CCUS SET-PLAN

Deliverable 3.4

RECOMMENDATIONS ON THE STEPS REQUIRED TO DELIVER THE R&I ACTIVITY 6: DEVELOPING NEXT-GENERATION CO_2 CAPTURE TECHNOLOGIES

JANUARY 2022

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Extended summary

Introduction

The central role that CCUS must play to enable climate ambitions has been confirmed and reinforced by different authoritative sources. CCUS has a particularly important role in decarbonizing hard-to-abate industrial sectors, where emissions reductions by energy and process efficiency would not be sufficient to meet mitigation targets. IPCC analysed several pathways that limit global warming to 1.5°C. The amount of CO_2 captured by CCUS is in the range 5.5 - 18.5 Gt CO_2 in 2050 for scenarios also consistent with net-zero emissions from the energy sector and industry by then. Importantly, a large share of this CCUS capacity is carbon dioxide removal (CDR), which comprise bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS), with a capacity in the range 3.5 - 16 Gt CO_2 in 2050.

Although showing smaller absolute numbers, the IEA report "Net Zero by 2050" echoes the conclusions by IPCC. In the Net-Zero Emissions by 2050 Scenario (NZE), 1.6 Gt CO_2 per year is captured globally by 2030, rising to 7.6 Gt CO_2 in 2050. Around 95 % of captured CO_2 in 2050 is stored in permanent geological storage (CCS). With respect to CDR technologies, a total of 2.4 Gt CO_2 is removed from the atmosphere by 2050, through a combination of BECCS and DACCS, of which about 80 % is permanently stored, while the remaining CO_2 is used to provide synthetic fuels.

Full-scale commercial CCS projects will require all the parts of the value chain to be operational. The elements of the chain, i.e., capture, transport, and permanent storage, must be developed and implemented in phase with each other. The technical development has reached a maturity stage where the whole CCS value chain can be implemented and operated, although further optimization and development is needed to reduce cost and energy penalty.

Maturity of capture technologies

Looking at the capture part of the value chain, many different technologies have entered the scene during the last 25 years. Post-combustion CO_2 capture using absorption by liquid solvents is amongst the most mature technologies. Commercial (or near to commercial) absorption-based systems are available, normally based on amine solvents. Several other solvents are also being developed, to reduce energy consumption, increase selectivity and limit hazardous emissions. The range in TRL spans from 3 up to 9 for the different liquid solvents, where amine solvents and physical solvents are at level 9, i.e., at the highest level according to the EPRI definition. Adsorption by solid sorbents is another capture technology where there are options that show TRL level of 9, such as pressure and vacuum swing adsorption (PSA and VSA) in a pre-combustion setting.

Other capture technologies are membranes, solid looping, low-temperature separation, hybrid processes, fuel cells with CO_2 capture, direct air capture, inherent CO_2 capture, and oxy-combustion capture technology. Within each technology there can be several different options with a range of TRL level. However, in general

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Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

these technologies are less mature than absorption with amine solvents and, to some extent, solid sorbent adsorption. Their highest TRL level is typically in the range 5-7.

Status of capture in energy and industry sectors

Different energy and industrial sectors have different characteristics with respect to CO_2 capture, which can affect the choice of capture technology, as well as the possible business cases. The Sleipner and Snøhvit projects in Norway are examples of projects within the oil and gas sector where CO_2 capture is a necessity from both a technical and commercial point of view. They are capturing about 1 and 0.7 Mtpy CO_2 from natural gas streams ("natural gas sweetening"), respectively, to be able to sell the gas or process the gas further to LNG. The CO_2 capture is an integrated part of the main revenue process stream. Most other sectors and plants will see a quite different picture, where early movers must rely heavily on funding such as EU Innovation Fund etc. In the longer run, the industries commitment to operate with lower carbon footprint, customers preferences for low-carbon products, and new economic incentives, are parts of what is needed to see a possible sound business case.

Coal and gas power generation was earlier the main sector in discussion when talking about CO_2 capture. In 2019 they contributed about 700 Mtpy of the EU ETS CO_2 emissions. However, there are no ongoing large demonstration or commercial scale capture projects in Europe. The situation for coal generation is unsure and no commercial coal capture plants seems to be planned for the coming years. Within gas power generation, three planned capture projects have been identified; CCS Ravenna Hub in Italy, Caledonia Clean Energy in UK, and H2M in the Netherlands, the latter being a gas turbine plant to be converted to operate on hydrogen produced from natural gas with CCS.

Power and heat generation from waste, WtE, is a more recent sector adopting CO_2 capture as a possible way forward for CO_2 emissions reductions. One plant is in commercial operation, AVR-Duiven. Several new ones are planned, some of them rather well developed, such as Fortum Oslo Varme and Amager Bakke WtE. WtE with CCS contributes to carbon dioxide removal (CDR) due to the biogenic fraction of waste. Projects that will have even higher CDR impact are also planned, such as the Drax Power and the BECCS@STHLM projects. They will generate power and heat from bioenergy with carbon capture and storage (BECCS).

Industry sectors such as cement and lime, iron and steel, and chemicals industry, are sectors where CO_2 capture can be a main possibility for emissions reduction. Iron and steel are developing commercial projects that includes both post-combustion capture (The Fresme and the 3D project) and use of hydrogen for reduction (H2morrow steel and Hybrit projects). Cement industry do also have several projects in the pipeline. Post-combustion will be used at the Norcem project, where construction has recently started, and it is also planned at the ECCO2 Carboneras project and the Slite plant Gotland. Fuel-shift to biomass plus oxy-combustion kiln is planned for the K6 project at EQIOM Lumbres plant. Capture from chemical industry is planned as part of the Kairos@C project at port of Antwerp.

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Ongoing and planned European capture capacity

The global status of on-going commercially operating CCUS projects is reported by the Global CCUS Institute. Status of 2020 was 26 projects, of which only two projects were reported from Europe, the Sleipner and Snøhvit projects in Norway, capturing about 1 and 0.7 Mtpy CO_2 from natural gas streams ("natural gas sweetening"), respectively. The present study has identified five additional ongoing capture projects, covering sectors as WtE, geothermal CHP, direct air capture and hydrogen production. The seven projects together are capturing about 2.5 Mtpy of CO_2.

According to the sources examined, by 2030, approximately 69 million tonnes of CO_2 are planned to be captured in European projects per year. Of the 69 Mt per year, 2.5 Mtpy is ongoing capture today, about 2.8 Mtpy will come from the recently funded large-scale Innovation Fund projects, while projects amounting to 0.7 Mtpy are decided and funded by other means. I.e., of the planned capture capacity by 2030, as much as about 63 Mt per year seem not finally decided yet.

A large share of the increase in CO_2 capture capacity until 2030 is from hydrogen produced from natural gas with CCS. For this value chain to be operational there will be need for a hydrogen market and infrastructure, and end-user processes and technologies that are modified so they can utilise hydrogen. This must be developed in phase with the CCS part of the value chain. Hydrogen produced from natural gas with CO_2 capture is commercially available technology, however, with the large volumes involved, improved processes with higher efficiency and cost improvements would be beneficial.

Ongoing and planned CO_2 capture capacity is mainly located in North-western Europe. Most of the CCS activity is concentrated within a few countries. Especially UK will be responsible for a very large share of planned CCS capacity. A broader implementation plan for CCS in Europe is likely needed to meet the needed targets for CCS capacity, and to reduce the risk associated with having too few countries involved.

If all planned projects are realised, Europe can meet the minimum capture volume in 2030 that is needed to match the 2-degree scenario, while falling far below the 2030 volume needed to be on track to meet the 1.5-degree scenario. Many more large-scale, commercial CCS projects will need to be in the pipeline in the short term to enable the possibility to reach a net zero scenario in 2050.

Recommended steps to deliver next-generation CO_2 capture technologies

To meet the European climate objectives for 2030, more operational CCUS projects at commercial scale are needed in a short timeframe. Commercial technological solutions exist and will need to be deployed. However, technological development is essential to reduce the cost and energy requirements of CCS and make it more attractive as an emissions reduction pathway. The development of next-generation CO_2 capture technologies will require a range of validation steps, from pilot testing up to commercial scale. The availability of accumulated experience from development and maturing of existing capture technologies can prove very helpful for the development of the next-generation technologies that will advance CCUS deployment in Europe. In addition, the *SET Plan working group on Capture* performed several consultations with relevant

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Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

stakeholders involved in the development of CO_2 capture technologies along the entire TRL scale. The objective of such consultations was to identify key R&I priorities for the development of the next generation CO_2 capture technologies. Altogether, the following guidelines were elaborated from these consultations:

- Capture technologies should be developed to enable high capture rates (>95%) and CDR schemes. The development of a clear and shared framework for carbon accounting and for guaranteeing the sustainability of bioresources is fundamental to enable CDR solutions.
- The identification of suitable capture technologies for specific industrial applications should include considerations on the match between the energy requirements and the energy availability at plant site. Technology development should be guided by considerations of accessibility to clean and sustainable energy sources.
- Other technical aspects should be given importance, such as flexibility, compactness, and potential for heat integration and process intensification.
- Technological advancements are needed for the development of novel reactor designs, modularisation, and cost-effective materials.
- Cost reduction can be pursued both in terms of CAPEX and OPEX. The development of a funnel of large projects, based on CO_2 capture technologies at different high Technology Readiness Levels (TRL), will contribute to bring down costs.
- The formation of industrial clusters should be supported as they offer opportunities for energy integration, sharing of common infrastructure, and risk reduction for each cluster partner.
- Control of emissions and other health, safety, and environmental considerations are critical for reaching commercialisation of capture technologies. As such, they should be addressed early in the development of new technologies.
- Next generation CO_2 capture technologies must guarantee the quality and continuity of the industrial production or process where they are applied (via technology qualification).
- The development of a stable framework to enable early movers is essential to create the conditions to achieve climate goals: standards, funding and incentives, risk sharing, and business models. It is particularly important to support projects whose implementation contributes to developing a CCS and CCU network, for instance capture projects that will feed large transport and storage infrastructure projects (e.g., the Northern Lights/Longship project in Norway, which is the first European, commercial, full-chain CCS project to become operational).

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Introduction

The central role that CCUS must play to enable climate ambitions has been confirmed and reinforced by different authoritative sources. CCUS has a particularly important role in decarbonizing hard-to-abate industrial sectors, where emissions reductions by energy and process efficiency would not be sufficient to meet mitigation targets. IPCC[1] analysed several pathways that limit global warming to 1.5°C. Of totally 90 scenarios analysed, 18 scenarios are also consistent with net-zero emissions from the energy sector and industry in 2050[2]. The amount of CO_2 captured by CCUS in these scenarios is in the range 5.5 - 18.5 Gt CO_2 per year[2]. Importantly, a large share of this CCUS capacity is carbon dioxide removal (CDR) which comprise bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). The 18 scenarios include CDR capacity in the range 3.5 - 16 Gt CO_2 in 2050[2].

Although showing smaller absolute numbers, the IEA report "Net Zero by 2050" echoes the conclusions by IPCC. In the Net-Zero Emissions by 2050 Scenario (NZE), 1.6 Gt CO_2 per year is captured globally by 2030, rising to 7.6 Gt CO_2 in 2050. Around 95 % of captured CO_2 in 2050 is stored in permanent geological storage (CCS). With respect to CDR technologies, a total of 2.4 Gt CO_2 is removed from the atmosphere by 2050, through a combination of BECCS and DACCS, of which about 80 % is permanently stored, while the remaining CO_2 is used to provide synthetic fuels.

Completed in 2020, the report[3] "Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios" shows the analysis of the role of CCUS in the EU trajectory towards net-zero. While the climate contribution of CCU remains unclear, CCU technologies have the potential to contribute to emissions reduction, avoid the generation of new emissions by reusing existing emissions, and, in certain pathways to also store CO_2 in a manner intended to be permanent.

Full-scale commercial CCS projects will require all the parts of the value chain to be operational. The elements of the chain, i.e., capture, transport, and permanent storage, must be developed and implemented in phase with each other. The technical development has reached a maturity stage where the whole CCS value chain can be implemented and operated. The barriers might be more difficult to overcome on the political and financial side.

This said, the political and financial issues are closely linked with the technical development. The cost and energy requirements of CCS must be further reduced to make it more attractive as an emissions reduction pathway. However, CCS is needed, and even though the technology will develop further, its utilization at large scale must start in a very short timeframe.

[1] IPCC, 2018, Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty
[2] IEA, 2021, Net Zero by 2050 - A Roadmap for the Global Energy Sector
[3] Butnar, Cronin and Pye, 2020, Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios (available at: https://www.ccus-setplan.eu/resources/)

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Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

The report will focus on the capture-related aspects of the CCUS value chain. It will describe the status of CO_2 capture in a European perspective and outline recommendations for the steps required to develop next generation capture technologies necessary for enabling CCUS.

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Rue de la Science 14b
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CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Status of CO_2 capture in Europe

This chapter first gives an overview of the different capture technologies and how they have developed during the last eight years with respect to TRL level. Next, a status is provided on CO_2 capture within the different industry and energy sectors, which technologies have been evaluated and tested, and special requirements to the capture technology imposed by sector-specific conditions. Last, an overview of ongoing and planned European commercial CO_2 capture projects is given, including the related volumes of captured CO_2 and how it compares with necessary volumes to reach emission targets. The very recently granted EU Innovation Fund large-scale projects are included in the project overview.

Overview of CO_2 capture technologies

The technologies discussed below are mainly those for which a TRL development history can be established from different reference literature[5-13].

Absorption by Liquid Solvents

Absorption is a process where a fluid permeates or is dissolved by a liquid. Due to the different solubilities of the gas components in a particular solvent, the solvent can be used for selective separation. The regeneration process relies on the change in solubility obtained at different thermodynamic conditions. Most commonly regeneration is performed by means of a temperature increase, although in some cases also a pressure decrease could be used (alone or in parallel to the temperature increase). Absorption processes are amongst the most mature options for CO_2 capture. Commercial (or near to commercial) absorption-based systems are indeed available, normally based on amine solvents. Several absorption-based systems are under development, where the key difference is normally the solvent utilised. The following 11 options are included in the analysis:

- Conventional amine solvents
- Physical solvent
- Benfield process and variants
- Sterically hindered amine
- Chilled ammonia process
- Water-Lean solvent
- Biphasic solvents
- Amino acid-based solvent
- Precipitating solvents
- Encapsulated solvents
- Ionic liquids

Adsorption by Solid Sorbents

Adsorption is a process where one or more components of a gas or liquid stream are selectively adsorbed onto the surface of a solid adsorbent. In commercial processes, the adsorbent is usually in the form of small particles in a fixed bed. More recently systems with fluidized and moving beds are under development. As for absorption, regeneration of the adsorbent can be obtained through a pressure decrease (Pressure Swing Adsorption), a temperature increase (Temperature Swing Adsorption) or a combination of the two. Whilst adsorption-based systems are commercially available for certain applications, with respect to CO_2 capture

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B-1150 Brussels
Belgium

they have yet to reach full maturity (although a commercial application exist for hydrogen production). The adsorption-based systems are normally classified based on the regeneration method. The following 4 options are included in the analysis:

- Pressure Swing Adsorption (PSA) / Vacuum Swing Adsorption (VSA)
- Temperature Swing Adsorption (TSA)
- Sorbent-Enhanced Water Gas Shift (SEWGS)
- Enzyme Catalysed Adsorption

Membranes

A membrane can be used to selectively transfer certain chemical species through a wall – a permeant. The term often used for this transport is permeation and the selectively separated species are transported to the so-called permeate side of the membrane. The chemical species that do not cross the membrane wall are called retentate and the side of the membrane where they remain is called retentate side. Membrane technology can be used to separate CO_2 from other components of a gas mixture. CO_2 can be either selectively removed by the membrane or other components be removed so to concentrate CO_2 in the retentate stream. The technology has not yet been applied at commercial scale for CO_2 capture, but on-going research is progressing for a range of applications. Several types of membrane exist and are often characterized by the material ensuring the permeation process. The following 6 options are included in the analysis:

- Natural gas processing
- Polymeric membranes
- Dense inorganic membrane (H_2 separation)
- Dense inorganic membrane (CO_2 separation)
- Room Temperature Ionic Liquid (RTIL) Membranes
- Membrane contactors

Solid Looping

This group of technologies includes systems characterized by solid looping, normally at high temperatures. The underlying processes involve reversible fast gas–solid reactions in reactors operating at different thermodynamic conditions. The regenerable sorbents – metal oxides (MeOx) or other compounds – react with either O_2 (chemical looping combustion or reforming) or CO_2 (calcium looping), selectively transporting the molecule to the second reactor where the opposite reaction occurs. To ensure the solid looping, circulating fluidized bed reactors are the mostly used technology. Although the high temperatures might entail process challenges, they have also demonstrated to be potentially beneficial for efficient process integration. The following 3 options are included in the analysis:

- Calcium looping
- Chemical looping combustion

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CO_2 Value Europe AISBL
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B-1150 Brussels
Belgium

- Chemical Looping Steam Reforming

Low Temperature Separation Processes

In a low-temperature CO_2 separation process, a gas mixture is conditioned to specific pressure-temperature levels to allow physical phase separation of CO_2 from the other components. The process could be either vapour-liquid separation (CO_2-rich liquid phase), vapour-solid separation (solid CO_2) or a combination such as CO_2 slurry separation. With respect to CO_2 capture application, low-temperature CO_2 separation have not achieved widespread commercial deployment. The processes can be classified based on the low temperature level reached, where cryogenics is defined as temperatures below 120 K or approximately -153 °C. The following 2 options are included in the analysis:

- Low temperature separation
- Cryogenic capture

Hybrid processes

Hybrid approaches combine different capture technologies. The underlying idea is to design processes where each technology works in its ideal conditions. Normally this involves a two-step process: the first step includes a technology that performs well for bulk separation (e.g., adsorption or membranes); the second step includes a technology that performs well for purification of the CO_2-rich streams (e.g., low temperature separation). Several hybrid schemes are possible, depending on the combinations of capture technologies. The following 3 options are included in the analysis:

- Polymeric Membranes – Cryogenic Hybrid
- Polymeric Membranes – Solvent Hybrid
- Pressure Swing Adsorption – Cryogenic Hybrid

Fuel Cells with CO_2 capture

Fuel cells are electrochemically devices that convert chemical energy into electricity and heat. They are normally classified based on the electrolyte used. Given the possibility to direct convert chemical energy into electricity, fuel cells can potentially reach very high efficiencies. In some cases, fuel cells can also be used to facilitate CO_2 capture schemes while producing power. Depending on the capture strategies implemented and on the type of fuel cell, further CO_2 purification processes might be needed to reach CO_2 product specifications. Therefore, fuel cell might also be considered for hybrid processes (although those are not covered here). The following 2 options are included in the analysis:

- Molten carbonate fuel cell (MCFC)
- Solid oxide fuel cell (SOFC)

Direct Air Capture

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Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Direct air capture (DAC) is a technology to separate and concentrate CO_2 from the atmosphere. Given the extremely low concentration of CO_2 in air, this is an energy intensive process which must rely on renewable forms of energy to ensure a net removal of CO_2 from the atmosphere. Although capture of CO_2 from air can be based on different separation technologies, in this report DAC is considered a technology itself.

Inherent CO_2 capture

Inherent CO_2 capture is a broad definition to encompass technologies where CO_2 separation is inherently integrated in the process design without demanding additional energy to perform such separation. Those technologies are normally feasible only for certain processes (e.g., the Calix Advanced Calciner for lime and cement manufacturing) and as such their impact is limited to specific sectors. Given their nature, these technologies have significant potential in terms of capture cost reduction. However, involving a tight integration at process level, they cannot be used as retrofit options. The following 2 options are included in the analysis:

- Calix advanced calciner
- HIsarna ironmaking process

Oxy-combustion

CO_2 capture by oxy-combustion refers to a process where the combustion of hydrocarbon or carbonaceous fuel is carried out in an oxygen enriched atmosphere – pure oxygen or more often a mixture of pure oxygen and CO_2-rich recycled flue gas. The resulting flue gas consists mainly of CO_2 and water which can be easily separated. The oxy-combustion concept removes the need for separation of nitrogen from the flue gas. An air separation process is introduced to obtain the pure oxygen. The air separation process can rely on mature technologies, such as cryogenic distillation. Oxy-combustion options might differ based on the carbonaceous fuel and on the reactor utilised for the combustion. Some process cycles have also been designed which involve inherent separation of CO_2. Oxy-combustion technologies were first developed for coal and gas power generation. In the later years, oxy-combustion technologies have been developed for kiln and calciners in cement industry. More recently, oxy-fired waste-to-energy (WtE) furnaces, both grate and fluidised bed, are being researched and developed at pilot scale level. The following 6 options are included in the analysis:

- Oxy-fired circulating fluidised bed coal boiler
- Oxy-fired pulverised coal boiler
- Oxy-fired gas turbine cycles – Allam cycle
- Oxy-fired gas turbine cycles – CES cycle
- Oxy-fired kiln and calciner in cement
- Oxy-fired WtE furnaces (grate/fluidised bed)

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TRL evolution of capture technologies

The Technology Readiness Level (TRL) scale used hereafter is adapted by the initial definition given by the Electric Power Research Institute (EPRI)[4]. Table 1 gives an overview of the various levels and their descriptive definitions.

Table 1: TRL levels definition

	TRL	Descriptive definitions
Demonstration	9	Normal commercial service
	8	Commercial demonstration, fully functional prototype
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles observed, initial concept

Table 2 provides an overview of the evolution of TRL level for selected capture technologies. It covers the period 2014 – 2020 and is based on the sources given in the table. Bearing in mind that the comparison of figures from different sources does not ensure complete consistency, the proposed analysis provides a general overview of the recent developments. Useful information could be extrapolated such as which capture technologies are ready, which ones have been developed the last years, and if there are some where the development have been limited.

Table 2: TRL evolution for the selected capture technologies

Capture Technology	TRL 2014[5]	TRL 2017/2018[6,7]	TRL 2019/2020[8,9]
Absorption by Liquid Solvents			
Conventional amine solvents	9	9	9
Physical solvent	9	-	9
Benfield process and variants	-	9	9
Sterically hindered amine	6-8	-	6-9
Chilled ammonia process	-	-	6-7

[4] Freeman and Bohwn (2011), Energy Procedia, 4, 1791–1796
[5] IEAGHG, 2014, Assessment of CO_2 capture technologies and their potential to reduce costs
[6] Wood, 2018, Assessing the Cost Reduction Potential and Competitiveness of Novel (Next Generation) UK Carbon Capture Technology
[7] Bui et al., 2018, Energy & Environmental Science, 11, 1062
[8] IEAGHG, 2019, Further assessment of emerging CO_2 capture technologies for the power sector and their potential to reduce costs
[9] Global CCUS Institute, 2021, Technology readiness and costs of CCUS

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Water-lean solvent	-	-	4-7
Biphasic solvents	4	4-6	5-6
Amino acid-based solvent	-	-	4-5
Precipitating solvents	4-5	4-5	4-6
Encapsulated solvents	1	2-3	2-3
Ionic liquids	1	1-3	2-3
Adsorption by Solid Sorbents			
Pressure Swing Adsorption (PSA) and Vacuum Swing Adsorption (VSA) (*)	3/-	5-7 / 8-9	6 / 9
Temperature Swing Adsorption (TSA)	1	5-7	5-7
Sorbent-Enhanced Water Gas Shift (SEWGS)	5	5	5
Enzyme Catalysed Adsorption	1	6	6
Membranes			
Natural gas processing	-	8	9
Polymeric membranes	6	6-7	7
Dense inorganic membrane (H_2 separation)	5	5	5-6
Dense inorganic membrane (CO_2 separation)	-	3	5-6
Room Temperature Ionic Liquid (RTIL) membranes	2	-	2
Membrane contactors	-	-	5-6
Solid Looping			
Calcium looping	6	6-7	6-7
Chemical looping combustion	2	6	4-6
Chemical looping steam reforming	3	3	-
Low Temperature Separation Processes			
Low temperature separation	2	2-3	-
Cryogenic capture	3	4	5
Hybrid processes			
Polymeric Membranes – Cryogenic	6	6	6
Polymeric Membranes – Solvent	-	-	4
Pressure Swing Adsorption – Cryogenic	-	-	6-9(**)
Fuel cells with CO_2 capture			
Molten carbonate fuel cell (MCFC)	-	7	7
Solid oxide fuel cell (SOFC)	6	6	-
Direct Air Capture	-	7	5
Inherent CO_2 capture			
Calix advanced calciner	-	-	5-6
HIsarna ironmaking process			8 (estimate**)
Oxy-combustion			

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Oxy-fired circulating fluidised bed boiler	7	7	-
Oxy-fired pulverised coal boiler	7	7	-
Oxy-fired kiln and calciner in cement	4***		6***
Oxy-fired WtE furnaces (grate / fluidised bed)			4-5****
Oxy-fired gas turbine cycles – Allam cycle	2	7	6-7
Oxy-fired gas turbine cycles – CES cycle	5	5	-

** The technology is developed both for post- and pre-combustion applications. As such the TRL level for both routes are reported as post-combustion TRL / pre-combustion TRL.*

*** Value retrieved from Low carbon energy observatory*[10]

**** Values retrieved from Hills et al.*[11] *and Plaza et al.*[12]

***** Value retrieved Ditaranto (2021)*[13]

Status of CO_2 capture in energy and industry sectors

The status of CO_2 capture in European energy and industry sectors is discussed considering the following sectors:

- Coal power generation
- Gas power generation
- Waste to Energy
- Iron and steel
- Cement and lime
- Pulp and paper
- Refineries
- Oil and gas production
- Hydrogen production
- Chemical and metallurgical industry

Between the sectors, there will be some general differences that will affect the choice of capture technologies, such as CO_2 concentrations, scale of CO_2 emissions, impurities in the flue gases, availability of heat, steam, and power, etc. Commercial challenges for CO_2 capture may differ as well since different sectors will most likely see different business cases. There are also issues not being related to any sector, but merely being plant specific, such as location and transport infrastructure, space considerations, power infrastructure, etc.

The assessment provided is partly based on work of IEA[14], Global CCUS Institute[9], and Bains et al[15], in addition to other references specifically addressed in the text.

[10] Low carbon energy observatory, 2019, Carbon capture utilisation and storage: technology development report
[11] Hill et al., 2016, Carbon capture in the cement industry: technologies, progress and retrofitting, Environ. Sci. Technol., 50, 1, 368–377
[12] Plaza et al., 2020, CO_2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations, Energies, 13(21)
[13] Ditaranto M., 2021, Technical solutions for CO_2 capture in the waste sector. Presented at the online Tekna CO_2 conference January 2021 (in Norwegian).
[14] IEA, 2020, EnergyTechnologyPerspectives
[15] Bains et al, 2017, Progress in Energy and Combustion Science, 63, 146-172

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Coal power generation

Coal power contributed about 15 % of electricity production in EU plus UK in 2019, whereas it contributed 31 % of EU ETS emissions (480 Mt CO_2eq out of totally 1555 Mt CO_2eq)[16]. Coal power generation has become increasingly expensive, partly due to the increased ETS CO_2 price[17].

CO_2 emissions are combustion-generated from furnaces where coal is combusted with air. Pulverized fuel furnaces are the most common but other types are used, such as fluidised bed furnaces. Flue gases will generally have CO_2 concentration of 10 – 15 vol% (wet gas), at temperature of 40 – 65 °C and atmospheric pressure.

Post-combustion capture with liquid solvents (amines) is commercial technology and have been demonstrated at full scale at Boundary Dam in Canada since 2014, and Petra Nova in the US in the period 2017-2020. Oxy-combustion was demonstrated at Schwarze Pumpe at 30 MW_{th} scale in the period 2009 – 2014, and in the larger Callide demonstration project in Australia 2012 – 2015 where a 30 MW_{el} boiler was retrofitted to oxy-combustion. There are at present no on-going large-scale capture demonstration activities in Europe within coal power generation.

Gas power generation

Gas power plants produced about 21 % of the EU plus UK power generation in 2019[16]. The CO_2 emissions (EU ETS) from the gas power sector were about 235 Mt CO_2[18]. CO_2 emissions are mainly from combined cycle plants with natural gas fired gas turbines. Due to the large air excess in a gas turbine, CO_2 concentrations in the flue gas will be low, normally 3 – 5 vol% (wet) with temperature about 90 – 100 °C and at atmospheric pressure. The low CO_2 concentration compared to coal power plants almost doubles the specific energy demand for CO_2 capture. On the other hand, there will be less impurities in the flue gas.

Post-combustion with liquid solvents (amines) is commercially available, but no commercial scale plants are in operation, neither in Europe nor elsewhere. Fuel-shift to hydrogen will reduce CO_2 emissions, however, this is not yet mature and commercially available technology. Due to cleaner flue gas than from solid fuels, gas power generation can be more suited for membranes and solid sorbents technology.

Waste to Energy

In 2018, there were 492 WtE plants in Europe, thermally incinerating 96 million tonnes of waste per year[19]. The specific CO_2 emission is about 1 tonne of CO_2 per tonne of waste, so CO_2 emissions will be close to 100 Mtpy[20]. The WtE sector recovers about 39 TWh of electricity and 90 TWh of heat from waste, contributing to CO_2 savings if the alternative was fossil fuels. About half of the CO_2 emissions from WtE are biogenic and this might result in carbon dioxide removal if a CCS scheme is implemented.

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[16] Agora Energiewende and Sandbag (2020): The European Power Sector in 2019: Up-to-Date Analysis on the Electricity Transition
[17] https://www.euractiv.com/section/climate-environment/news/europe-halfway-towards-closing-all-coal-power-plants-by-2030/ (24 Mar 2021)
[18] https://ember-climate.org/commentary/2021/04/16/gas-power-euets/
[19] CEWEP - The Confederation of European Waste-to-Energy Plants
[20] https://www.endrava.com/the-ccs-potential-for-waste-to-energy-plants/

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

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B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

Combustion of municipal solid waste (MSW) in grate-fired furnaces are the main source to CO_2 emissions from WtE. Other CO_2 emissions come from combustion of waste-derived solid fuels (RDF, SRF, waste-wood, etc.) in different types of furnaces, including fluidised bed. Flue gases will generally have CO_2 concentrations of 10 – 12 vol% (wet), with temperature of 50 – 100 °C, and at atmospheric pressure.

Post-combustion with liquid solvents (amines) are available technology for WtE. One commercial plant is in operation, capturing 60 000 - 100 000 tpy from incineration of residual waste at the AVR-Duiven plant in The Netherlands. The CO_2 is used in the horticultural sector. A larger plant is planned at Fortum Oslo Varme in Norway, capturing about 360 000 tpy of CO_2.

Oxy-fuel combustion in incineration plants is potentially an energy efficient alternative, which might decrease the energy penalty while decreasing emission of NOx and other pollutants. However, the technology is not mature yet, with ongoing projects aiming to increase its TRL level through a combination of pilot-scale testing and modelling[13].

Iron and steel

The EU crude steel production was 157 million tonnes in 2019, contributing 8.4 % of world global production of 1.87 billion tonnes[21]. About 60 % of EU crude steel is made via the integrated blast furnace - basic oxygen furnace (BF-BOF) route. The remaining is produced in electric arc furnaces (EAF) fed with scrap steel, iron pellets or direct reduced iron (DRI). The EU steel industry currently accounts for about 220 Mt GHG emissions annually, including both direct and indirect emissions[22]. On average, steel production in the EU is among the most CO_2 efficient worldwide.

The CO_2 emissions of the BF-BOF route are mainly from the iron ore and coke, and from limestone added to the process. On average, the emission factor of European BF-BOF steel is 1.89 tonne CO_2 per tonne steel (both direct and indirect emissions)[23]. Flue gases will generally have CO_2 concentration of 20 – 27 vol% (BF) and 16 – 42 vol% (BOF). Temperature will be about 100 °C, and atmospheric pressure.

Several pathways for CO_2 reduction have been investigated by the European steel industry, notably through the ULCOS Programme. The main capture technologies being explored are amine scrubbing, VSA, PSA and cryogenics[24]. One of the most promising adsorption-based technologies for the steel sector is Sorption Enhanced Water-Gas Shift technology (SEWGS), which has been tested in a pilot plant at LKAB in Sweden (STEPWISE and FReSMe projects). A cryogenic separation step may be needed after the PSA/VSA to achieve needed CO_2 purity for further CO_2 use or storage. The HIsarna process is an alternative hot metal production process that produces a high concentration CO_2 stream free of nitrogen, and where the CO_2 can be made ready for use or storage via cryogenic separation only. Liquid solvent technology for CO_2 removal from steel

[21] https://www.eurofer.eu/assets/Uploads/Annual-Report-2020.pdf
[22] https://ec.europa.eu/info/sites/default/files/swd-competitive-clean-european-steel_en.pdf (May 2021)
[23] ZEP (Nov 2015). CCS for industry. Modelling the lowest-cost route to decarbonising Europe.
[24] ECN, TNO (Nov 2019). Decarbonisation options for the Dutch steel industry.

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production flue gas is currently being developed and tested in the 3D project (DMX Demonstration Dunkirk) in France.

Use of biomass and hydrogen are less mature technologies for CO_2 reduction, however, planned projects such as the Swedish HYBRIT project, the ArcelorMittal Torero plant in Belgium, and H2morrow steel in Germany will investigate these options. The HYBRIT project (Hydrogen Breakthrough Ironmaking Technology) was recently awarded grants from the EU large-scale innovation fund. It will replace coal-based blast furnaces with direct hydrogen-based reduction technology. The project will produce approximately 1.2 Mt crude steel annually, representing 25% of Sweden's production. This will reduce greenhouse gas emissions by 14.3 Mt CO_2 over the first 10 years of operation.

Cement and lime

Cement production is an energy-intensive process and generates substantial CO_2 emissions. The CO_2 emissions from EU cement sector is about 110 – 120 Mt CO_2 per year[25]. The most energy-intensive component is generally referred to as clinker burning. The specific CO_2 emissions from this component have continuously decreased since 1990 due to increased energy efficiency and the increased utilisation of alternative fuels and clinker substitutes in cement blending[23]. However, CO_2 emissions from the calcination process to produce the clinker are inherently unavoidable since as much as 60-65 % of the CO_2 comes from the calcination process itself, with the remaining 40-35 % from the fuel combustion to generate the needed heat for kiln and calciner. Flue gas from calciner and clinker kiln are normally mixed since kiln off-gas flows through calciner and pre-heater. Flue gases will generally have rather high CO_2 concentration, 18 – 22 vol% (wet), with temperature of about 100 °C and atmospheric pressure.

Post-combustion capture using liquid solvents is mature technology. A full-scale commercial plant using amine solvents will be built at the Norcem cement plant in Brevik in Norway. It will be operational by 2024 and the 400 000 tonnes of CO_2 captured per year will be transported with ship and stored at Northern Lights offshore storage site west of Norway. The CCU Lighthouse Carboneras project in Spain is also building a large-scale capture plant using liquid solvents, capturing 70 000 tonnes CO_2 per year in the first phase. Another capture solution for cement is the Calix technology, using indirect heating of the calciner which will directly separate the CO_2 released in the calcination process, i.e., about 60 % of the total CO_2 emissions from the cement plant. This has been demonstrated in the LEILAC1 pilot plant and is now scaled-up in the LEILAC2 project to capture 100 000 tonnes of CO_2 per year.

Other capture technologies that are being developed for cement industry are post-combustion calcium looping and oxyfuel technology. The latter will be demonstrated at large scale in the K6 project that recently was awarded funding from the EU large-scale innovation fund. Located at the Lumbres cement plant in France, the project will use biomass-containing and other alternative fuels, as well as already decarbonated

[25] https://newclimate.org/wp-content/uploads/2020/12/SGCCC-EU-Cement-paper-NewClimate_Nov2020.pdf

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raw materials. In addition, a novel industrial-scale oxy-fuel kiln will capture more than 90 % of the remaining CO_2, avoiding in total 8.1 Mt CO_2eq emissions over the first ten years of operation.

Pulp and paper

In 2016, the European pulp and paper industry emitted about 100 Mt CO_2, of which about 68 Mt originates from biogenic sources and the remaining 32 Mt from burning fossil fuels in boilers and lime kilns[26]. The biogenic CO_2 are thus twice as large as the fossil CO_2 and consequently, capturing CO_2 from the pulp and paper mills and permanently storing it, is an effective carbon negative option. As such, the pulp and paper industry could be a low-hanging fruit for demonstration of bio-CCUS and industrial CCUS.

Three major emission point sources can be identified, namely the recovery boiler, the lime kiln and the multi-fuel boiler, also called the power boiler. Flue gases will generally have CO_2 concentrations of 10 – 25 vol% (wet), with temperature of 180 – 250 °C and atmospheric pressure.

Post-combustion capture schemes are deemed as technically viable[27], with similar challenges (e.g., presence of impurities in the flue gas) as in other possible capture applications. Oxy-combustion might be theoretically possible but entail challenges such as operational conditions, availability requirements, temperature profiles and impurity levels. Pre-combustion capture could be an option to tackle certain point sources, those involving a gasification process, but overall seems less relevant for the pulp and paper sector. No technology has been tested at scale.

Refineries

Emissions from the refining sector in the EU ETS was 128 Mt CO_2eq. in 2014, representing 7 % of the total verified EU ETS emissions that year[28]. Refineries are complex industrial sites that are highly integrated and characterised by diverse process configurations. Thus, a single site will have numerous possible CO_2 emissions points, often characterized by medium to small CO_2 concentrations (< 11%)[29]. Typical CO_2 point sources are the on-site power generation, the crude distillation, the fluid catalytic cracking, and the steam methane reformer for hydrogen production.

Fluid catalytic cracking is often the single largest source. The CO_2 concentration is rather low, 8 – 12 %. Hydrogen production generates a CO_2-rich stream after hydrogen purification, with CO_2 concentrations up to 50 %. However, the stream contains unburnt components and are generally recycled as a fuel to provide thermal energy for the reaction process. Utilities and process heaters create combustion derived emissions with CO_2 generally at low concentrations, about 3 – 12 %.

No single CO_2 capture technology is applicable across the industry sector. The integration of absorption by liquid solvents is studied in several projects. In parallel, other technologies are under scrutiny such as chemical looping combustion as well as the utilization of solid adsorbents. Pre-combustion options might be

[26] REINVENT – PROJECT NR 730053. Climate innovations in the paper industry: Prospects for decarbonisation (Sept 2018).
[27] Arasto, 2015, CCUS and Pulp and Paper Industry, CCUS in process industry workshop
[28] Overview of the refining industry in the European Union Emissions Trading System (EU ETS). Panorama 2016, IFP EN.
[29] SINTEF Energy Research, 2017, Understanding the cost of retrofitting CO_2 capture to an integrated oil refinery

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CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

available when integrated with hydrogen production. Oxy-combustion technology for fluid catalytic crackers has also been evaluated as a possible CO_2 reducing measure from refineries.

Oil and gas production

The two largest operational CCS facilities in Europe today are the Sleipner and Snøhvit gas production installations in Norway. At the Sleipner facility offshore west of Norway, CO_2 is removed from the produced natural gas, compressed, and sent back under the seabed for permanent storage. Approximately 1 million tonnes of CO_2 per year have been stored since 1996. At the Snøhvit coastal onshore facility north in Norway, CO_2 is removed from the natural gas before producing LNG. The CO_2 is compressed and piped back to the offshore field where it is permanently stored. The capacity is to capture and store about 0.7 million tonnes of CO_2 per year.

The largest emissions from oil and gas production, other than CO_2 potentially present in the produced gas, are generally related to offshore power production by gas turbines and diesel engines, and gas -fired steam and power production at onshore facilities. For the onshore installations, post-combustion amine capture is a mature technology that can be used.

Hydrogen production

Approximately 120Mt of hydrogen is produced annually on a global scale[30]. The vast majority of this hydrogen (around 95 %) is generated from natural gas and coal. The European Union (EU) annual consumption of hydrogen is around 9.7 Mt[31]. Refineries make up for approximately 30% of the total hydrogen consumption. Currently, only about 1% of hydrogen production from fossil fuels includes CCS[32].

In a European perspective, the main production route for hydrogen from fossil fuel consists of the reforming of natural gas, so-called blue hydrogen. The most common scheme entails a steam methane reforming (SMR) process followed by hydrogen purification – normally a pressure swing adsorption (PSA) unit. Two CO_2 sources can be identified in such a hydrogen production plant. The first source consists of the CO_2 in the syngas, resulting from the reforming of natural gas. This CO_2 can either be captured upstream the PSA unit or downstream from its tail gas. The second source consists of the CO_2 in the flue gas resulting from natural gas combustion to supply thermal energy to the SMR process. Flue gases will generally have the following properties:

Stream:	CO_2 concentration:	Temperature and pressure:
Syngas upstream PSA	15-20 vol% (wet)	20-50 °C, 20-40 bar
PSA tail gas	48-52 vol% (wet)	20-50 °C, 1.1-1.5 bar
Flue gas from SMR	16-21 vol% (wet)	100-170 °C, atmospheric pressure

[30] IEA International Energy Agency. World Energy Outlook 2019.
[31] Fuel Cells and Hydrogen Joint Undertaking (FCH). Hydrogen Roadmap Europe - a Sustainable Pathway for the European Energy Transition. Brussels, Belgium; 2019.
[32] Global CCS Institute, 2021, Blue Hydrogen

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Although most of the hydrogen from natural gas is currently produced from SMR, other production routes exist, such as autothermal reforming (ATR) and partial oxidation (POX). These alternative production routes become especially relevant if high CO_2 capture rates are targeted.

Different capture technologies might be relevant, given the rather high CO_2 concentrations. Some have been tested at scale. The Port Arthur commercial hydrogen plant in the USA[33] is using PSA technology both for CO_2 capture from the syngas and for hydrogen purification. In Europe, at Port-Jérôme in France, Air Liquide has tested at industrial scale their hybrid technology that includes a combined cryogenic and membrane system.

The recent Hydrogen 4 Europe report[34] concludes that hydrogen will play a major role in the decarbonization of the energy sector. Hydrogen can provide an answer to the challenges of deep electrification and the limits of energy efficiency improvements. Low-carbon hydrogen plays a critical role in establishing a hydrogen economy in the first half of the outlook period. This is also verified by the large number of planned European projects involving hydrogen production with CCUS. Among them are the Kairos@C project and the SHARK project. Both projects were recently awarded funding from the EU large-scale innovation fund. The Kairos@C project will integrate CO_2 capture and purification from 5 different production units in the port of Antwerp in Belgium, among them 2 hydrogen plants. The SHARK project will reduce emissions at the Porvoo refinery in Finland, by moving from grey hydrogen to green hydrogen (electrolysis) and blue hydrogen by application of carbon capture and storage (CCS).

Chemical and metallurgical industry

Chemical industry comprises a variety of production processes and plants, such as ammonia and fertiliser production, methanol production, ethylene and other high-value chemicals production, plastics refining, and ethanol/bioethanol production. Globally, the sector is the largest industrial consumer of both oil and gas, and the largest industrial energy consumer overall. Yet, it is only the third sector in terms of direct CO_2 emissions, behind iron and steel and cement, since around half of the sector's energy input is consumed as feedstock, i.e., fuel used as raw material rather than as a source of energy. Direct CO_2 emissions from global primary chemical production were 920 Mt CO_2 in 2020 as given by IEA[35]. According to IEA, the demand for primary chemicals - being an indicator for the overall sector activity - will continue to increase, underscoring the need for reducing the sector's energy and CO_2 emissions intensity.

As will be seen in the next chapter, some commercial European CCUS projects within chemical industry are planned for the coming years. Several of them as part of industrial clusters. The already mentioned Kairos@C project in the port of Antwerp is one such project, where the integrated CO_2 capture and purification also involves 2 ethylene oxide plants and 1 ammonia plant.

The metallurgical industry comprises the metal industry except iron and steel production. It includes large industries as aluminium production, ferrosilicon, silicon-metal, as well as several others. The production is

[33] IEAGHG, 2018, the carbon capture project at Air Product's Port Arthur hydrogen production facility
[34] Home | Hydrogen4EU
[35] https://www.iea.org/reports/chemicals (Nov. 2021)

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium
CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium
+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

generally energy demanding and several processes will also need a carbon-containing reduction agent, where coal has been the default choice.

CO_2 emissions can be reduced by implementing CO_2 capture, replace fossil fuels with renewable power generation, replace renewable bio-carbon as reduction agent, or a combination of these measures. Very recently, the Eramet Norway company was awarded EUR 6.2 million for a large pilot project using bio-carbon in their manganese alloys production in Norway[36]. If all their three manganese plants in Norway can use bio-carbon, they will save 370 000 tonnes CO_2 per year, whereas the global potential is about 32 Mt CO_2. Another pilot project recently announced is the planned CO_2 capture pilot to be installed at one of the Elkem plants in Norway, producing ferrosilicon and microsilica. The test unit will be post-combustion technology using liquid solvents and will be delivered by Aker Carbon Capture[37].

Carbon dioxide removal

Carbon Dioxide Removal (CDR) is not an industry or energy sector in itself as the sectors described above, which generate an industrial or energy product in some way. CDR involves taking CO_2 out of the atmosphere, where it contributes to climate change, and putting it in a location where it will not affect the climate for an extended period of time[38]. Most emission scenarios consistent with < 2 °C temperature increase, involves a substantial share of CDR technologies, of which bioenergy with CCS (BECCS) is the main contributing technology.

BECCS are planned at large scale at the Drax Power Station in UK. Several other CCS projects are being developed, involving combined fuel feedstocks with a large fraction of biogenic material. Most WtE with CCS will be in this category, having a significant BECCS potential due to the biogenic carbon fraction in the waste. The BECCS@STHLM project was recently awarded funding from EU large-scale innovation fund. It will build a full CCS chain based on capture from Stockholm Exergi's existing heat and power biomass plant in Stockholm. It will capture in average nearly 800 000 tpy of biogenic CO_2 and store at the Northern Lights facility offshore Norway.

Direct air capture and storage (DACCS) is another CDR technology. In DACCS, CO_2 is extracted from the atmosphere by means of a gas separation technology. The Carbfix project in Iceland has built a pilot plant with Climeworks technology, and with regeneration heat provided by the geothermal power plant located at the same site. It will capture 4000 tonnes CO_2 per year that will be injected into the geothermal source and mineralised.

Another possible route to indirectly remove CO_2 from the atmosphere involves CO_2 capture from oceans. The technology would extract CO_2 from seawater that would then be able to dissolve additional CO_2 from the atmosphere to retain the state of equilibrium between atmosphere and the oceans[39]. There is a large

[36] https://presse.enova.no/pressreleases/eramet-norway-faar-621-millioner-kroner-fra-enova-til-banebrytende-biokarbonprosjekt-3143727
[37] https://www.elkem.com/investor/announcements/announcement/?itemid=8F34AF42688D0767 (October 2021)
[38] ZEP (July 2020). Europe needs a definition of Carbon Dioxide Removal.
[39] https://newsroom.ucla.edu/releases/using-seawater-to-reduce-co2-in-atmosphere (January 2021)

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Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

theoretical potential, however, the technology is currently in an early development phase and has not been tested at scale.

EU Innovation Fund projects

The EU Innovation Fund is one of the world's largest funding programmes for demonstration of low-carbon technologies. It will provide around EUR 25 billion of support in the period 2020-2030 for commercial demonstration of innovative low-carbon technologies, aiming to bring to the market industrial solutions to decarbonise Europe. Further goals are to help businesses invest in clean energy, boost economic growth, create future jobs, and reinforce European technological leadership on a global scale. This is done through calls for large- and small-scale projects on innovative low-carbon technologies and processes in energy-intensive industries, including products substituting carbon-intensive ones, carbon capture and utilisation (CCU), construction and operation of carbon capture and storage (CCS), innovative renewable energy generation and energy storage.

Projects are classified as large- or small-scale depending on whether the total capital costs are above or below EUR 7.5 million, respectively. The funding of the Innovation Fund comes from the EU ETS and as such will follow the carbon price. The estimated EUR 25 billion funding is based on a carbon price of EUR 50 per tonne CO_2.

The first call for large-scale projects were launched in July 2020, with total available grants of EUR 1 billion. The final evaluation results after a 2-stage process were published on 16 November 2021. Totally 7 projects were pre-selected for grant agreement preparations, of which 4 projects are CCS projects. The other 3 projects are within photovoltaics, methanol production from municipal non-recyclable waste, and hydrogen-based iron and steelmaking. A short presentation of the 4 CCS projects is provided below:

Kairos@C will develop a complete carbon, capture and storage (CCS) value chain that will avoid ca. 14.2 Mt CO_2 over the first 10 years of operation. It will kick-start the earlier launched Antwerp@C project, developing a CO_2 infrastructure in the port of Antwerp in Belgium. The large-scale CO_2 capture layout will be a first-of-its-kind multi-feed scheme, which optimises and integrates CO_2 capture and purification from 5 different production units: 2 hydrogen plants, 2 ethylene oxide plants, and 1 ammonia plant. The CO_2 storage will take place in storage sites in the North Sea (Norway, the Netherlands and/or in the UK). Coordinator is Air Liquide Large Industry SA.

BECCS@STHLM will create a full-scale Bio-Energy Carbon Capture and Storage facility at Stockholm Exergi's existing heat and power biomass plant in Stockholm. It will capture and store large quantities of biogenic CO_2 with a potential to avoid ca. 7.8 Mt CO_2 over the first 10 years of operation. The CO_2 will be transported by ship to Norway for storage. The project will participate in and promote a new market for negative emissions and be a catalyst for net carbon removals which will become an increasingly important instrument to reach climate neutrality. Coordinator is Stockholm Exergi.

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

K6 will reduce CO_2 emissions through implementation of a range of technological initiatives and innovations at the Lumbres cement plant in France, just about 55 km from Dunkirk. The project aims to maximise the usage of biomass-containing and other alternative fuels and to take advantage of already-decarbonated raw materials. A novel industrial-scale combination of an oxy-fuel kiln with carbon capture that replaces the existing wet kilns, will result in capturing over 90% of the remaining CO_2. This CO_2 will be transported by train and ship for storage in North Sea sites or utilized in products of concrete, resulting in an avoidance of 8.1 Mt CO_2eq emissions over the first ten years of operation. Coordinator is EQIOM.

SHARC – Sustainable Hydrogen and Recovery of Carbon – will reduce emissions at the Porvoo refinery, Finland, by moving from grey hydrogen towards green hydrogen through the introduction of electrolysis facilities and blue hydrogen by application of carbon capture and storage (CCS). Hydrogen is essential in the production processes of transportation fuels, so the green and blue hydrogen will reduce the carbon intensity of these fuels. SHARC will save more than 4 Mt CO_2 in the first 10 years of operation Coordinator is Neste Oyj.

The number of granted CCS projects is a clear indication of the need to quickly establish commercial CCS as a means for large-scale decarbonisation in a relatively short time frame. The CCS projects cover hydrogen production, chemical industry, cement production and BECCS. All of which are highly relevant sectors for potential decarbonization in a low-carbon industry and energy system. In addition, the HYBRIT project will decarbonise steel production by shifting to hydrogen, although without the CO_2 capture part since the hydrogen is from electrolysis.

Status of European ongoing and planned capture projects

In the GCCSI Global status of CCUS 2020[40] there are globally 26 projects defined as being in commercial operation today. Only two of these are in Europe, the Sleipner and Snøhvit projects in Norway, which are capturing CO_2 from natural gas streams ("natural gas sweetening"). Most of the operational projects are in United States and Canada. Furthermore, there are 13 commercial projects in the advanced development stage (reaching FEED). Two of these are in Europe, namely Fortum Oslo Varme WtE and Norcem cement plant, both being part of the Norwegian Langskip project[41]. Finally, GCCSI list 21 projects in an early development stage. Nine of these in Europe with seven in UK, one in The Netherlands and one in Ireland.

Several planned European projects are not on the GCCSI list. Most notably all the projects related to ports and industrial clusters in The Netherlands and Belgium. A better overview of European projects can be found on the ZEP homepage, providing an overview of European CCUS/CCU projects[42]. The ZEP projects map lists market-ready projects that will become operational before 2030. It is being updated on a regular basis.

[40] Global CCUS Institute, 2020, Global status of CCUS 2020
[41] https://CCUSnorway.com/
[42] https://zeroemissionsplatform.eu/about-CCUS-ccu/css-ccu-projects/

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

The tables below show an overview of commercial scale CO_2 capture projects in Europe until about 2035, as identified in this investigation. This is an update of the overview of European CCUS projects[42] that can be found on the ZEP homepage. Table 3 lists the identified ongoing projects, whereas Table 4 and Table 5 lists the identified planned projects including the recently published Innovation Fund projects described in the former section. This gives a snapshot of capture technologies being tested today, and what can be expected to come in the next years towards 2030.

It should be noted that a lot of projects on CO_2 capture are not listed in the Tables, such as projects that are less developed and smaller in size, as well as national lab- and pilot-scale projects. However, it is noted that there are activities in several countries where different industries and companies are evaluating measures to reduce their carbon footprint and produce their products with lower specific CO_2 emissions. Such products will in coming years likely see increased interest and price compared to their predecessors. This is an important consideration and assessments on the expected trade-offs need to be done by companies, to ensure retaining their competitiveness in global markets while delivering on the emissions reduction targets.

Table 3: Ongoing commercial scale European projects involving CO_2 capture.

Project	Lead country	Sector	Year start	CCS, CCU or other	CO_2 captured [Mtpy]	CO_2 stored [Mtpy]
CO_2 EOR Project Croatia	Croatia	Oil and gas	2015	CCS	**0.56**	**0.56**
Port-Jerome H2 Plant	France	Hydrogen production	2015	CCU	**0.1**	**0**
Orca (Climeworks, ON Power, Carbfix)	Iceland	Direct air capture	2020	CCS	**0.004**	**0.004**
Hellisheidi/Carbfix	Iceland	Geothermal CHP	2014	CCS	**0.012**	**0.012**
AVR-Duiven	Netherlands	WtE	2019	CCU	**0.1**	**0**
Snøhvit	Norway	Oil and gas	2008	CCS	**0.7**	**0.7**
Sleipner	Norway	Oil and gas	1996	CCS	**1.0**	**1.0**

Table 4: Planned commercial European projects involving CO_2 capture to come online by 2030.

Project	Lead country	Sector	Year start	CCS, CCU or other	CO_2 captured [Mtpy]	CO_2 stored [Mtpy]
Carbon2Product Austria	Austria	Cement	2030	CCU	**0.7**	**0**

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CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

North-C-Methanol (part of North-CCU-Hub)	Belgium	Methanol	2024	CCU	**0.065**	**0**
AlcoBioFuel (part of North-CCU-Hub)	Belgium	Biorefinery	2022	CCU	**0.16**	**0**
Kairos@C (initiating the Antwerp@C project)	Belgium	Capture cluster	< 2030	CCS	**1.4**	**1.4**
Antwerp@C Port of Antwerp (excl. Kairos@C)	Belgium	Capture cluster	2030	CCS	**7.6**	**7.6**
Carbon Connect Delta final phase	Belgium / Netherlands	Capture cluster	2030	CCS	**6.5**	**6.5**
iCORD (EOR)	Croatia	Fertilizer plant	2025	CCS	**1**	**1**
Bio-Refinery Project	Croatia	Bio-refinery	2024	CCS	**0.06**	**0.06**
Amager Bakke WtE	Denmark	WtE	2025	CCS	**0.5**	**0.5**
C4 – Carbon Capture Cluster Copenhagen	Denmark	Capture cluster		CCS	**2.5**	**2.5**
SHARC – Sustainable Hydrogen and Recovery of Carbon	Finland	Hydrogen production	< 2030	Estimated 50 % CCS	**0.2**	**0.2**
3D - DMX demonstration Dunkirk	France	Iron and steel	2025	CCS	**1**	**1**
K6 (EQIOM Lumbres plant)	France	Cement	< 2030	Estimated 50 % CCS	**0.4**	**0.4**
Normandy H2 production site	France	Hydrogen production	2030	CCS	**0.65**	**0.65**
H2morrow steel	Germany	Iron and steel	2028	CCS	**1.9**	**1.9**
Carbfix Project Silverstone	Iceland	Geothermal CHP	2025	CCS	**0.034**	**0.034**
CCS Ravenna Hub (Adriatic Blue CCS)	Italy	Power generation	2026	CCS	**2.5**	**2.5**
H-vision	Netherlands	Hydrogen production	2030	CCS	**2.7**	**2.7**
H2M - Hydrogen 2 Magnum (Eemshaven)	Netherlands	Power generation	2023	CCS	**1.3**	**1.3**

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Porthos	Netherlands	Capture cluster	2024	CCUS	**2.5**	**2.5**
Twence WtE CCSU	Netherlands	WtE		CCUS	**0.1**	**??**
Fortum Oslo Varme WtE (Longship)	Norway	WtE	2026	CCS	**0.36**	**0.36**
HyDemo	Norway	Hydrogen production		CCS	**0.2**	**0.2**
Norcem Full-scale CCS	Norway	Cement	2024	CCS	**0.4**	**0.4**
ECCO2 Carboneras LafargeHolcim first phase	Spain	Cement	2022	CCU	**0.07**	**0**
BECCS@STHLM Stockholm Exergi	Sweden	Biomass CHP	2025	CCS	**0.8**	**0.8**
PREEM CCS full scale	Sweden	Oil and gas	2025	CCS	**0.5**	**0.5**
Heidelberg Cement Slite plant Gotland	Sweden	Cement	2030	CCS	**1.8**	**1.8**
Caledonia Clean Energy	United Kingdom	Power generation	2024	CCS	**3**	**3**
HyNet NorthWest	United Kingdom	Hydrogen production	2030	CCS	**10**	**10**
Net Zero Teesside - CCGT	United Kingdom	Capture cluster		CCS	**10**	**10**
H2H Saltend (H2 to Humber Saltend)	United Kingdom	Hydrogen production	2027	CCS	**1.4**	**1.4**
Drax BECCS Project	United Kingdom	Power generation	2027	CCS	**4**	**4**

Comments to table: The EU Innovation Fund project HYBRIT is not included since it involves just green hydrogen (electrolysis), whereas e.g., H2morrow steel includes hydrogen from natural gas with CCS and is on the list above.

Table 5: Planned commercial European projects involving CO_2 capture to come online in time span approximately 2030 - 2035.

Project	Lead country	Sector	Year start	CCS, CCU or other	CO_2 captured [Mtpy]	CO_2 stored [Mtpy]
North-CCU-Hub final	Belgium	Methanol + other	> 2030	CCU	**1**	**0**

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Dunkirk North Sea Capture and Storage Cluster	France	Capture cluster	2035	CCS	**10**	**10**
ECCO2 Carboneras LafargeHolcim final phase	Spain	Cement	> 2030 (?)	CCU	**0.7**	**0**
H21 North of England	United Kingdom	Hydrogen production	2035	CCS	**20**	**20**

Comments to table: North-CCU-Hub includes North-C-Methanol and AlcoBioFuel projects shown in table above. Dunkirk Cluster includes the 3D project (DMX demonstration Dunkirk) shown in table above. ECCO2 Carboneras final phase includes the values from first phase shown in table above.

Figure 1 below shows the ongoing and planned CO_2 capture capacity versus the needed European CCS as described in the report[3] "Review of Carbon Capture Utilisation and Carbon Capture and Storage in future EU decarbonisation scenarios". From the projects and their status as identified in this study, the following main values can be estimated:

- Ongoing capture projects amount to about 2.5 Mt per year of CO_2 captured.
- By 2030 it is planned about 69 Mt of CO_2 captured per year.
- Of the 69 Mt per year, 2.5 Mt is ongoing capture, about 2.8 Mt[43] will come from the recently funded large-scale Innovation Fund projects, and projects amounting to 0.7 Mt are decided and funded by other means.
- Of the 69 Mt per year planned capture capacity by 2030, as much as about 63 Mt per year is not decided yet.

[43] When it is estimated that half of the CO_2 avoided in the K6 and SHARK projects are from CCS.

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

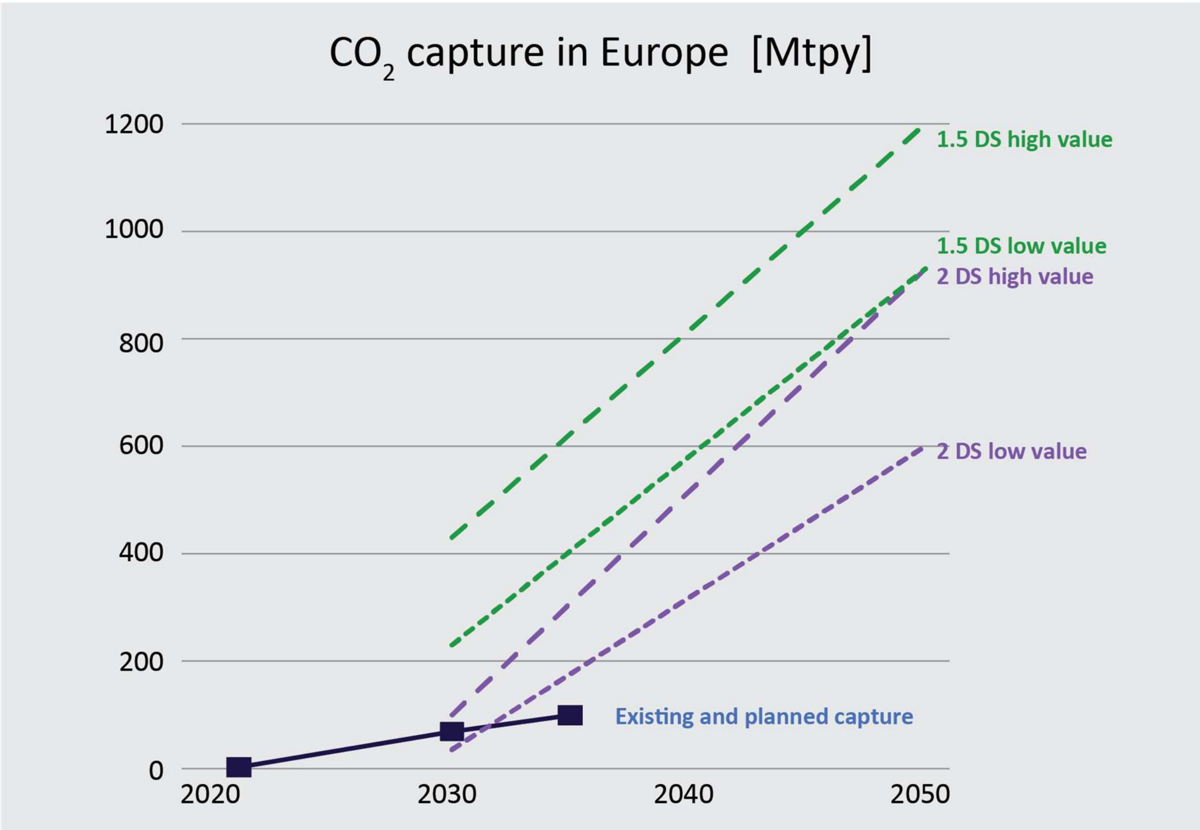

Figure 1: Planned CO_2 capture in Europe compared to needed CCS to meet emissions targets[3].

If all what is planned will be realised, the required figures for the 2-degree scenario in 2030 can be met, but it is far from meeting the 1.5-degree scenario. It is not likely that all the planned projects on this list will be realised. We need to see many more commercial projects to evolve in the next years until 2030, and a huge increase in commercial scale CO_2 capture capacity from 2030 onwards to 2050.

Figure 2 below shows a graphical representation of ongoing and planned CO_2 capture in Europe until about 2035, divided by sectors. Values are based on the tables above. The volume of ongoing CO_2 capture is small and mostly related to gas processing where the economic benefit of removing CO_2 from the gas makes it attractive, and where limited infrastructure is needed.

A large increase in CO_2 capture capacity is planned until 2030. A large share of this is from hydrogen produced from natural gas with CCS. For this value chain to be operational there will be need for a hydrogen market and infrastructure, and end-user processes and technologies that are modified so they can utilise hydrogen. This must be developed in phase with the CCS part of the value chain. A further large increase in CO_2 capture capacity is seen within this sector to 2035. Hydrogen produced from natural gas with CO_2 capture is commercially available technology, however, with the large volumes involved, efficiency and cost improvements are needed.

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS

Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Another large contribution to CO_2 capture will come from "capture clusters". This term is here used as an umbrella since these projects are not fully clear with respect to which industry sectors and amounts that will be involved in the end. Clusters can share transport and storage infrastructure and cooperate on the development process. The "risk sharing" and the possible reduced costs, can make it attractive being part of such a cluster. From a technical point of view there are no large barriers for implementation of CCS and needed infrastructure within industrial clusters.

Four large power generation projects have been identified. Of these, the Drax project is the largest, and it is also a BECCS project. Other plans for capture from power generation or CHP might be planned within the group here called "capture clusters" and thereby not being specifically visible in the overview.

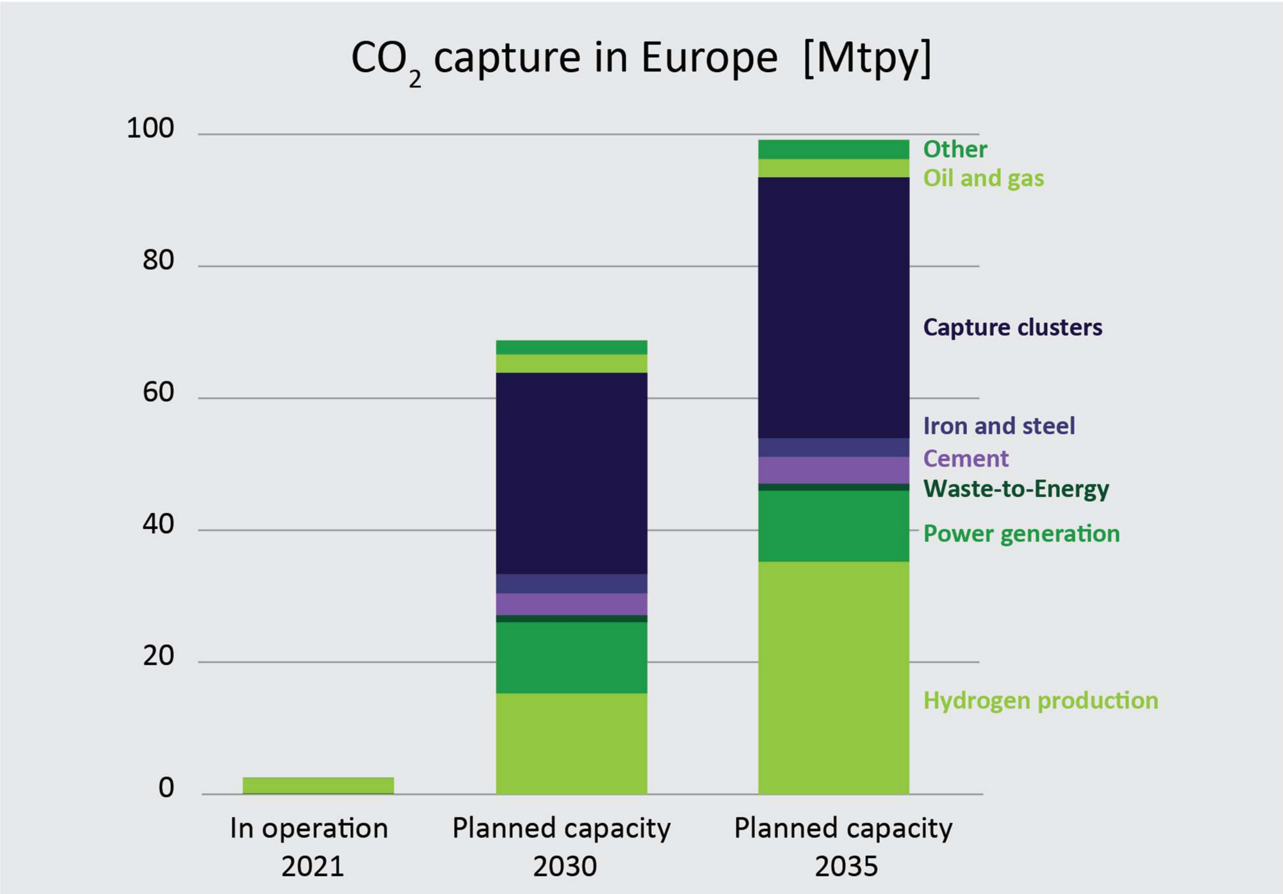

Figure 2: Planned CO_2 capture in Europe divided on sectors as estimated from projects overview.

It seems there are relatively limited plans for CO_2 capture within industrial sectors where CO_2 can be hard to abate with other technologies, e.g., cement, iron and steel, waste to energy and other industries. For some of these a reduction in emissions can be obtained by changing fuel, e.g., such as hydrogen use in iron and steel. Due to large amounts needed it will likely require hydrogen from natural gas with CCS. Capture from

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CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

these industrial sectors might be planned within the category "capture clusters", thereby explaining to some degree why it seems to be limited plans for commercial-scale capture.

The ongoing and planned CO_2 capture capacity is mainly in the north-west part of Europe, as shown in Figure 3. This is somewhat expected when considering the large storage capabilities in the North Sea, and the vast experience in offshore operations and geological mapping in this area. Close cooperation between stakeholders from different countries are generally needed to build a full CCS chain. This is also generally the case for the identified projects. Even though projects are attributed to one country, they often involve industry and stakeholders from other countries. However, most of the CCS activity are within a few countries. Especially UK is responsible for a very large share of planned CCS capacity. A broader implementation of CCS in Europe is likely needed to meet the needed targets for CCS capacity, and to reduce the risk associated with having all eggs in a very few baskets.

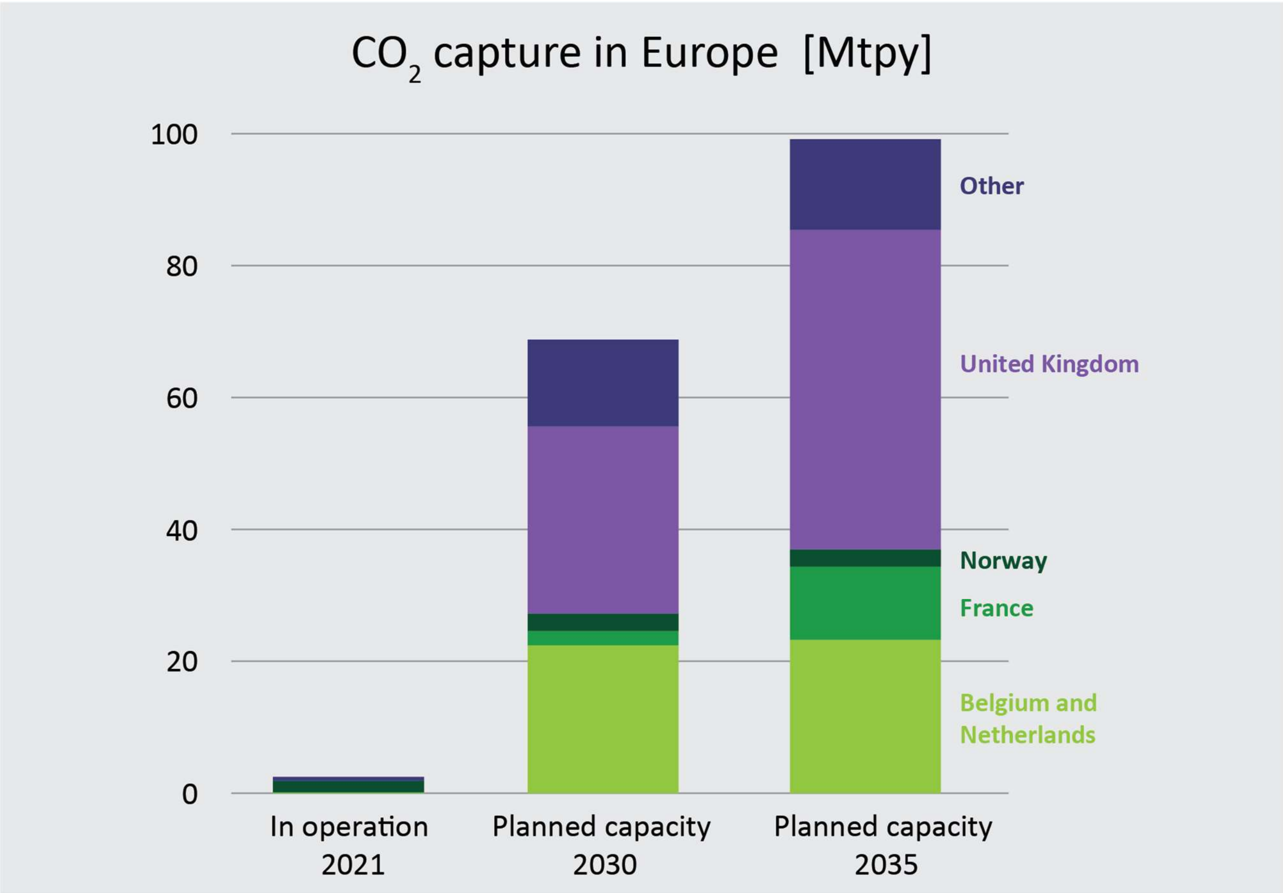

Figure 3: Planned CO_2 capture in Europe divided on countries as estimated from projects overview.

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

Developing next-generation capture technologies

The following section provides highlights on the recommended steps to develop the next generation of capture technologies. The overarching objective is to ensure the technological development necessary to enable large scale deployment of CO_2 capture in Europe. The analysis does not go into detail into specific technologies, rather provides general recommendations to guide research, development and innovation in the upcoming years. More technology specific indications could be found, for instance, in a dedicated report developed within the Mission Innovation framework[44]. The highlights presented in the next sub-sections are developed leveraging the lessons learnt from large industrial projects as well as consultations with relevant stakeholders. Many of the R&I needs identified align well and complement (or are complemented by) similar analyses performed independently, such as the one from the Carbon Sequestration Leadership Forum[45].

Development and maturing of capture technologies

The previous section on the "Current status of CO_2 capture" shows that CO_2 capture technologies are available, with several technology suppliers offering commercial solutions (TRL 9). One interesting aspect related to this is the availability of large experience in the development and maturing of capture technologies. Such accumulated experience can prove very helpful for the development of the "next-generation" of technologies that will advance CCUS deployment in Europe. The following section provides an overview of the key lessons learned from large scale CCUS projects. The focus is mainly on the industrial perspective[46,47,48] and on medium- to high-TRL capture technologies.

Several technological solutions exist to implement CO_2 capture and, indeed, industry does not mention the lack of capture technologies at scale as a hurdle that needs to be overcome to realise a full-scale project[35]. Given the portfolio of options, the identification of good matches between specific industrial application and capture technology becomes a critical step in the technological development. An appropriate selection should be based on several factors – technical, economic, environmental, safety, regulations.

At a technical level, one key issue is that of the energy requirements. Capture technologies can require either heat or power (or both). The access to heat and electricity should be an important factor guiding the technology screening. Opportunities for heat integration must be carefully assessed as an important driver to energy efficiency and, hence, to reduce costs while maximizing the beneficial environmental effect. In addition to the energy inputs, the necessity of other utilities should be checked, such as water. Other technical aspects might also have a significant role in establishing the suitability of a capture technology. One example is area occupation (footprint). In industrial sites where space availability is a challenge, the footprint

[44] Mission Innovation, 2018, Accelerating Breakthrough Innovation in Carbon Capture, Utilization, and Storage
[45] Carbon Sequestration Leadership Forum, 2021, CSLF 2021 Technology Roadmap
[46] Gassnova, 2020, Developing Longship – Key Lessons Learned
[47] CCUS Project Network, 2020, Industrial CO_2 capture projects: Lessons learned and needs for progressing towards full-scale implementation
[48] MIT, 2016, Lessons Learned from CCS Demonstration and Large Pilot Projects

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of a given technology becomes an important screening factor. Similarly, process intensification aspects and opportunities for modular configurations should be assessed.

The outlined technical factors are closely related to economic ones – e.g., energy requirements and heat integration affecting OPEX, footprint and process intensification affecting CAPEX. The reduction of costs is a well-known requirement to enable industrial deployment. In this regard, the availability of comprehensive techno-economic assessments is essential. It should be mentioned that the capture technology itself constitutes about 25 % of the total cost of a CO_2 capture plant[34]. Other systems, such as utility, support, and conditioning systems, take similar shares of the remaining costs.

HSE considerations, although often receiving little attention in early phases of technology development, are critical for reaching commercialization. In view of industrial deployment, it is fundamental to have an in-depth understanding of the expected air emissions, hazardous compounds in effluents, high pressures and temperatures, and fire and explosion hazard[35], and of the available methods to limit the risk for personnel injuries and equipment breakdown due to HSE issues.

HSE aspects are also important in relation to the constraints introduced by existing regulatory frameworks. Indeed, a favourable policy and regulatory framework is crucial for the large-scale deployment of CCS projects in this decade[35]. Regulatory drivers are needed to create the conditions for the development of robust business cases and to facilitate industrial investments[36], also towards technology development. Ideally, consistent regulatory environments are desirable. However, regulations are continuously evolving and might remain country specific. In this context, capture technologies demonstrating to be less problematic in terms of emissions can be favoured.

Overall, a capture technology should guarantee continuous and efficient operation of the industrial process and the quality of the industrial product (e.g., cement, steel, heat, power). Technologies that do not involve complex integration schemes, are easy to operate and reliable will have a competitive advantage.

An important distinction that should be made when describing the development of a capture technology regards its initial maturity level. The development of more advanced but unproven (at scale) technologies imply additional risks for the investors. Accordingly, technology qualification becomes a fundamental concern. The technology supplier must be able to inform industry about assumptions, uncertainties, and cost considerations[35] and ultimately to issue and back up performance guarantees[34]. Lower TRL technologies will require longer piloting phases to build the necessarily knowledge and confidence for the scale up. Undertaking R&D activities in parallel with structured engineering processes have proved to be good practice to support technology development[34]. Moreover, technology suppliers and industry should establish solid long-term relationships that spans beyond the technology development phase. Indeed, the technology deployment might result in future dependence on suppliers. Hence, the technology supplier should be perceived as well-established and reliable partners.

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

Communication at different levels is a decisive factor for successful technology development. Knowledge sharing among CCUS projects might prove a very effective tool to reduce risks, costs, and time to implementation. Several projects have performed onsite pilot campaigns to increase TRL level to commercial maturity. That means there is a wide accumulated experience on piloting and industrial operation that could be shared to accelerate technology development. Best practices guidance and knowledge sharing among projects for safe operation and pollution prevention will certainly pave the way for the deployment of CO_2 capture[34]. This is also a key element for communication with the public. An effective public outreach has demonstrated to be essential for the successful implementation of CO_2 capture projects[36]. The involvement of third parties, such as NGOs, in the communication with the public have proven beneficial in previous projects[35].

Considerations regarding the funding of the project and a sound business case play crucial roles. As investments barriers still exist for CCUS projects, early movers must rely on public financial support. It is envisaged that state aid will still be necessary to overcome first mover costs, although it has been shown that projects too heavily relying on public financial support are more prone to failure[36]. The cooperation between industry and the public sector is needed also in terms of risk sharing and to develop a stable regulatory environment to attract investments. Ultimately, to reach industrial-scale operation the conditions should be created to develop self-sustaining business models, where the primary hurdle to overcome is that of cost[35]. Systems like the EU Emissions Trading System (ETS) can contribute to the establishment of a business case and should be coupled with access to markets[36] and financial support for early movers (e.g., the Innovation Fund). Measures to generate income should be investigated and regulated (e.g., incentives for carbon dioxide removal practices). Also, it is essential to ensure a timed development of all elements of a CCUS chain. Regulated access to transport and storage infrastructure must be ensured to the successful implementation of industrial CO_2 capture projects.

R&I gaps and needs

In addition to the first-hand experience from large scale CCUS projects, several stakeholders are engaged in the development of CO_2 capture technologies along the entire TRL scale. To leverage on such widespread expertise and further identify key Research & Innovation (R&I) priorities, a series of four webinars were arranged by the SET Plan working group on Capture under the title “Defining gaps and R&I priorities enabling CO_2 capture in Europe”. The webinars were arranged in the period from November 2019 to May 2020. The first webinar was on "Industry and end-users' perspective", the second on "R&I needs for CO_2 capture for H2 production and transport", the third on "R&I needs for CO_2 capture in industry", and the fourth on "The potential of industry clusters to advance CO_2 capture".

A small group of stakeholders from national funding agencies and industry provided important advice to the organization of the webinars, including GASSNOVA, CATO, the European Turbine Network and the CCUS Project Network. The webinars engaged numerous relevant stakeholders, mainly from industry and public funding agencies, but also representatives of technology suppliers as well as research and academia. The

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+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

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Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

webinars provided a platform for the stakeholders to present projects and views, and to actively participate in discussions around key topics. Similar consultations were also carried out in other frameworks, such as SET Plan workshops and meetings. During the webinars and the additional consultations, tens of different R&I needs were brought up. These can be summarised to – although not limited to – the following areas:

CO_2 capture in industry including clusters and energy applications

- Integration and synergies with other sectors and renewable solutions
- Process intensification, including utilisation of waste heat
- Retrofitability
- Part-load operation and flexibility
- Buffer storage and shared transportation infrastructure
- Treatment of waste products from capture plants
- Water consumption (with reference to the EU water directive)
- Degradation and life span of capture technologies
- Flexible electricity production
- Hydrogen applications (e.g., fuel switching, chemical conversions)
- Business models

Cost reduction of CO_2 capture technologies

- Increase the number of high-TRL CO_2 capture technologies (from TRL 5-6 to TRL 7-9)
- Develop the next generation of CO_2 capture technologies
- Modularisation of capture technologies, compact capture technology
- Revenue streams via carbon removal technologies
- Fuel flexible combustion systems

Technological elements for capture and utilisation

- Flexible, modular and energy efficient capture and purification technologies considering specificities of the downstream application
- Novel reactor design for efficient integration of capture and conversion stages
- Intensification for reduced energy consumption (including waste heat valorisation) and waste generation
- Novel and cost-effective materials (membranes, adsorbents, absorbents) with high durability and recyclability for increased capture rates.

Standardisation, regulatory and legal issues

- Standard CO_2 specifications for transport, storage, and utilization
- Incentives for carbon negative solutions
- Incentives and market-pull mechanisms for low-carbon products

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CONTACT DETAILS
Carbon Capture & Storage Association
Rue de la Science 14b
B-1040 Brussels
Belgium

CO_2 Value Europe AISBL
Avenue de Tervueren 188A
B-1150 Brussels
Belgium

+32 2 880 3651 impacts9@ccsassociation.org www.ccus-setplan.eu

- Shared frameworks and methods for measuring biogenic/fossil CO_2 ratio
- Data on emissions and hazardous effluents from CO_2 capture technologies
- Reliable methods for measurement and monitoring of CO_2 stream composition, pressure, and temperature.
- Harmonization of legal standards / regulations relevant for the development of a European CO_2 transport- and storage-network.

Priorities for developing next-generation CO_2 capture technologies

For the development of this report as well as of the CCUS Roadmap to 2030[49], the *SET Plan working group on Capture* organized consultations with several stakeholders to identify the priorities for developing next-generation CO_2 capture technologies. Based on the inputs received, the following important guidelines for the development of the next generation CO_2 technologies were synthesized:

- Capture technologies should be developed to enable high capture rates (>95%) and carbon dioxide removal (CDR) schemes.
- The energy requirement for the CO_2 capture process is an important factor to match between the capture technology and the industrial application.
- Other technical aspects might become important in certain industrial applications, such as flexibility, compactness and potential for heat integration and process intensification.
- Technological advancements are needed for the development of novel reactor designs, modularisation, and cost-effective materials.
- Cost reduction can be pursued both in terms of CAPEX and OPEX. The development of a funnel of large projects, based on different high-TRL CO_2 capture technologies, will contribute to bring down costs.
- Industrial clusters offer opportunities thanks to energy integration, share of common infrastructures, knowledge-sharing, and risk reduction. The development of business models is expected to be facilitated by clustering.
- Control of emissions and other HSE considerations are critical for reaching commercialization of capture technologies.
- The CO_2 capture technology should guarantee the quality and continuity of the industrial or energy process where it is applied (via technology qualification).
- Development of a stable framework to enable early movers, including standards, funding and incentives, risk sharing and business models.

[49] CCUS SET Plan - Implementing Working group (IWG9), 2021, CCUS Roadmap to 2030. Available at: https://www.ccus-setplan.eu/wp-content/uploads/2021/11/CCUS-SET-Plan_CCUS-Roadmap-2030.pdf

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Conclusions and recommendations

Carbon capture technologies can be applied to a variety of carbon dioxide emitting processes, as power and heat generation, cement production, iron and steel, waste-to-energy plants, low-carbon hydrogen manufacturing and other industrial processes (ammonia, lime, ceramics, glass, petrochemical, fertiliser, pulp and paper, oil and gas, etc.). The CO_2 is separated from the process emissions by chemical or physical processes, e.g., amine solvents for chemical absorption of CO_2, or selective membranes for physical separation of CO_2. When CO_2 is separated from a stream where parts or all the CO_2 stems from biogenic sources, and is permanently stored, it is a carbon dioxide removal technology (Bio-CCS/BECCS, Waste-to-Energy with CCS, etc.). Direct Air Capture where CO_2 is separated directly from the air, is another carbon dioxide removal technology that has emerged in later times.

Carbon capture technologies currently capture up to 95% of the CO_2 emissions, however it is technically feasible to achieve capture rates >95% with only minor efficiency and financial penalties compared to a capture facility capturing at 90%. Capture rates above 99% are possible, as technologies develop through continuous R&I and deployment.

A large increase in CO_2 capture capacity is planned until 2030, with a large share of this coming from the manufacturing of low-carbon hydrogen produced from natural gas with CCS, which is a commercially available technology. Another large contribution to CO_2 capture will come from "capture clusters". Here, this term is used as an umbrella term, since for these projects, it is not fully clear which industry sectors will be involved in the end, and to which extent. Clusters can share transport and storage infrastructure and cooperate on the development process. From a technical point of view, there are no large barriers. The "risk sharing" and the possible reduced costs can make it attractive to be part of such a cluster.

Ongoing and planned CO_2 capture capacity is mainly located in North-western Europe. Most of the CCS activity is concentrated within a few countries. Especially UK is responsible for a very large share of planned CCS capacity. A broader implementation plan for CCS in Europe is likely needed to meet the needed targets for CCS capacity, and to reduce the risk associated with having too few countries involved.

By 2030, approximately 69 million tonnes of CO_2 are planned to be captured per year. Of the 69 Mt per year, 2.5 Mtpy is ongoing capture today, about 2.8 Mtpy will come from the recently funded large-scale Innovation Fund projects, and projects amounting to 0.7 Mtpy are decided and funded by other means. I.e., of the planned 69 Mt per year capture capacity by 2030, as much as about 63 Mt per year seem not decided yet. If all planned projects are realised, Europe can meet the minimum capture volume in 2030 that is needed to match the 2-degree scenario, while falling far below the 2030 volume needed to be on track to meet the 1.5-degree scenario. Many more large-scale, commercial CCS projects will need to be in the pipeline in the short term to enable the possibility to reach a net zero scenario in 2050.

In this context, research and innovation must play a major role to support the necessary advancements. Lessons learnt from large industrial projects and consultations with relevant stakeholders allowed to pinpoint

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gaps and barriers as well as research priorities for the development of the next-generation CO_2 capture technologies. The following R&I needs are identified as key to enable CO_2 capture at the level required to meet climate goals:

- Capture technologies should be developed to enable high capture rates (>95%) and CDR schemes. The development of a clear and shared framework for carbon accounting and for guaranteeing the sustainability of bioresources is fundamental to enable CDR solutions.
- The energy requirements for the CO_2 capture process must be very well matched with the industrial application and what it can provide of heat, quality of heat, power supply etc. Technology development should be guided by considerations of accessibility to clean and sustainable energy sources.
- Other technical aspects should be given importance, such as flexibility, compactness, and potential for heat integration and process intensification.
- Technological advancements are needed for the development of novel reactor designs, modularisation, and cost-effective materials.
- Cost reduction can be pursued both in terms of CAPEX and OPEX. The development of a funnel of large projects, based on CO_2 capture technologies at different high Technology Readiness Levels (TRL), will contribute to bring down costs.
- The formation of industrial clusters should be supported as they offer opportunities for energy integration, sharing of common infrastructure, and risk reduction for each cluster partner.
- Control of emissions and other health, safety, and environmental considerations are critical for reaching commercialisation of capture technologies. As such, they should be addressed early in the development of new technologies.
- Next generation CO_2 capture technologies must guarantee the quality and continuity of the industrial production or process where they are applied (via technology qualification).
- The development of a stable framework to enable early movers is essential to create the conditions to achieve climate goals: standards, funding and incentives, risk sharing, and business models.
- It is particularly important to support projects whose implementation contributes to developing a CCS and CCU network, for instance capture projects that will feed large transport and storage infrastructure projects (e.g., the Northern Lights/Longship project in Norway, which is the first European, commercial, full-chain CCS project to become operational).

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