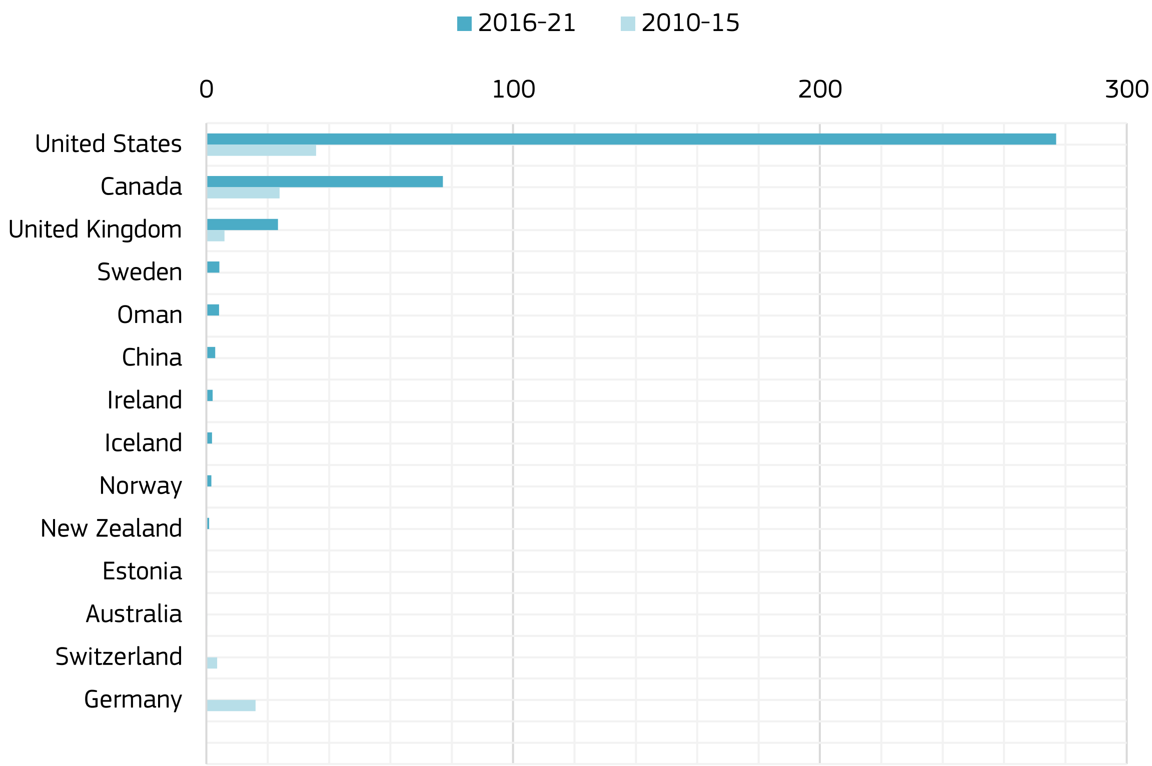


Source: JRC

In addition to public and private sources of finance, venture capital (VC) financing can play an important role in the development of a technology. This is primarily because of venture capitalists' tendency to fund firms with high potential but risky growth trajectories and returns (Bellucci *et al.*, 2021).

Our analysis shows that the USA is the leader in early stage[5] venture capital investments (Figure 10) with investments soaring to EUR 277 million between 2016-21. Withing EU countries, Sweden ranks the highest in CCUS venture capital with EUR 4.5 million between 2016-2021. It is interesting to note that while in some countries such as Germany venture between 2010 and 2015 capital investments were notable (EUR 16 million), in the years 2016-2021 they plummeted.

Figure 10. 2010-2021 Top countries - VC investments - Early stages (EUR million)

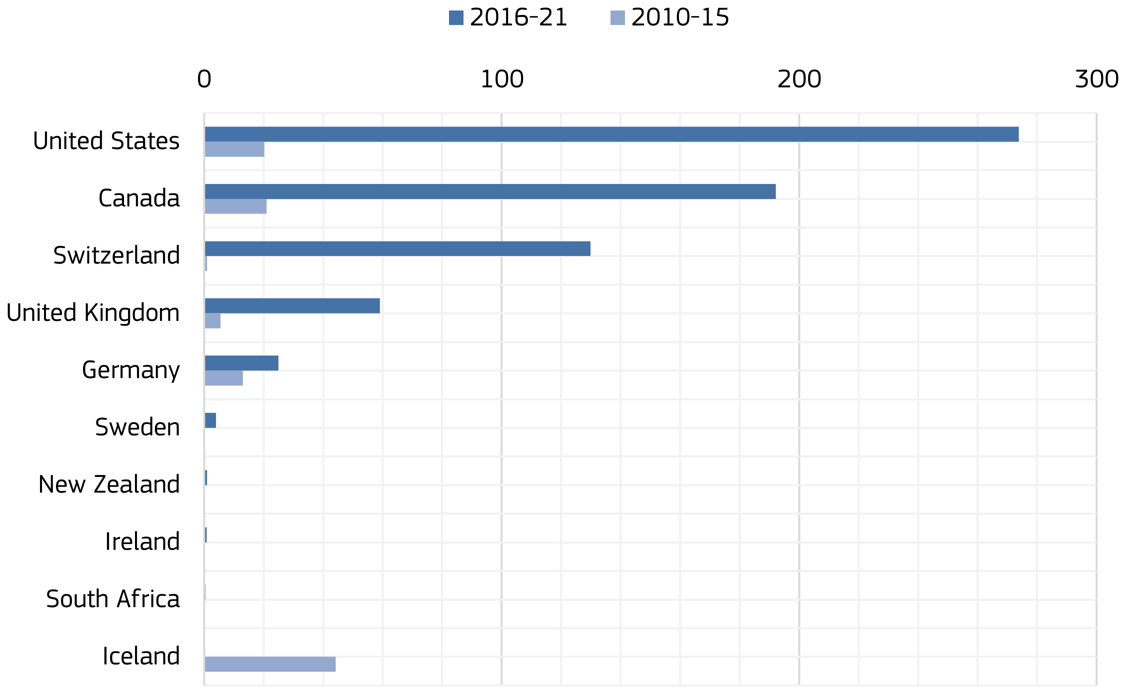


Source: JRC based on Pitchbook

When it comes to later stage private investments which mainly represents scale-ups, our analysis shows that the USA is by far still in the lead with nearly EUR 274 million in venture capital between 2016 and 2021. In contrast to early stage investments, Germany has the lead in later stage venture capital between 2016 and 2021, which is almost double from the venture capital in the years 2010-2015 (Figure 11).

[5] The early stages indicator include Pre-Seed, Accelerator/Incubator, Angel, Seed and Early stage VC investments; it also include public grants. At the time they raise such investments, those companies can usually be considered as start-ups.

Figure 11. 2010-2021 Top countries - VC investments - Later stages (EUR million)



Source: JRC based on Pitchbook

2.6 Patenting trends

Patents' activity is an important indicator of the level of development and competitiveness in a given technological area. Patents on CCUS are identified by using the relevant Y code families (Y02C and Y02P) of the Coordinated Patent Classification (CPC) for climate change.

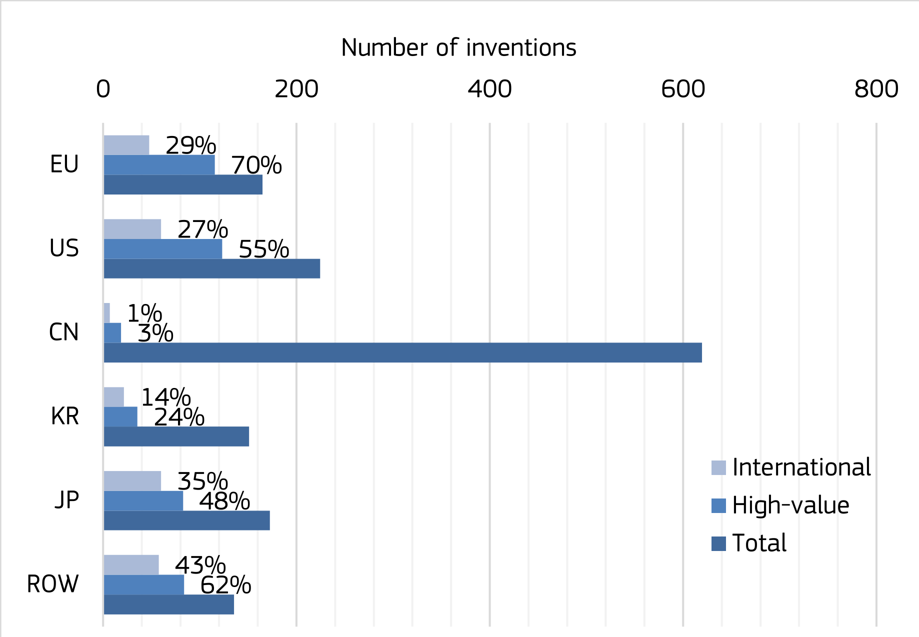
In the EU, between 2017 and 2019, we have identified 165 inventions in total,[6] 70% of which are high-value.[7] This is the highest percentage of high-value inventions when compared to other parts of and the rest of the world (Figure 12). The EU, the US and Japan have been the regions with the highest numbers of high-value inventions between 2009 and 2019 (Figure 13). Among EU member states, France is the country with the highest number of high-value inventions, followed by Germany and the Netherlands (Figure 14).

Figure 15 shows the companies that have been leading in high-value inventions in the world (a) and in the EU (b). Air Liquide (FR) and Linde (DE) are leading both within global companies and within the EU.

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

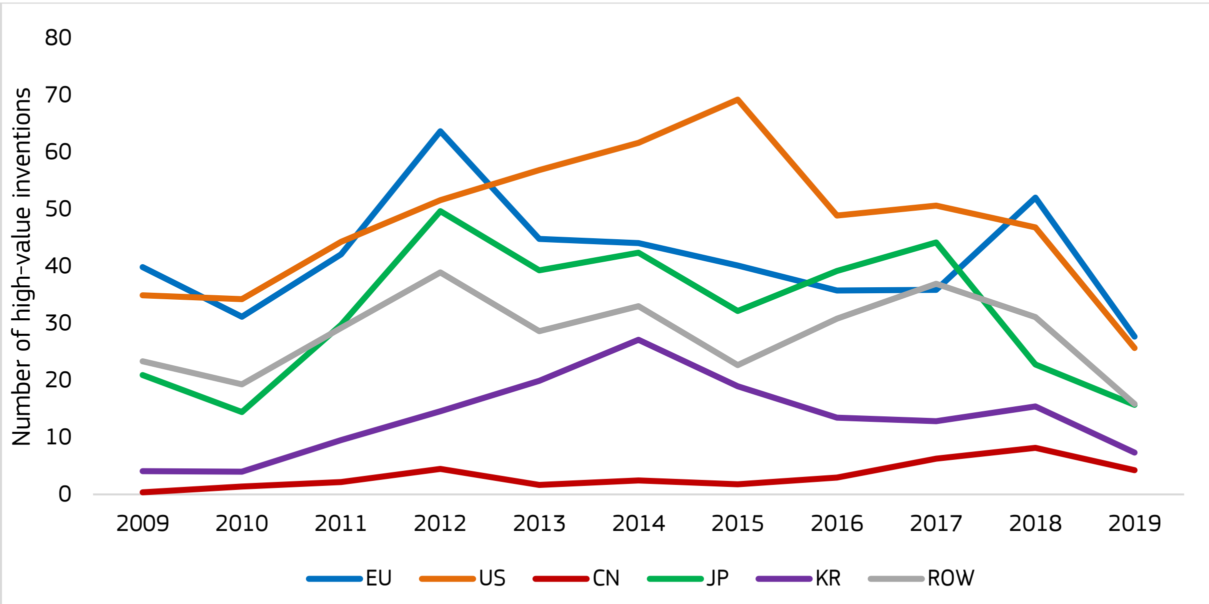
[7] High-value inventions (or high-value patent families) refer to patent families that include patent applications filed in more than one patent office.

Figure 12. Number of inventions and share of high-value and international activity (2017-2019)



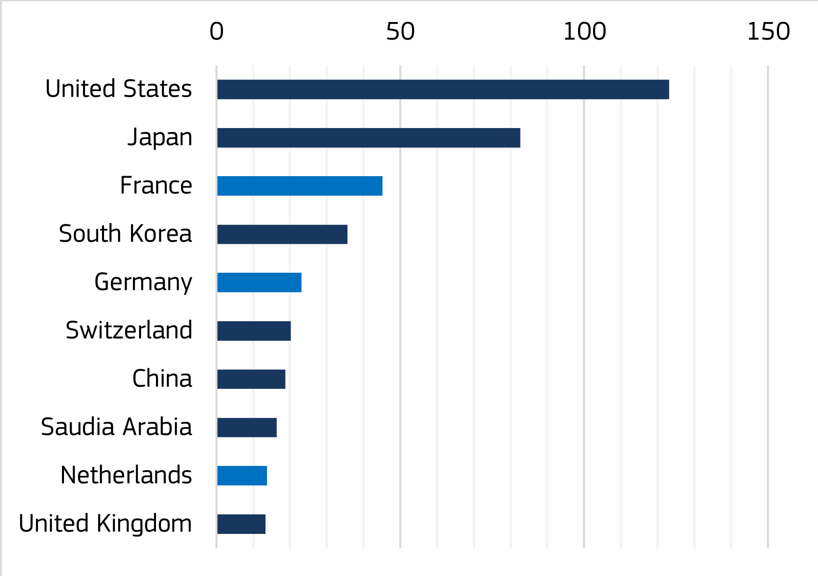
Source: JRC based on EPO Patstat

Figure 13. Number of high-value inventions and international activity (2009-2019)



Source: JRC based on EPO Patstat

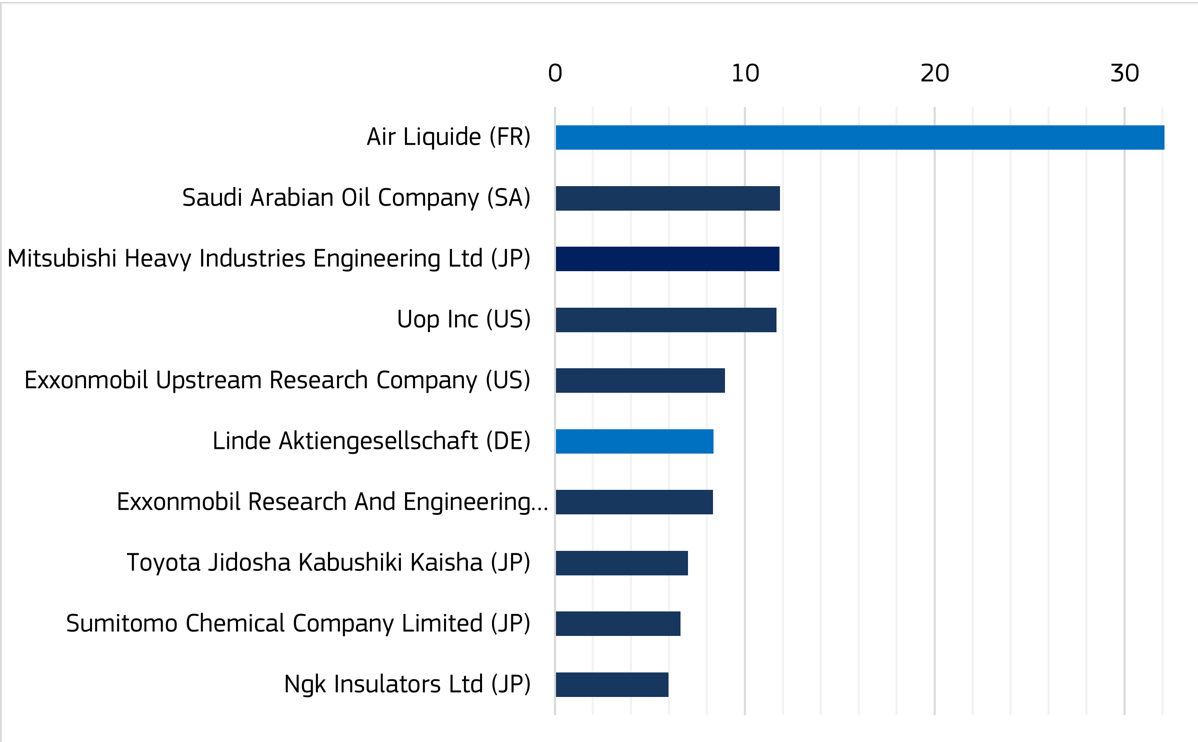
Figure 14. High-value inventions - Top 10 countries (2017-2019)



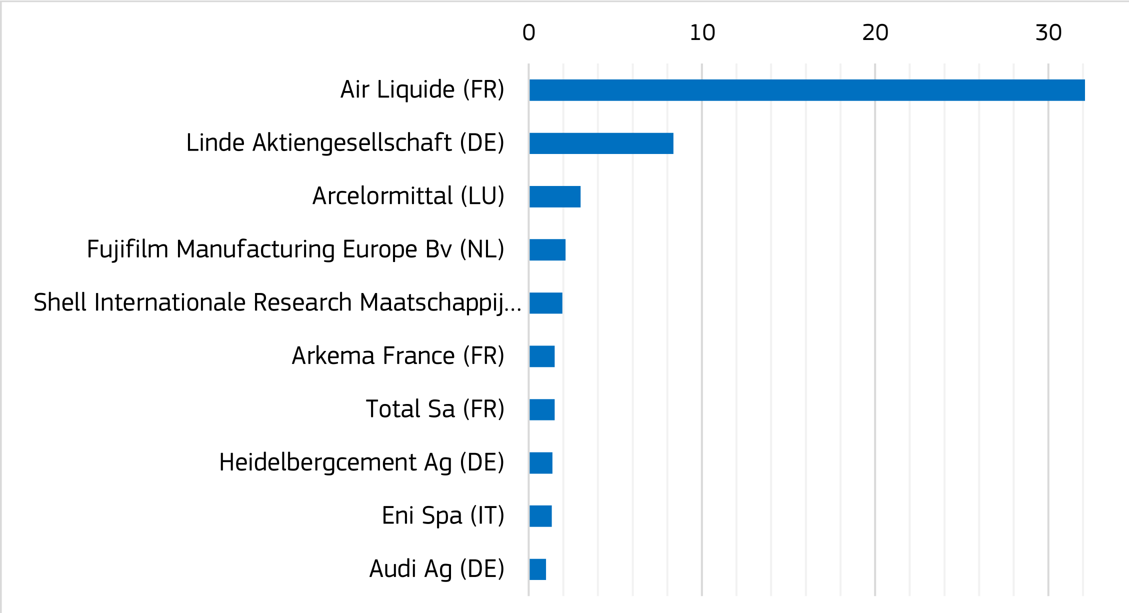
Source: JRC based on EPO Patstat

Figure 15. High-value inventions (2017-2019), a) top 10 companies and b) top 10 EU companies

a)



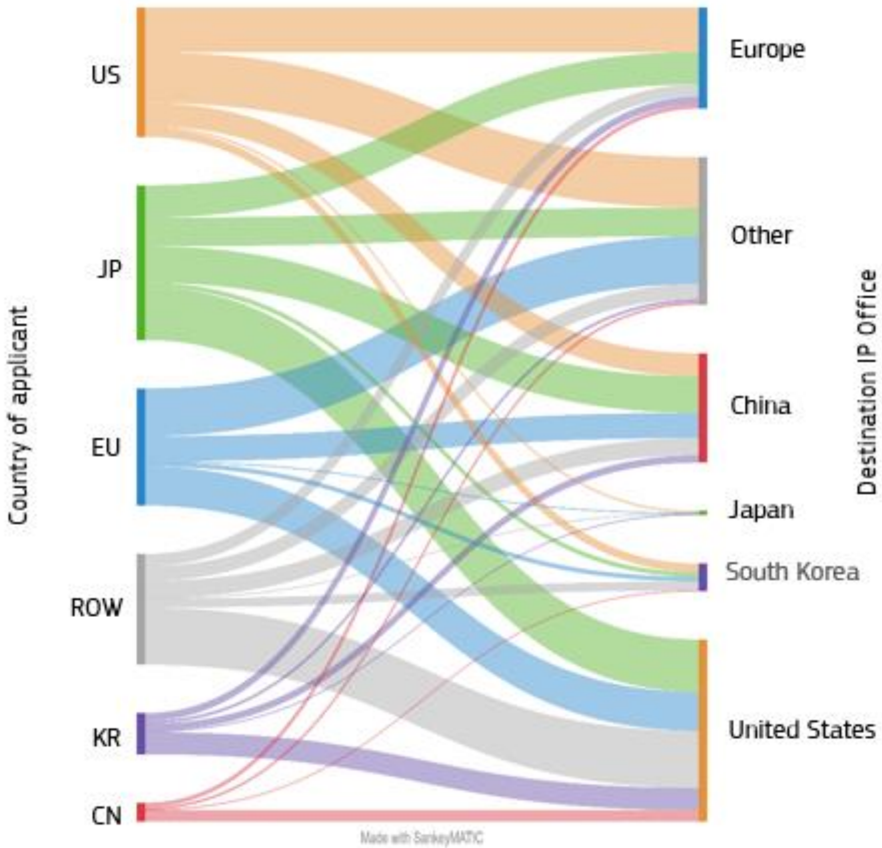
b)



Source: JRC based on EPO Patstat

To protect their inventions, countries are applying mostly in European and US IP offices. US applicants turn to Europe as well as China. Japan is applying mostly in Europe, China and the US. The EU is also mostly applying in US, China but other countries as well (Figure 16).

Figure 16. International protection of high-value inventions (2017-2019)



Source: JRC based on EPO Patstat

2.7 Bibliometric trends/Level of scientific publications

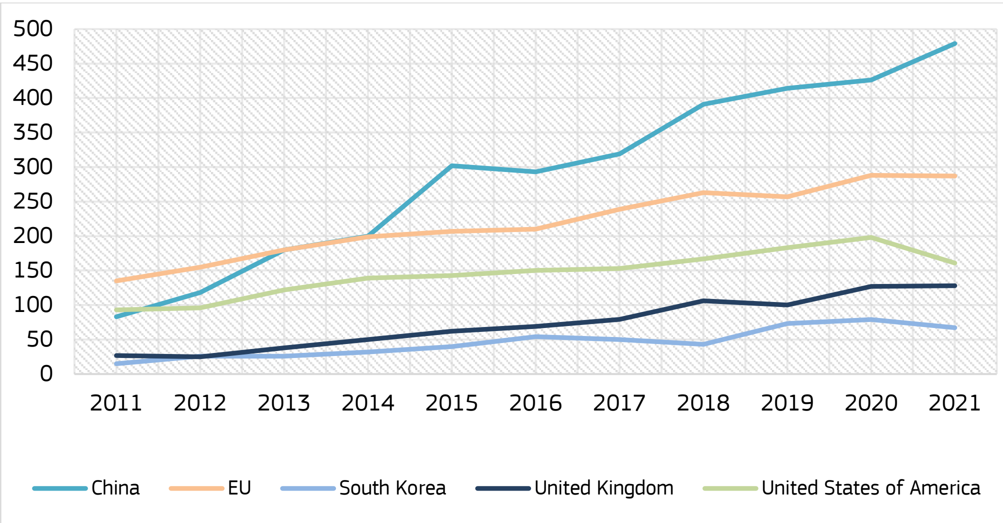
Given the potential that is attributed to CCUS in helping countries to achieve ambitious net zero climate goals, a growing research interest is attracted to different fields. Bibliometric analysis is a useful tool to search through published information on a specific topic and is widely applied to evaluate 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.[8] The keywords used to create the datasets were based on the technology classification presented in Table 1.

Publications in CO_2 capture have been increasing in the last ten years. The EU has been leading the way on the number of peer-reviewed articles per year until 2013 but China has since taken over (Figure 17a). Within the EU, Spain, Italy, Germany, Netherlands and France have been the top five countries in peer-reviewed articles (Figure 17b).

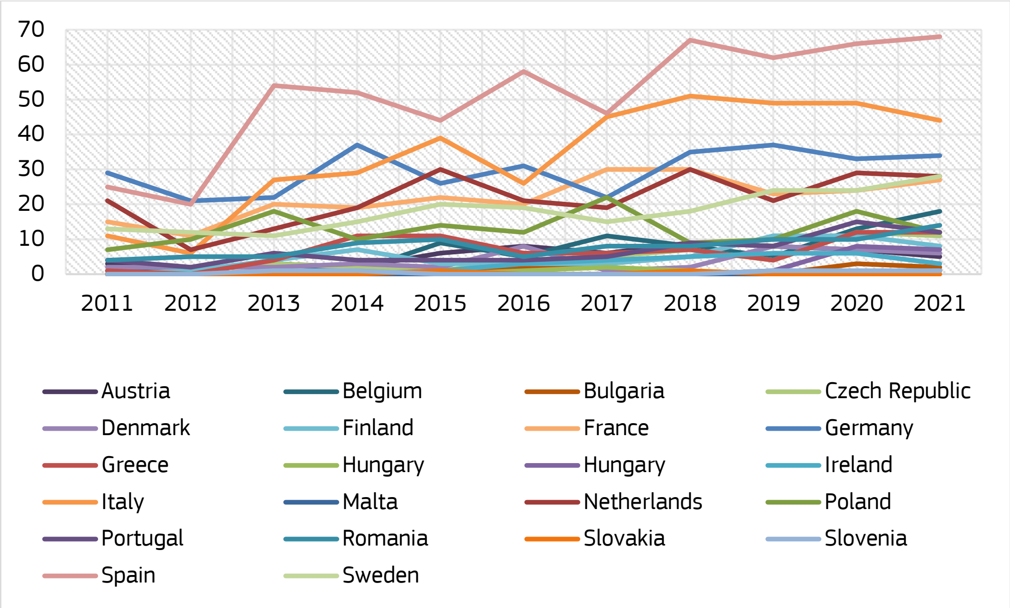
Figure 17. Number of peer-reviewed articles in CO_2 capture per year 2011-2021 a) in the top 5 countries of the world b) within EU countries

a)



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

b)



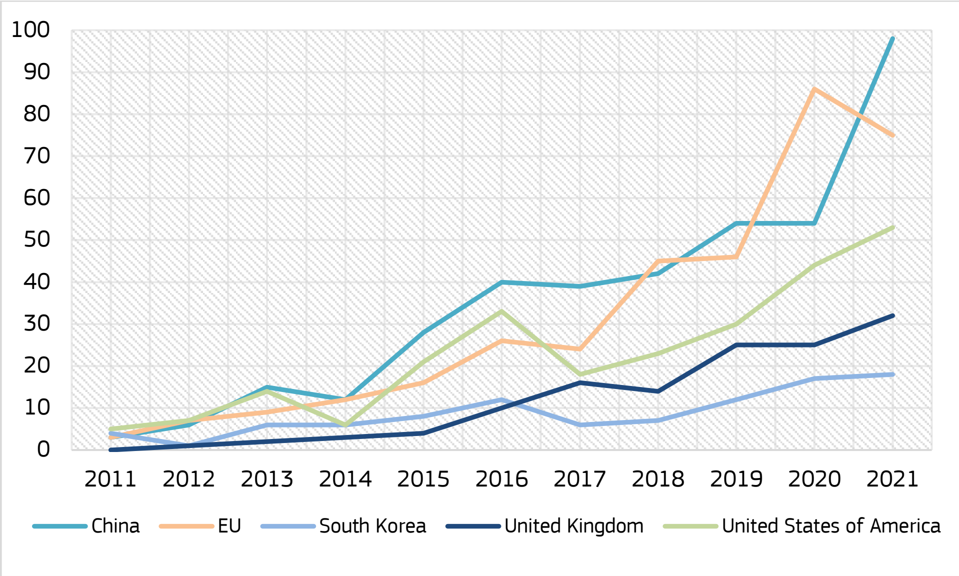
Source: JRC TIM

Regarding CO_2 capture specific technologies, adsorption and absorption are dominating the number of publications with China having the lead since 2012 and 2015, respectively. In 2021, publications from China in adsorption reached 479. Far fewer articles are published on high temperature looping and membranes. In last years, the EU and China have been alternating in the leading position publishing on high temperature looping. In 2021, China had 30 and the EU had 19 articles published. On membranes, China had 36 and the EU 16 articles published in 2021.

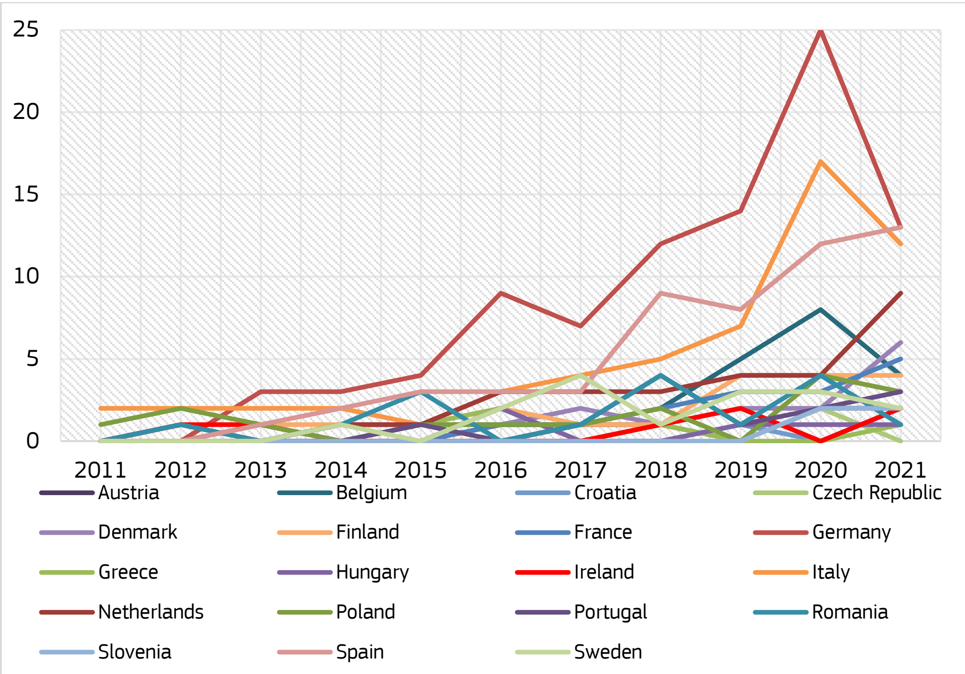
China has led in number of publications on CO_2 utilisation until 2018. Since then, EU and China are leading on the interchangeably topic (Figure 18a). In 2021, China had 98 and the EU had 75 articles published. Within EU countries, Germany is the leading country since 2013. It is followed by Italy and Spain. In 2021, Germany, Italy and Spain had almost the same number of publications, i.e. 13, 12 and 13, respectively (Figure 18b).

Figure 18. Number of peer-reviewed articles in CO_2 utilisation per year 2011-2021 a) in the top 5 countries of the world, b) within EU countries

a)



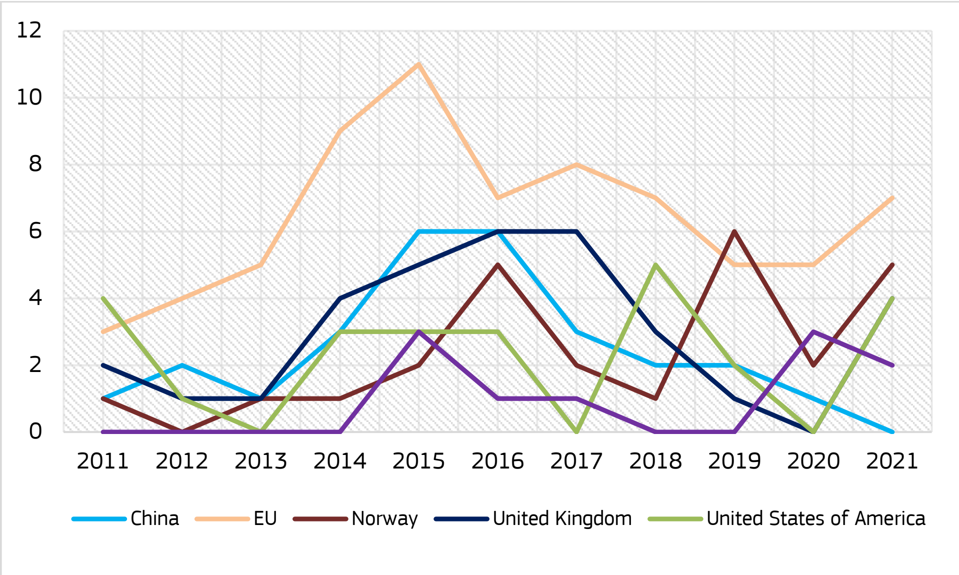
b)



Source: JRC TIM

On CO_2 transport, the EU is leading in peer-reviewed articles, with France having the highest number published (Figure 19). In 2021, France published 12 articles on the subject, followed by Spain with 7 articles and Sweden with 4 articles.

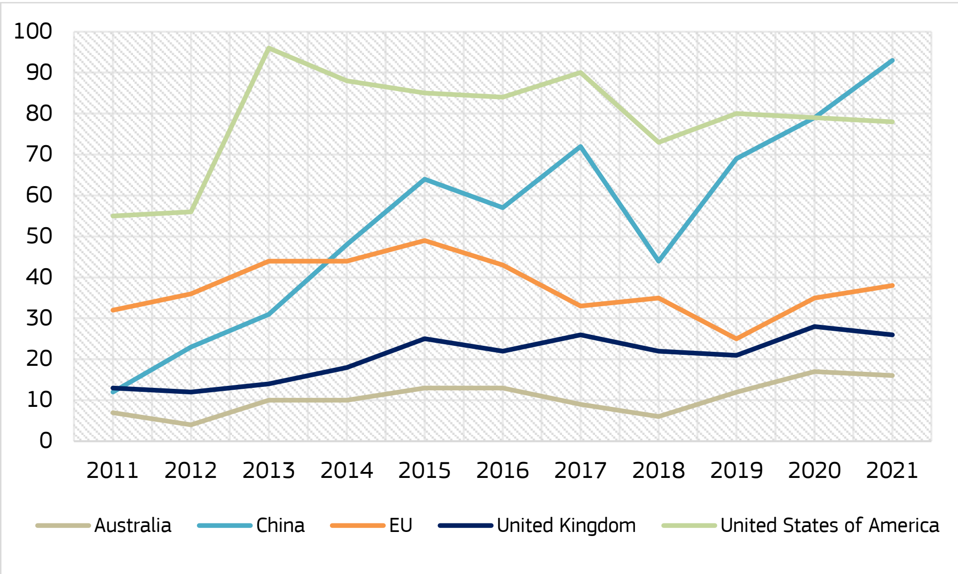
Figure 19. Number of peer-reviewed articles per year 2010-2022 in CO_2 transport per year 2011-2021 in the top 5 countries of the world



Source: JRC TIM

On CO_2 storage, the United States of America have been the country with the highest number of publications, followed by China which overtook in 2020. In 2021 the USA and China had 73 and 98 relevant publications, respectively. The EU has been far behind with 38 CO_2 storage peer-reviewed articles published in 2021 (Figure 20). 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 20. Number of peer-reviewed articles per year 2011-2021 in CO_2 storage in the top 5 countries of the world



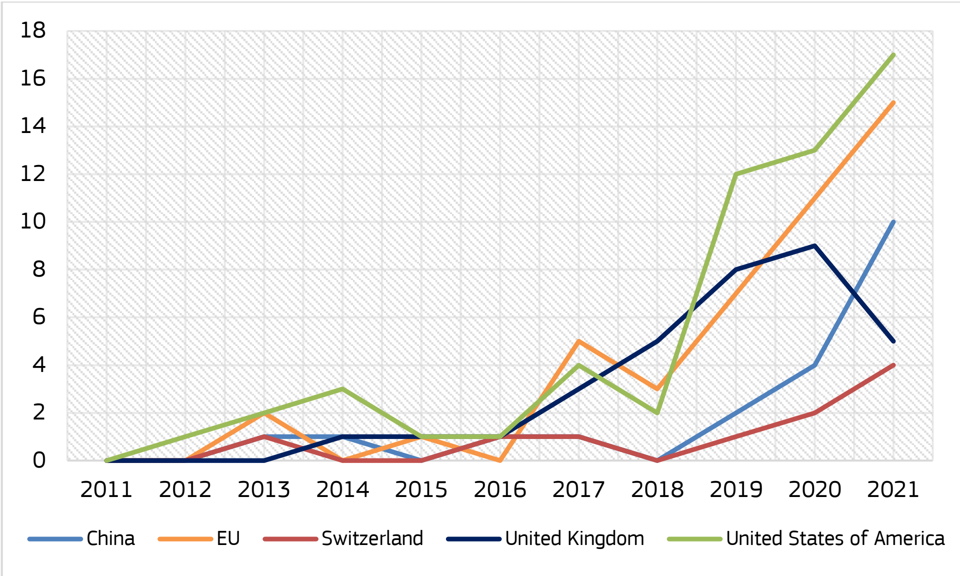
Source: JRC TIM

Peer-reviewed publications in technological carbon dioxide removal solutions such as bionenergy with carbon capture and storage (BECCS) as well as direct air capture (DAC) have increased substantially since 2017. This may be due to 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.

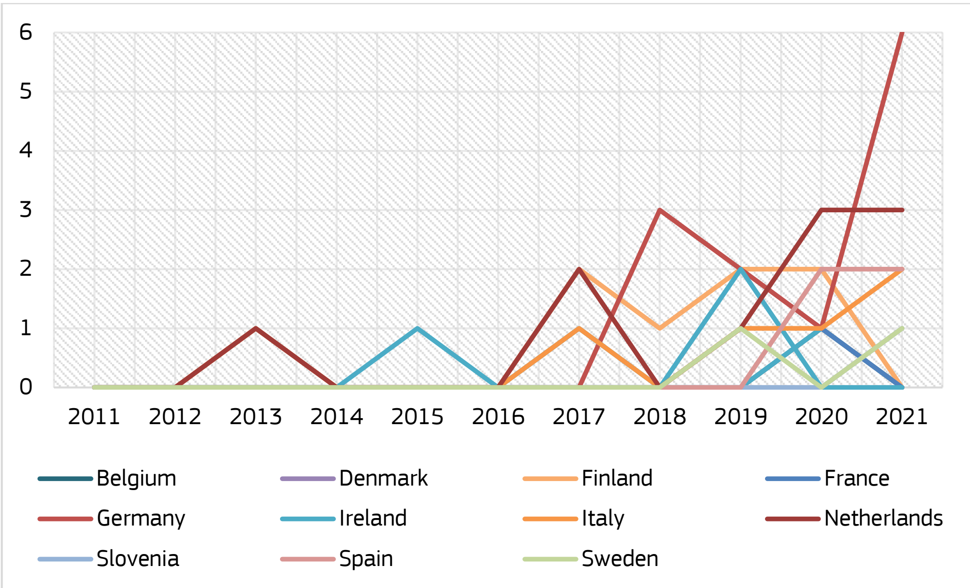
The USA, the EU, the UK, China and Switzerland are the top 5 regions in DAC peer-reviewed publications (Figure 21a). In the EU, Germany (6), the Netherlands (2), Finland (2), Spain and Italy (2) were the countries with the most published articles in 2021 (Figure 13b).

Figure 21. Number of peer-reviewed articles per year 2011-2021 in direct air capture a) in the top 5 countries of the world and b) within EU countries

a)



b)

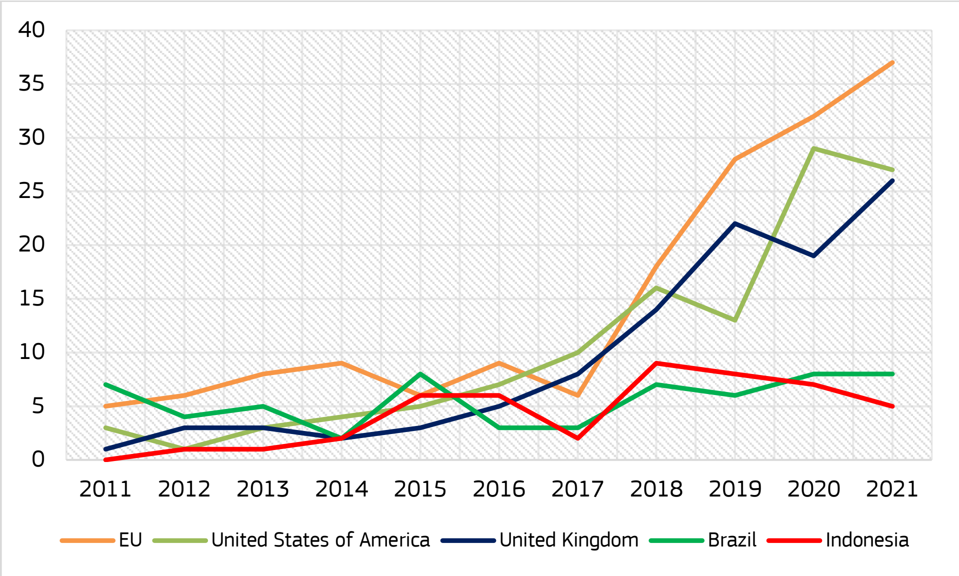


Source: JRC TIM

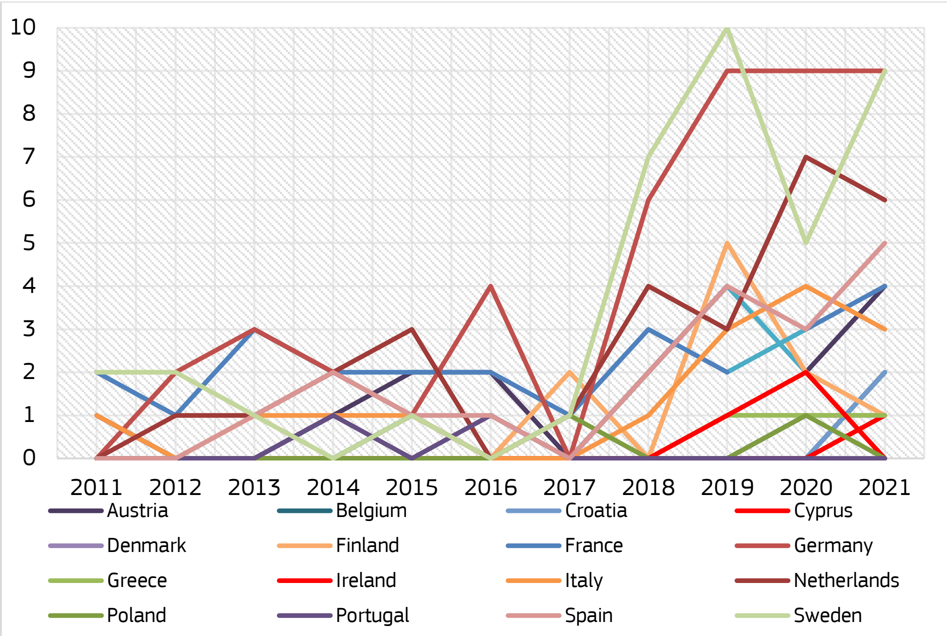
For BECCS, the top 5 countries hosting institutions publishing peer-reviewed articles are the EU, the US, the UK, Brazil and Indonesia (Figure 22a). In the EU, Germany and Sweden published 9 articles each, followed by the NL with 6 articles, Spain with 5 and France with 4 articles (Figure 14b).

Figure 22. Number of peer-reviewed articles per year 2011-2021 in bioenergy with CCS (BECCS) a) in the top 5 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 article in a journal, book or author is cited by other articles, 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 articles published have been highly cited.

Citations on research published from EU institutions are the second highest in the world, following China which comes first. We identified 546 highly cited articles in CO_2 capture which represent 21% of the total highly cited articles published. These come mostly from Spain (158), Germany (95), Italy (80), the Netherlands (71) and Sweden (58). The most highly cited articles from the EU refer on absorption (122) and adsorption technologies (147). For absorption, these originate primarily from France (24), Italy (22), Spain (21), Germany (19), and the Netherlands (16). For adsorption, the top five countries with the most highly cited articles are from Spain (44), the Netherlands (22), Italy (19), Germany (15) and France (14).

The same trend is observed for CO_2 utilisation, where citations in 84 highly cited EU-originating articles represent 21% of the total, just after China and followed by the USA. These articles come mostly from Germany (25), Spain (13), Netherlands (11), Italy (9) and Belgium (7).

Highly cited articles on CO_2 transport related research are primarily originating from the EU (11), representing 35% of the highly cited articles in the world. Netherlands (3), Germany (2), Italy (2), Sweden (2) and Austria (2) are the top 5 EU countries in highly cited articles in the domain. On CO_2 storage, the dynamic changes as the most highly cited articles come from USA (151) with the EU well below this with 58 highly cited articles, or 14% or the highly cited articles in this subject worldwide.

On BECCS, EU originating research comes first on highly cited articles (50) with a 30% share, followed by the UK with 39 highly cited articles or a 23% share. These articles originate mainly from Germany (19), Sweden (14), the Netherlands (12), Austria (8), France (5) and Italy (5). When it comes to DAC, EU originating research represents 37% with 19 highly cited articles, followed by the USA with 27%. The EU originating articles come mainly from Germany (6), Finland (4), Italy (3), Ireland (3) and the Netherlands (2).

With regards to participation in co-operation and networks, EU originating articles on CO_2 capture are products of collaboration mostly with the UK and Switzerland. Spain, France and the UK tend to produce more joint articles in CO_2 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 UK. In high temperature looping technology and membrane related publications, the EU is mostly collaborating with the USA. Within Europe, the UK, Spain and France appear to collaborate more prominently on absorption-relevant research articles Italy, Netherlands and Switzerland is another prominent network of collaboration as well as Norway with Sweden and Finland. On adsorption, collaborations are identified within the UK, Spain and Poland. Another important network appears within Italy, Norway and Sweden. Spain appears to collaborate with Sweden and Finland on high temperature looping. Poland, Norway, France and Belgium and the UK, Germany and Switzerland are also important collaboration networks on this technology. Italy, the UK and Czech Republic and Germany with Spain and Netherlands are the most prominent collaboration networks on membranes.

On CO_2 transport and storage and CO_2 utilisation the EU is mostly collaborating with the UK and the US with China. Within Europe, Germany is collaborating quite prominently with the Netherlands on CO_2 transport research. Similarly the UK with Sweden, Austria and Finland. Norway collaborates with the majority of the active countries in the field. On CO_2 storage related publications, prominent networks in Europe include the UK and Germany, Norway, Denmark and the Netherlands and Spain, Switzerland and Ireland. CO_2 utilisation related research publications are identified in networks between the UK, Spain and France, Germany, Switzerland and Belgium, and Italy, the Netherlands and Norway.

BECCS is the only field in which the EU is collaborating mostly with China. Collaborations in DAC, follow a similar trend with CO_2 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, Norway and Finland and Italy, the Netherlands and Ireland 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 also collaborating with Switzerland, Belgium and Cyprus.

2.8 Impact and trends of EU-supported Research and Innovation

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

H2020 IMPACTS9 – Starting on May 2019 (finished April 2022), aimed to support the realisation of the SET Plan Implementation Plan on CCS and CCU.[9]

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.

[9] 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).

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

CO_2 capture and utilisation in H2020

Levelised Cost of Electricity, LCOE (EUR/MWh), cost of capture (EUR/tCO_2), cost of CO_2 avoided (EUR/tCO_2), capture rate (%), energy for solvent regeneration or obtained O_2, 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 CO_2 adsorption has been a main focus of H2020 projects.

Projects focusing on and Chemical Looping Combustion CLC received important support in 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 regards to increases in TRL, these projects have swift 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 regads to CO_2 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 currently completed. Two of the projects mark “successful testing”. Out of the five new projects added on CO_2 utilisation, two are focusing on chemicals (C4U and SELECTCO2) and three are focusing on fuels (EcoFuel, LAURELIN, 4AirCRAFT).

CO_2 transport, storage and monitoring in H2020

Most of the projects that have been identified within H2020 with focus on CO_2 storage have been completed.

CARBFIX 2, completed just at the time of writing this report, aimed at upscaling and optimizing 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 CO_2 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 CO_2 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.

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 CO_2 geological sequestration operations.

Another new project, PilotSTRATEGY is investigating geological CO_2 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 CO_2 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 CO_2 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 in 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, Athos, 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

3.1 Turnover and gross value added

While more and more projects are added in the CCUS pipeline, it cannot be considered as a mainstream business yet. Market analyses report that the global CCUS market was worth nearly EUR[10] 2.7 billion (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 had 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 CO_2 Enhanced Oil Recovery (EOR) in the country.

Table 4. Overall revenue by major countries, 2021.

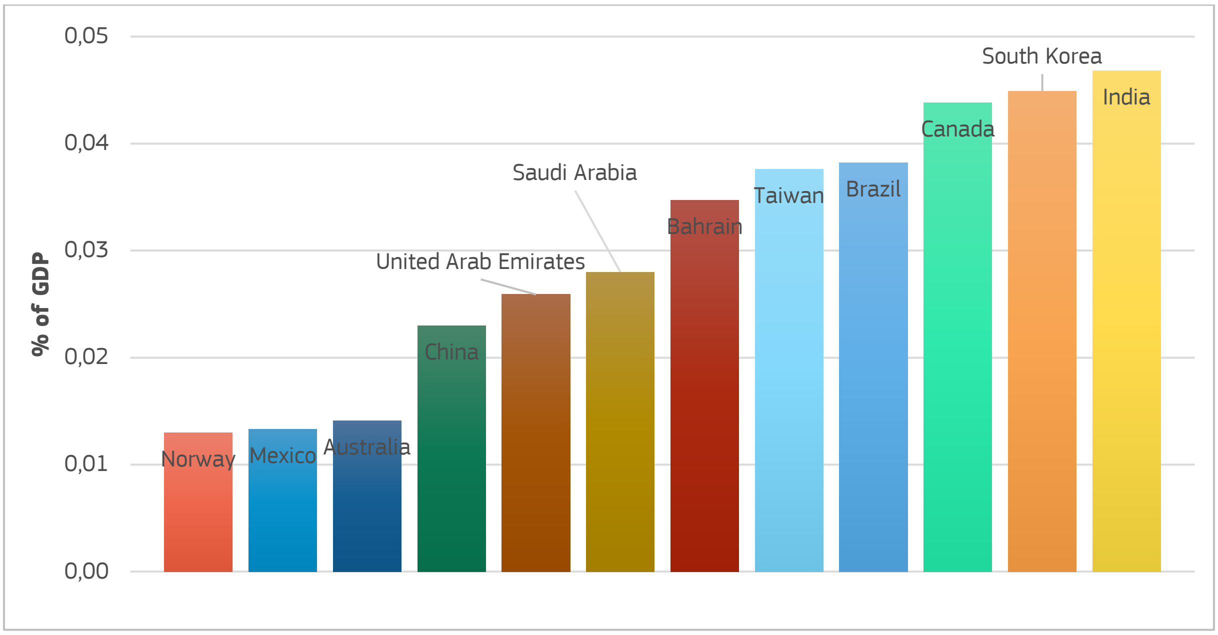
Country	EUR Million
USA	1 945
Australia	158
Norway	152
Malaysia	126
Indonesia	123
Russia	95
Europe	92
China	76
Saudi Arabia	47
UAE	47
Brazil	38
UK	27
Canada	23

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

It is important to highlight that there is economic activity relevant to CCUS in countries where there may not be actual projects in operation or in planning and construction. Figure 23 and Figure 24 show the value added by non and by EU country. The figures show that there is value added in countries such as in Taiwan, Malaysia or Bahrain and Italy, Germay and Romania. While there are no CCUS projects at any stage in these countries, there are still companies active in the field (see section 3.3). The figures indicate only values for 2021. Some countries such as Japan and the UK enjoyed also a value added from CCUS activities but in 2019.

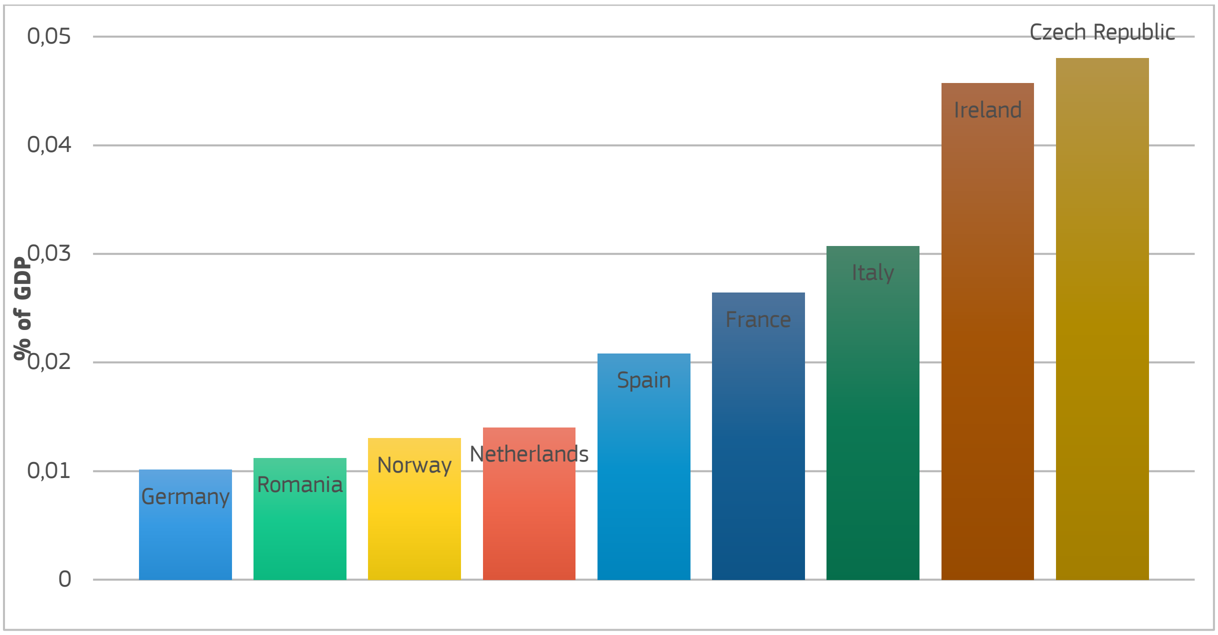
[10] Exchange rate 1 USD = 0.94899 EUR (source: oanda. Accessed 20/5/2022.)

Figure 23. Value added by non-EU country (% of GDP), 2021



Source: JRC with data from Polaris Market Research Analysis.

Figure 24. Value added by EU country (% of GDP), 2021



Source: JRC with data from Polaris Market Research Analysis.

3.2 Environmental and socio-economic sustainability

The purpose of CCUS is to reduce CO_2 emissions by capturing and permanently storing CO_2. Thus, it is important that far more CO_2 is stored than what is emitted as a result of the construction, operation and decommissioning of the CCUS chain. The EU Taxonomy[11] includes CCUS stating that "CCS can be eligible in any sector/activity if it enables that primary activity to operate in compliance with the threshold – for example, steel, cement or electricity production".

[11] The EU taxonomy is a classification system, establishing a list of environmentally sustainable economic activities.

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 are primarily basing their results on literature reviews. Although CCS can have a large role in the abatement of CO_2 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 CO_2 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 CO_2 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 recognized 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 regards to how it can provide societal benefits. A recent study provides guidelines for carbon capture and utilisation (European Commission-Directorate General for Energ*y 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 CO_2-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 will also be expected for GWP because of the lower emission factor of natural gas and comparable percentages of CO_2 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).

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_2eq	79	275	17	25	176	8	76	245	14	110	170	6
EP	gPO4eq	0.06	0.30	11	0.01	0.09	3	0.017	0.134	8	0.035	0.035	1
AP	gSO_2eq	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_2H_4eq	-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			
TETP	g1,4DBeq	0.13	0.51	3	0.16	0.16	1	0.002[1]	0.045	2			

1) 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: Pulverized 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, HTTP: 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.

With regards to water use, early studies 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, however, showed a percentage increase of less than 50 per cent for coal-fired power generation. This decrease resulted from the use of a more advanced CO_2 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 CO_2 capture systems and approaches have different impacts, with significant variability among reported values. The same conclusion on cooling was reached also by a 2020 study. They also found that in cases where water scarcity does not already exist, the addition of CCS will not generally induce scarcity. Considering 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). Thus, this reveals a potential field in need for study.

When it comes to carbon dioxide removal technologies, land use and hardware distribution are commonly raised, but research suggests that DAC units have minimal land requirements compared to other, such as for example Bioenergy with Carbon Capture and Storage (BECCS) (Kapetaki, 2019). Similar finding applies to water use too (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).

Regarding carbon removals, utmost attention needs to be paid to their quality and credibility. For this reason, the European Commission is developing a new framework for the certification of carbon removals in 2022. This certification mechanism will provide more clarity on the quality of carbon removals, and ensure their environmental integrity. It will address the lack of standardisation of existing frameworks and contribute to a level playing field (European Commission, 2021a).

When it comes to circularity, technologies that convert CO_2 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 CO_2 as a source for carbon used as material has been reported like a promising option on this front (Kaiser and Bringezu, 2020).

On other environmental issues, one of the biggest perceived risks stemming from CCS operation has been considered the potential for leakages of CO_2 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 CO_2 capture are some areas for potentially useful research (Mission Innovation, 2017). To date, no major incidents have been reported with regards to the operation of CCUS projects.

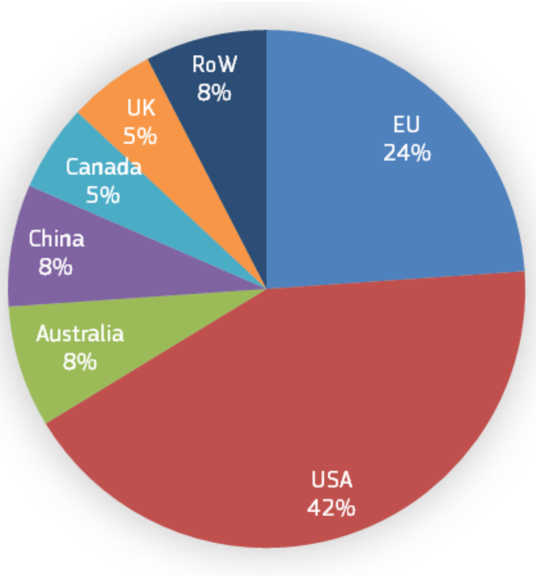
Finally, on the social aspect, CCUS projects have suffered to date from severe criticism and lack of public acceptance. There have been failures to deliver whole projects due to lack of public acceptance, such as for example in the case of Barendrecht, the Netherlands. CCUS projects are complex with 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).

3.3 Role of EU Companies

Market research identified 186 key companies world wide with activity in CCUS. In reality, we are expecting these to be much more dependant 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 with 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 taking up 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 USA is leading the way as 42% of the key companies identified are American or are based in the USA.

Figure 25. 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 mid 2000s it was primarily utilities that were involved in CCUS, the focus has now shifted to industry. HeidelbergCement is the company primarily active on developing CCUS in the cement industry. Initiatives such as the Antwerp@C and Porthos demonstrate the interest of chemical and oil and gas companies such as AirLiquide, BASF, Borealis, TOTAL, ExxonMobil and Ineos to get involved. The recently announced projects benefitting from the Innovation Fund also revealed certain interest in BECCS, as Stockholm Exergi is a project developer of such project. Oil companies such as ENI and Shell are assessing hydrogen projects. Regarding steel, ArcelorMittal is pursuing several CCUS options by building pilot plants at its Dunkirk and Ghent steel plants and the company is also interested in CO_2 use.[12] ThyssenKrupp's is active on CO_2 use and its pilot plant is synthesising methanol from blast furnace and basic oxygen furnace gas. It aims also to produce ammonia, using the nitrogen by-product from waste separation. Tata Steel has been running a pilot plant with a capacity of 0.06 Mt/year at their steel plant site in IJmuiden, Netherlands, since 2010. To scale up the technology, however, Tata Steel is currently considering building a larger demonstration plant in India and it is not clear whether this technology will be deployed in the EU (Somers, 2021).

In North America the landscape is very different. There most of CCUS development are occuring 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, 2022) provided a technology compendium intended to showcase commercially-available CCS technologies worldwide. In terms of CO_2 capture they listed 16 companies 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 CO_2 transport, the publication identified 5 companies out of which 2 in the EU (MAN Energy Solutions and Svanehøj). On CO_2 storage, none of the companies listed are in the EU. On the full value chain, 2 companies (Linde (DE) and Schlumberger (FR)) are EU companies. These lists show that the EU is relatively well positioned on CO_2 capture technologies. When it

[12] ArcellorMittal.

comes to transport, storage and full value chain the EU is far behind and is striving to get a share against the USA and Canada.

Our in-house analysis showed that from 2015 onwards, 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 showed that the EU is lagging behind on this front. Out of the 92 companies identified only 8 are within the EU (287K (HR), Caphenia (DE), Carbon Collect (IE), Carbonworks (FR), Liquid Wind (SE), Purcity (DK), Redoxnrg (EE), and Sunfire (DE)).

3.4 Employment in value chain

Market research indicates that currently, there are approximately 6 400 people employed in the CCUS chain world wide (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 are not always updating publically available information, especially on employment, these numbers of jobs can only be indicative.

Table 6. Employment by 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

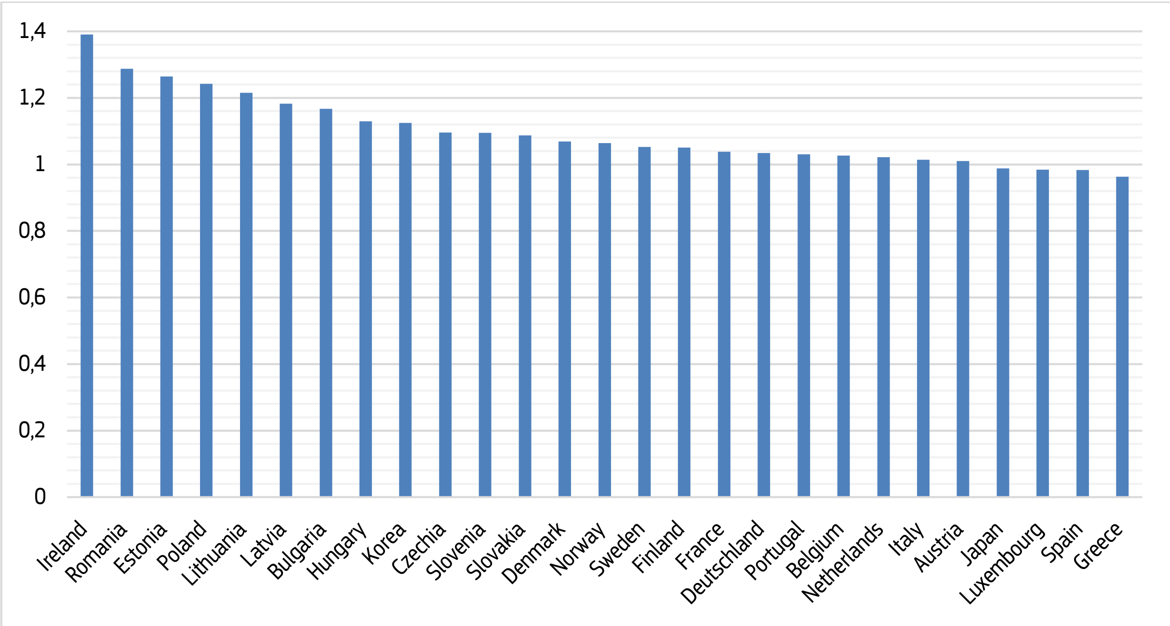
Source: Secondary Research, Primary Interviews and Polaris Market Research Analysis.

Market research estimates that within the EU member states, Ireland has the highest labour productivity ratio[13] when it comes to CCUS, followed by Romania, Estonia, Poland and Lithuania (Figure 26a). Turkey, Columbia, Israel, Korea and Chile are the top 5 countries with the highest labour productivity ration outside the EU (Figure 21b).

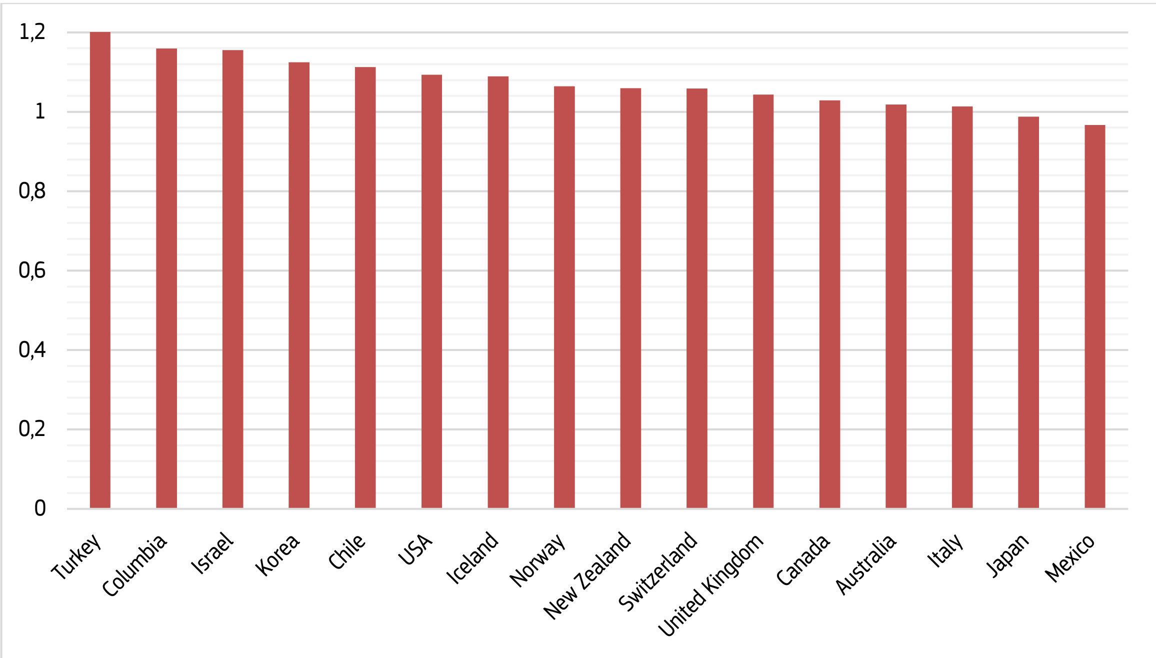
Figure 26. Labour productivity estimate by a) EU member state and b) worldwide, 2021.

a)

[13] The real gross domestic product (GDP) per hour worked.



b)



Source: JRC with data from Polaris Market Research Analysis.

2021 has seen unprecedented advancement for CCUS projects. According to the IEA, the employment benefits from the development of these projects would be significant. Job creation opportunities lie along the highly complex and fragmented value chain for CCUS. According to (Serin *et al.*, 2021) CCUS investments can generate a substantial number of jobs in the short, medium and long terms. 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.

3.5 Energy intensity

Most carbon capture technologies aim to prevent at least 90% of the CO_2 in flue gases from reaching the atmosphere. But as the technology approaches 100% efficiency, it gets more expensive and takes more energy to capture additional CO_2. From an engineering perspective, it is easier to capture carbon from a gas with a higher concentration of CO_2 because more molecules of carbon dioxide are flowing past the scrubbers. This is one of the reasons DAC cost can be attributed to.

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% points (Supekar and Skerlos, 2015). Carbon capture reduces the net electricity output by 24% in a typical coal plant and 14% in a typical a 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.[14] 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 CO_2 and SO_2 capture and 14 MW for the amine and heat regeneration (IEAGHG, 2015).

3.6 EU production

The majority of the operating CCS facilities worldwide capture CO_2 for natural gas processing. The Sleipner CO_2 injection in Norway was the world's first industrial offshore CCS project. Natural gas produced in the Sleipner Vest field contains approximately 9% CO_2 and must be reduced to less than 2.5% for the gas to meet specifications prior to being sold. The unwanted CO_2 is captured with amine scrubbing using aqueous N-methyldiethanolamine (MDEA) solutions.

In addition to natural gas processing, large-scale CCS facilities are currently in operation for chemical, hydrogen and steel production as well as power generation. Unit 3 at the Boundary Dam power station in Saskatchewan is retrofitted with a capture facility based on regenerable amine technology by Shell Cansolv. The Petra Nova project used a proprietary amine solvent, KS-1, which was developed by the Kansai Electric Power Co. and Mitsubishi Heavy Industries, Ltd (Yamada, 2021).

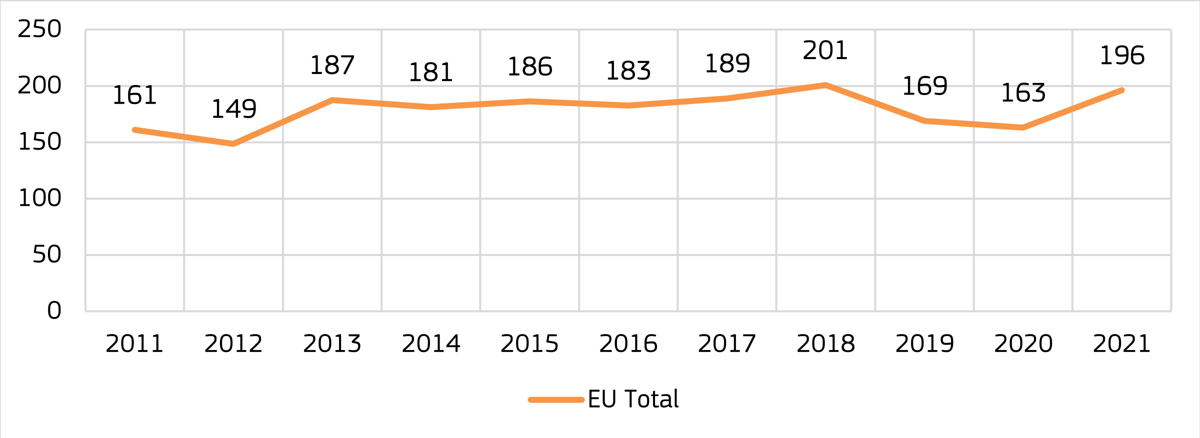
According to (Yamada, 2021), most of the projects in operation use either Monoethanolamine (MEA) or Methyldiethanolamine (MDEA) for CO_2 capture. Besides gas scrubbing for CO_2 capture, MEA is used as feedstock in the production of detergents, emulsifiers, polishes, pharmaceuticals, corrosion inhibitors, and chemical intermediates (Frauenkron *et al.*, 2002). In this study, we examine the production of solvents for carbon capture used on MEA using PRODCOM[15] code 20144233. No codes relating to MDEA were identified. Given the different uses of MEA, and the somehow limited deployment of CO_2 capture projects in Europe, the analysis below can be only indicative.

Figure 27 shows that the production value of MEA has been relatively steady in the past ten years. The maximum value in 2018 reached EUR 153 million. Denmark and Spain are the top MEA producer countries in Europe with a total production value of EUR 6 million and EUR 3 million, respectively.

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

[15] Prodcom provides statistics on the production of manufactured goods carried out by enterprises on the national territory of the reporting countries.

Figure 27. Total Production Value of MEA in the EU (EUR Million)



Source: JRC based on PRODCOM data.

4 EU position and Global competitiveness

4.1 Global & EU market leaders (Market share)

The most prominent market players for CCUS were identified in 3.3. The majority of the companies have not announced the value of the projects they are involved in. Along with this, the companies are involved in a wide range of stages across the overall value chain, so it is challenging to derive a market share at this instance.

4.2 Trade (Import/export) and trade balance

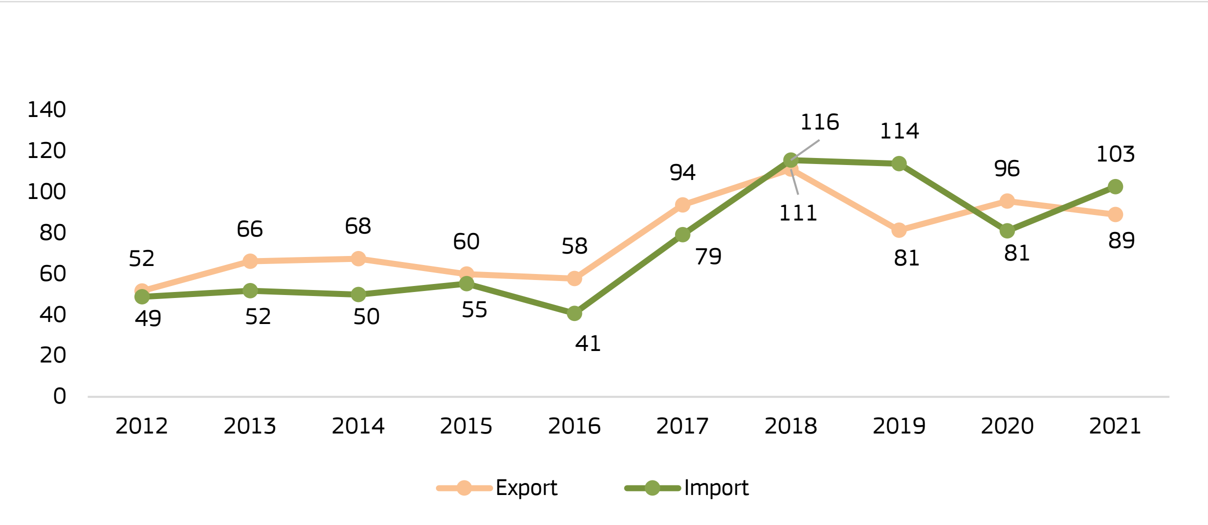
As in section 3.6, in trade and trade balance analysis we have considered only solvents (amines) for CO_2 capture as this is the technology that the majority of commercial CCUS projects in operation are using. However, since for trade there is more data available, we expanded the analysis to include Diethanolamine (DEA), Triethanolamine (TEA) and Methyldiethanolamine (MDEA) which are also used for CO_2 capture.[16]

Our analysis indicates that Belgium, Spain, Germany, Italy and France are the top 5 importers of these solvents in Europe. Belgium, Germany, Sweden, Netherlands and Spain are the top 5 exporters. This activity cannot be linked however with CO_2 capture as there are no CCUS projects in operation or in construction in these countries.[17]

The United States, United Kingdom, China, Norway and Turkey are the top 5 importers of these solvents from the EU. Saudi Arabia, The United States, Mexico, Russia and the United Kingdom are the top 5 exporters to the EU. This activity can be justified when it comes to the US as there are many CCUS facilities operating in various industries. However, we reckon that any activity is mostly related to the oil and gas industry of the above countries.

Figure 28 shows that the EU exports and imports have been fairly steady since 2016. After this, there was an increase in both types of activity. The overall balance remained relatively steady through the last ten years.

Figure 28. Extra-EU Import & Export (EUR Million)



Source: JRC based on COMEXT data

4.3 Resources efficiency and dependence in relation to EU competitiveness

Resource efficiency and critical material dependency are topics that have gained little or no attention when it comes to CCUS. Thus, there is a need for a comprehensive analysis on the subject.

In the previous section covering production and trade (3.6 and 4.2) we focused on chemical solvents as this is the technology that is mostly used in operating commercial CCUS projects. However, other materials such as

[16] COMEXT and COMTRADE codes: 292211, 292212, 292215, 292217. Comext is Eurostat's reference database for detailed statistics on international trade in goods. UN COMTRADE is the United Nations International Trade Statistics Database.

[17] Projects LEILAC in Belgium and STEPWISE in Sweden are in construction and in operation respectively but none plans to/use(s) solvents for CO_2 capture.

membranes (polymeric, ceramic, etc.), adsorbents etc. can and are also used for carbon capture. At present, the main commercially available adsorbents are activated carbons, zeolites, hollow fibers, 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.

In their analysis, ZEP considered carbon steel for equipment and pipelines manufacturing (ZEP, 2011b). (Parker, Meyer and Meadows, 2009) listed materials that are used for CO_2 injection wells (Table 7). These materials include corrosion resistant alloys. Depending on their composition, they may contain critical materials, such as titanium and cobalt, but also other materials such as nickel. The latter may become under shortage or price volatility due to international geopolitical/environmental conditions.[18] Carbon steel may also contain some alloying elements which are critical such as silicon.

Table 7. Typical construction materials for CO_2 injection wells.

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

Source: (Parker, Meyer and Meadows, 2009)

For other materials that can be used in the CCUS value chain, a thorough analysis is needed to clearly identify any challenges associated with their supply. For example, for aluminium which is a component of alumina, copper, iron, manganese and steel, shortages have been reported in Europe in the last two years.[19] On the other hand, Europe is amongst the world leaders in supplying the world's demand for natural zeolites.[20] Moreover, the captured CO_2 can be used to produce high value chemicals, building materials etc. If this potential materialises, it is plausible that EU companies can benefit.

Biomass is another relevant material, used for bioenergy with carbon capture and storage (BECCS). Biomass feedstock is derived from a residual product (e.g. sugar cane waste) or dedicated energy crops (e.g. fast-growing tree species like willows trees) planted purely as a feedstock. Algae cultivation and municipal organic solid waste is being tested. 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). Even if the potential is there, the supply chain would need to be developed to mobilise all these resources. This means that an enormous effort must be done in all Member States, as the maturity

[18] Reuters, 2022
[19] Bloomberg, 2022; Financial Times, 2021; S&P Global Market Intelligence, 2020.
[20] Chemeurope.com

and reliability of several key biomass conversion technologies is still an issue and their progress towards market deployment is an important concern (Panoutsou and Maniatis, 2021).

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). Sections covering production and trade (3.6 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. Other repercussions are connected to the impact of increasing MEA output on the environment as the manufacturing process is resulting in CO_2 emissions. The energy required and its source to keep up with an increasing demand for MEA, should also not be overlooked.

Research has concentrated on improving the technical and economic efficiency of this solvent. CO_2 absorbing capacity of MEA is concentration dependent, ranging from 447.9 ± 18.1 to 581.3 ± 32.3 g CO_2/kg MEA (Huertas *et al.*, 2015). On the CO_2 capture process itself, energy required to regenerate the solvent is very high (U.S. Department of Energy, 2019). Todays amines' processes will require 0.29 kWe/kgCO_2 including compression for 90% capture (Herzog, 2018).

On technology autonomy and/or dependence, analysis on section 3.3 showed the EU is relatively well positioned on CO_2 capture technologies. When it comes to transport, storage and full value chain, the EU is far behind and is striving to get a share against the USA and Canada.

5 Conclusions

From the analysis of the previous chapters the following key points can be deduced:

- CO_2 capture, transport and storage technology components are commercially available for most industries
- The number of commercial facilities in the pipeline has increased but more is needed to achieve ambitious targets
- CCUS costs are still considerable but expected to fall as/if/when capacity increases
- France, Germany, the Netherlands are the front runners in public and private R&I investments and top patenting companies
- These countries are also on the top 5 of peer review publications but are overtaken by Spain and Italy
- There is a need for (supply) a thorough value chain identification and mapping
- Demand for materials required in the CCUS value chain is also a field in need for study
- In summary, EU is in a good position when it comes to publications, patents, private and public R&I but lags behind on venture capital companies compared to other world areas

Different roadmaps identify CCUS as part of the technologies necessary to facilitate the transition towards zero-emissions' industrial and energy sectors. However, **CCUS has not yet completely met the expectations and requirements in terms of implementation rate**. The main barriers to develop CCUS projects in the world have been discussed extensively and appear persisting. The most important ones are regulatory implementation, economics, risk and uncertainties associated with projects as well as public acceptance. While the technology and technical implementation are not within the main challenges for CCUS development, research is ongoing to address specific bottlenecks.

In short, for CO_2 capture, areas for research include improving solvents' performance and environmental friendliness. For sorbents and membranes, advancement in materials and process integration will be key. Technological advancements to enable high capture rates and low energy requirements should be supported - novel reactor designs, modularisation, and cost-effective materials are some of these. Flexibility, compactness, and potential for heat integration and process intensification are also important. In addition to CO_2 separation, understanding the potential of carbon capture in H_2 production will have to be pursued, i.e. H_2 production based on fossil (or biomass) fuels.

For CO_2 utilisation, the resolution of technological challenges is needed to advance the TRL and specific incentives will be essential to set the basis of CO_2 roll-out of as raw material. For this, LCA analyses evaluating the CO_2 emissions savings of CO_2 utilisation plants vs. conventional of the integrated approaches, will be essential. Increasing the efficiency of CO_2 utilisation pathways will require intensified research on improved catalysts. Proposed, better processes including reactor designs, must target higher efficiency levels, and lowering costs and new routes to carbon-based functional materials from CO_2 should be created. The scientific community is also advocating for research relevant to the electrochemical and photochemical conversion of CO_2. CO_2 use for mineralisation implies permanent storage of CO_2. Thus, from the CO_2 emissions reduction standpoint, it is advisable to prioritise research in this technology and accelerate its development but also tailor material properties to enable carbon storage in products.

Concerning CO_2 transport and storage, technical aspects and infrastructure should be improved. In addition to pipelines, the role of shipping should also be looked at. Technical aspects such as impact of CO_2 composition and impurities as well as fluctuating flows on the pipelines are also important. According to the scientific community, the research priorities for CO_2 storage should be concentrated in increasing capacity, understanding large scale and optimising injection. Monitoring techniques to demonstrate containment and enable storage site closure should also be pursued. Monitoring should also be used to assess anomalies and provide assurance. Characterization of fault and fracture systems, seismic risk forecasting and well management and well integrity are also areas for suggested research. R&I activities supporting CO_2 storage appraisal, mapping and development are vital to develop European CO_2 storage capacity, to reduce costs of CO_2 storage and evaluate potential risks associated with storage.

In many occasions, it was the public that caused project cancellation so incorporating social aspects into the studies is crucial. Further, **models that take into account life cycle technoeconomic, environmental, and social considerations should be developed to guide decision making**.

Carbon dioxide removal technologies have gained interest in the last years. However, future endeavours will still need to examine barriers of this technology such as ability to be replicated in bigger scale, cost, land and energy requirement. The development of a clear and robust framework for carbon accounting and for guaranteeing the sustainability of bioresources is fundamental to enable such solutions. The European Commission is currently working on this topic and it is expected to have a regulatory framework on carbon removal certification by the end of 2022.

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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
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 tons 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 A

List of projects identified

Table 8. Projects identified exploring different CCUS aspects

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

Source: JRC analysis

Table 9. 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

Project Acronym	Capture	Transport	Storage/ Monitoring	Use	Other*	Funding (EUR)
FUNMIN				✓	✓	700 000
LAUNCH	✓			✓	✓	5 100 000
MemCCSea	✓			✓	✓	1 700 000
NEWEST-CCUS	✓			✓	✓	2 200 000
PrISMa	✓			✓	✓	2 100 000
REX-CO2			✓	✓	✓	2 500 000
SENSE			✓	✓	✓	2 700 000
SUCCEED			✓	✓	✓	2 500 000

Source: JRC analysis

*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 10. Ongoing H2020 projects identified in the field of carbon capture and utilisation with EU funding contribution >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
BIOCONCO2	✓						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
CATCO2NVERS	✓						6 641 111	6 641 111
CHEERS					✓		9 727 105	16 818 668
CLEANKER					✓		8 972 201	9 237 851
CO2Fokus	✓						3 994 950	3 994 950
CO2LIFE	✓						1 302 710	1 302 710
CO2MPRISE	✓						702 000	702 000
CO2SMOS	✓						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
eCOCO2	✓						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
ICO2CHEM*	✓						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.CO2M*	✓						4 264 453	4 264 453
MOF4AIR			✓				9 947 143	11 094 138
OCEAN*	✓						5 523 650	5 523 650

Project acronym	CO_2 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
SELECTCO2	✓						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

Source: JRC analysis
*These projects are expected to be completed by the time this report is published

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