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CIMAC White Paper on

CCUS – Carbon Capture, Utilisation and Storage

The first edition of this CIMAC Guideline / White Paper was approved by the members of the CIMAC WG 5 'Exhaust Emissions Control' on June 24th 2022.

Abbreviations

ABC	Ammonium bicarbonate
ABS	American Bureau of Shipping (a maritime classification society)
AC	Ammonium Carbonate
AIP	Approval in Principle
BECCS	BioEnergy with Carbon Capture and Storage
BESS	Battery Energy Storage System
CAP	Chilled Ammonia Process
CC	Carbon Capture
CCC	Cryogenic Carbon Capture
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and Storage
CFB	Circulating Fluidized Bed
CII	Carbon Intensity Indicator (index introduced by the IMO)
DAC	Direct Air Capture
DSME	Daewoo Shipbuilding & Marine Engineering
DNV	Det Norske Veritas (a classification society)
EC	European Commission (European Union)
EEPR	European Energy Programme for Recovery
EEXI	Energy Efficiency existing ship Index (index introduced by the IMO)
EOR	Enhanced Oil Recovery
ERCOT	Electric Reliability Council of Texas
ETS	Emission Trading System
EU	European Union
EUR	EURO, national currency of the EU member states, who have adopted it
GBP	British pound sterling, official currency of the United Kingdom
GHG	Green House Gas
IEA	International Energy Association
IGCC	Integrated Gasification Combined Cycle
IMO	International Maritime Organisation
ISO	Independent System Operator (in US)

LNG	Liquefied Natural Gas
MCT	Mineral Carbonation Technology
MEPC	Marine Environment Protection Committee, addresses environmental issues under IMO's remit
NMRI	(Japan's) National Maritime Research Institute
NPD	Norwegian Petroleum Directorate
PJM	Regional Transmission Organization (RTO) in the United States
R&D	Research & Development
SEWGS	Sorption Enhanced Water Gas Shift
TRL	Technological Readiness Level
UN	United Nations
USA	United States of America
USD	United States Dollar, official currency of the United States of America
45Q	US tax credit for carbon oxide sequestration

Content

1 Introduction

The IEA (International Energy Association) has consistently highlighted the important role of CCUS (Carbon Capture Utilisation and Storage) in achieving net zero emissions, indicating that without CCUS there would be limited or no solutions for tackling emissions from heavy industry sectors, including cement manufacturing. CCUS also provides an option to address emissions from existing energy assets, to support a cost-competitive scaling up of low-carbon hydrogen production, and to remove carbon from the atmosphere.

On average, capture capacity of about 3 million tonnes of CO_2 ($MtCO_2$) has been added worldwide each year since 2010, with annual capture capacity now reaching over 40 $MtCO_2$. However, many high-profile projects and government funding programmes have been terminated during the years. The combination of strengthened climate goals, an improved investment environment and new business models have set the stage for greater success than in the past for the coming years /1A/. The UN foresees CCUS technology as an important option in fighting climate change, estimating that CCUS technology could mitigate up to 6.3 gigatonnes of CO_2 by 2050 /1B/. Figure 1 is showing the main steps of the CCUS process.

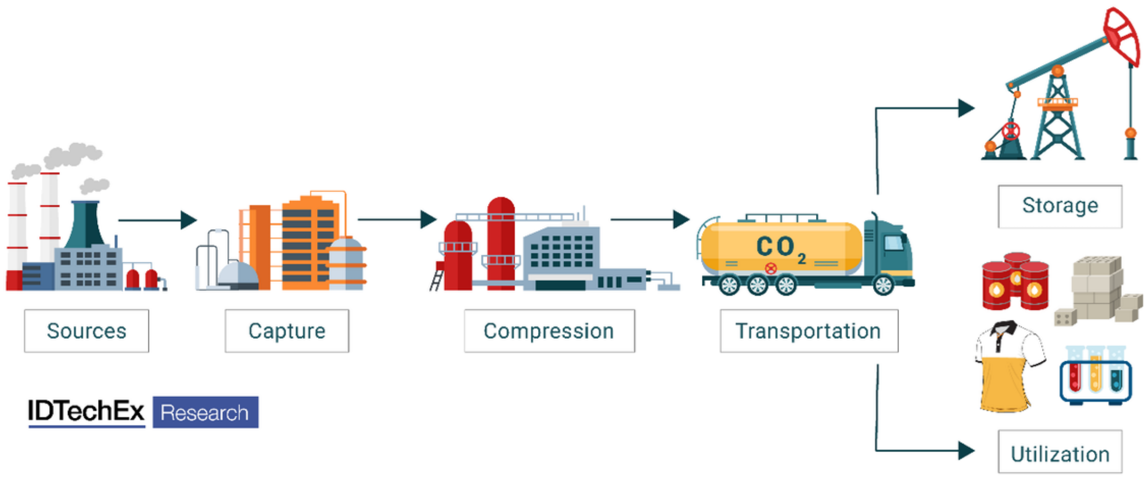

Figure 1. The main steps involved in carbon capture, utilization, and storage /2/.

CCUS is not only of interest for land-based activities, but also the maritime sector is active in this field. IMO (International Maritime Organisation) has set ambitious future GHG reduction targets and the marine transport sector is therefore looking on different solutions to make vessels more climate friendly. Carbon Capture (CC) is an option being reviewed as relevant for certain ship segments.

Intent of this document is to give the reader a general overview (status, development needs, challenges still to overcome, etc.) of some of the CCUS technologies and summary to existing activities that have reached the industrial piloting phase or seen as promising developments. In addition, DAC (Direct Air Capture) is briefly introduced. For further information on these technologies, the reader is referred to the quoted reference literature. There is also a large amount of (scientific) literature on technologies in the R&D phase, and recent announcements on new projects from different stakeholders, but those will not be included in this document due to their early development stage.

2 CCUS – references today and future development

2.1 Past – up to 2020

Carbon capture and storage has never been developed at scale in Europe. Several projects have been launched since 2008 in the power sector, notably as part of the European Energy Programme for Recovery (EEPR), for an estimated EU subsidy of 1 billion euros /3/. All of them except one failed and were terminated /4A/. Compostilla, a pilot oxy-combustion CFB boiler plant (30 MWth) in Spain, was finished providing an operational pilot plant for capture, transport and storage. The Compostilla CCS project was cancelled after the project had fulfilled the commitment under the terms of the grant from EEPR. Overall, the project was awarded funding in year 2009 and was closed in 2013 /4B/, /4C/.

According to sources /5A & 5B/ (table 1.1 in /5A/, also included as Annex 1 of this report), in 2020 there were 21 large-scale commercial CCUS facilities around the world in operation with a capacity to capture up to 40 Mt CO_2 per year. Majority of these plants are removing CO_2 from extracted natural gas and CO_2 is in most cases used for EOR (Enhanced Oil Recovery), a technology to boost extraction from oil fields. EOR is most common example of CCU, Carbon Capture and Utilization. In the "CCUS projects in operation 2020" table in Annex 1, there are only 2 (coal fired) power plants using post-combustion CO_2 removal. CO_2 removed in these plants is/was used for EOR, and today one of these "CCU" facilities has been closed. In Figure 2, power plant projects that were planned with CCUS situated in USA and Canada are shown. Of these plants, only Boundary Dam (a 160 MWe coal-fired plant with a large-scale demonstration CCU on plant unit 3) in Canada is today in operation. Petra Nova facility was closed in May 2020 due to economic reasons /1B/. Edwardsport and Kemper coal gasification (IGCC) plant (with pre-combustion CO_2 removal) projects were cancelled several years ago due to cost reasons and operational difficulties.

Figure 2. CCUS power plant projects in North America /6/.

2.2 Future development

By end of November 2021, more than 100 new CCUS facilities were announced and the global project pipeline for CO_2 capture capacity was on track to quadruple, see Annex 2. The boost in CCUS project activity is underpinned by three key developments /1A/:

- First, a growing recognition that CCUS is necessary to meet national, regional, and even corporate net zero goals.
- Second, the growing interest in producing hydrogen with a low-carbon footprint has resulted in almost 50 facilities under development to capture CO_2 from hydrogen-related processes.
- Finally, the investment environment for CCUS has substantially improved as a result of new policy incentives. Since the start of 2020, governments and industry have committed more than USD 25 billion in funding specifically for CCUS projects and programmes.

CCUS projects are now operating or under development in 25 countries around the world, with the United States and Europe accounting for *three-quarters* of the projects in development.

The expansion of the 45Q tax credit /7/ in the United States in 2018 – providing a credit of USD 50 per tonne of CO_2 that is permanently stored – was a major catalyst for new investment plans. This tax credit can be “stacked” with other incentives. Bipartisan proposals before Congress could see the 45Q tax credit for CO_2 storage increased to USD 85 per tonne of CO_2 and USD 120 per tonne for direct air capture. An additional USD 12 billion of support for CCUS investment in the United States was included in the Infrastructure Investment and Jobs Act signed by President Biden in November 2021. In Europe, Norway has committed USD 1.8 billion to the Longship project, which includes the Northern Lights /8/ offshore storage hub; the United Kingdom has established a GBP 1 billion CCS Infrastructure Fund /9/ with a target of building four CCUS hubs by 2030; and four CCUS projects have been selected in the first funding call /10/ of the European Commission’s EUR 10 billion Innovation Fund.

Information about additional CCUS programs can be found in source /1A/.

3 Carbon Capture and Storage, and Direct Air Capture technologies

3.1 Carbon Capture Technologies (from point sources)

The carbon capture plants require additional energy consumption, e.g. heat needed for CO_2 desorption, electricity for fans, pumps and compressors, etc. CO_2 capture processes therefore lead to an efficiency loss estimated at 8–12 percentage points for (existing) pulverized coal fired power plants /11/.

Depending at which stage in the combustion process the fossil carbon is separated and concentrated, carbon capture technologies are usually classified into the following categories:

- *Post-combustion processes* extract diluted CO_2 from the combustion flue-gas. The Carbon Capture process relies on chemical or physical interactions to separate CO_2 from the gas mixture. Absorption processes deploying aqueous solutions of amines as chemical solvents represent the most commonly adopted technology. Alternatively, absorption processes using other solvents (e.g. chilled ammonia), adsorption-based separations, cryogenic separation and membrane-based separations can also be utilized. Post-combustion is the most developed and used technology today.

- *Oxy-combustion processes* consist of burning a fuel with oxygen instead of air. The flue gases produced by the oxy-combustion process are mainly water and CO_2, from which CO_2 is easily obtained after condensing and removing the water.

- *Pre-combustion processes* involve conversion (gasification or partial oxidation) of the fuel into a synthesis gas (carbon monoxide and hydrogen) which is then reacted with steam in a “water gas shift” reactor to convert CO into CO_2 or CO can be upgraded to other compounds such as synthetic fuels. The water gas shift process produces highly concentrated CO_2 that is removable by absorption, adsorption or chemical looping. The CO_2 removal can also be combined with enhancement of the water gas shift reaction, e.g. SEWGS (sorption enhanced water gas shift), the remaining H_2 can then be burnt directly.

In the following chapters, the most common post-combustion processes are described (amine process and briefly chilled ammonia, antisublimation and membrane processes).

3.1.1 Amine process

The amine process is based on the chemistry of the amine-CO_2-H_2O system and the ability of the amine solution to absorb CO_2 at low temperatures and to release the CO_2 at moderately elevated temperatures. CO_2 and water produce carbonic acid to react with the amine solution in the absorption column, forming chemical compounds (carbamate or bicarbonate) and resulting in the removal of CO_2 from the gaseous (flue) stream.

In the process shown in below Figure 3, CO_2 is absorbed in an amine solution at a temperature < 50 °C (flue gas entering the absorber to be cooled down to this temperature) and at atmospheric pressure. CO_2-loaded amine is stripped (chemical desorption) in the regenerator at a relatively higher temperature to separate the CO_2 and to regenerate the amine solution for reuse. The CO_2-loaded stream leaves the top of the regeneration columns after having gone through a high-efficiency mist eliminator to minimise water and amine carry-over. The CO_2 compression system may involve the use of integrally geared centrifugal compressors with multiple compression stages, equipped with intercoolers and aftercoolers, where the CO_2 is cooled using condensate from the steam/water cycle as the cooling medium. A CO_2 drying unit is provided to remove moisture from the CO_2 product.

Impurities in the CO_2 stream can affect CO_2 capture processes which are sensitive to pollutants and CO_2 transport and storage. For example, NO_2 and SO_2 from flue-gas react with amines to form stable, non-regenerable salts and thus cause a loss of amines. With amines, the maximum SO_2 specification is usually set at < 40 mg/Nm^3 and the NO_2 maximum specification at < 50 mg/Nm^3 based on a daily average level and standard conditions at a flue gas oxygen level of 6 vol-% O_2.

In the process, due to the cyclic exposure of the amine to variable process conditions, a small fraction of the amine will undergo irreversible chemical degradation, mainly caused by temperature, O_2 and traces of strong acids. In the continuous liquid closed-loop process, these trace/degradation compounds will accumulate, requiring inactive stable organic salt by-products to be removed from the active portion of the amine solution. A typical target CO_2 removal efficiency is 90%, however, efficiencies of up to 99% could be achieved in well-designed absorbers. See source /11/ chapter 11.2.4.1.1 for a more detailed process description.

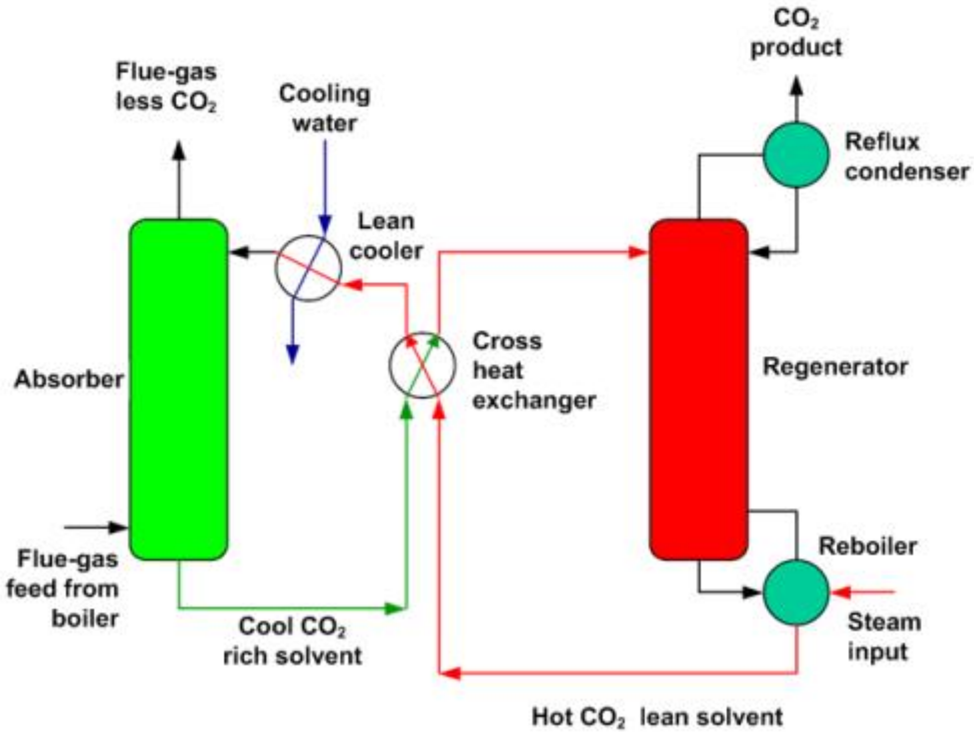

Figure 3. Amine CC process /11/.

3.1.2 Chilled Ammonia

Figure 4 shows the main flow diagram of the chilled ammonia process. The flue-gas is cooled and sent to the CO_2 absorber, where the CO_2 in the flue-gas reacts with ammonium carbonate to form ammonium bicarbonate (ABC). The flue-gas stream, with most of the CO_2 removed, returns to the existing stack for discharge, and the bleed stream is sent to the plant waste water treatment system for processing. The rich ammonium bicarbonate (ABC) solution is sent to a regenerator column under pressure. Heat is added in the regenerator to separate the CO_2 and return the ammonium carbonate (AC) solution to the CO_2 absorber for reuse. The CO_2 stream is scrubbed to remove excess ammonia, then compressed and transported to the storage system. In the Chilled Ammonia Process (CAP), CO_2 is absorbed in an ammoniated solution at temperatures lower than the flue-gas desulphurisation system exit temperature. Therefore, cooling of the flue-gas is a necessary step within the process, resulting in condensation of moisture from the flue-gas.

Typical CO_2 capture rates achieved in pilot plants have been above 90%. For more information about the ammonia process see chapter 11.2.4.1.2 /11/.

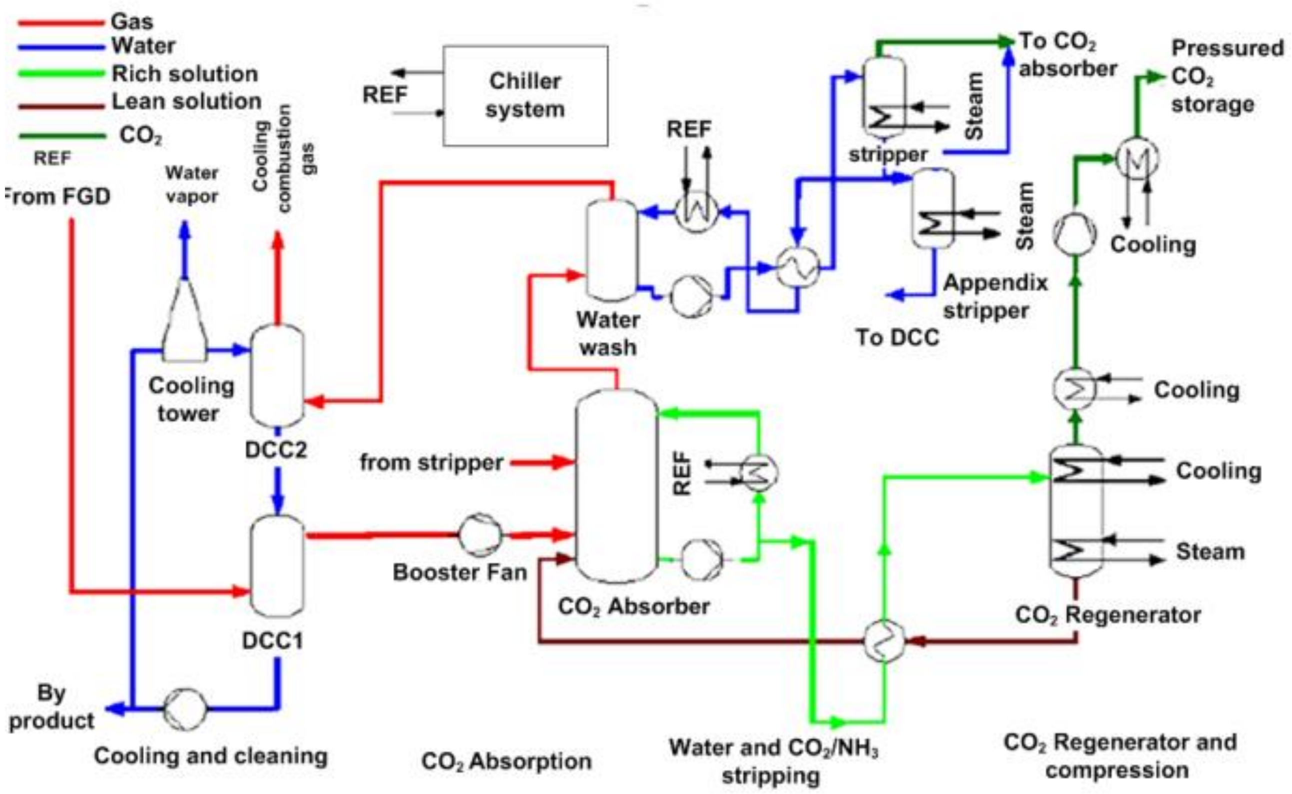

Figure 4. Chilled Ammonia main flow diagram /11/.

3.1.3 Cryogenic Carbon Capture – "antisublimation" principle

The Cryogenic Carbon Capture (CCC) technology uses phase change to separate carbon dioxide (CO_2) and other pollutants from the flue gas. Cooling the CO_2 at pressures < 5 bar to approximately -140 °C results in the gas transforming into a solid without passing through the liquid phase (desublimation); thus, the CO_2 is separated from the remaining gas, pressurized, and melted. The CCC process is minimally invasive and highly efficient, effectively utilizing heat integration to achieve a 50 percent reduction in parasitic power demand compared to an amine absorption process /12/. In Figure 5 the CCC main principle is shown.

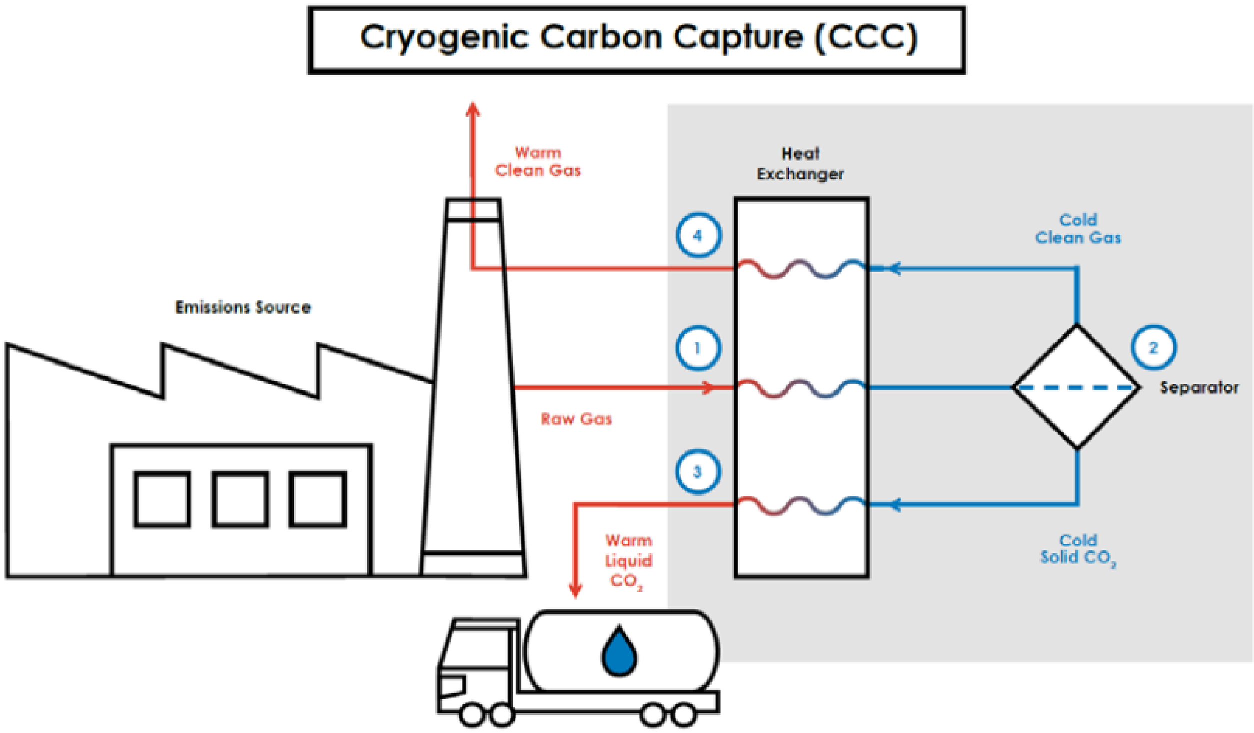

Figure 5. CCC overview /13/. The CCC process (1) cools exhaust gas stream to the point that the CO_2 freezes using mostly heat recuperation, (2) separates solid CO_2 as it freezes from the flue gas, (3) melts the CO_2 through heat recuperation and pressurizes it to form a pure liquid, and (4) warms up the gas releasing it to the atmosphere. See appendix slides for more detailed flow diagrams. “Gas” in the figure is flue gas.

An economic evaluation has been performed for the low temperature process and the results were compared to a chemical absorption process with monoethanolamine. CO_2 capture by anti-sublimation (cryogenic or “cooling the flue gases down to the freezing temperature of CO_2 “) showed a better performance concerning the energy demand but with a reduced economic benefit due to higher equipment costs /14/.

3.1.4 Membrane Process

Membrane separation is based on polymeric or inorganic devices (membranes) with high CO_2 selectivity, which let CO_2 pass through but act as barriers to retain the other gases in the gas stream. Their TRLs (Technology Readiness Levels) vary according to the fuel and application. Membranes for CO_2 removal from syngas and biogas are already commercially available, while membranes for flue gas treatment are currently under development. The only existing large-scale carbon capture plant based on membrane separation is operated by Petrobras in Brazil /5A/ in a natural gas processing plant to strip the CO_2 out of the pre-salt fields' natural gas (the plant is included in the list of Annex 1). Removed CO_2 is reinjected into wells for enhanced oil recovery (EOR).

3.2 Direct Air Capture

Direct air capture has the potential to actively remove CO_2 from the atmosphere. Capturing carbon directly from the air and storing it could compensate the CO_2 emission from fossil fuel use and is an alternative to bioenergy with carbon capture and storage (BECCS) for reducing the concentration of carbon dioxide (CO_2) in the atmosphere. Direct air capture plants are already operating on a small scale, but their costs are currently high. In the following two different DAC technologies are briefly described mentioning their respective pioneering companies as examples, there are also several others working in this field.

3.2.1 Climeworks and Global Thermostat

Climeworks AG is a Swiss company specializing in carbon dioxide capture technology from ambient air /15A, 15B/, Global Thermostat is a US company with the same target and comparable cyclic absorption process /15C, 16/.

CO_2 collectors selectively capture carbon dioxide in a two-step process. First, air is drawn into the collector with a fan. Carbon dioxide is captured on the surface of a highly selective sorbent material that sits inside the collectors. After the filter material is full of carbon dioxide, the collector is closed and the temperature is increased to between 80 and 100 °C to release the carbon dioxide. The biggest installation by Climeworks is the Orca facility situated at the Hellisheiði geothermal power plant in Iceland which can remove 4000 tons CO_2 from the air per year. Below Figure 6 gives an overview of the Climeworks DAC principle.

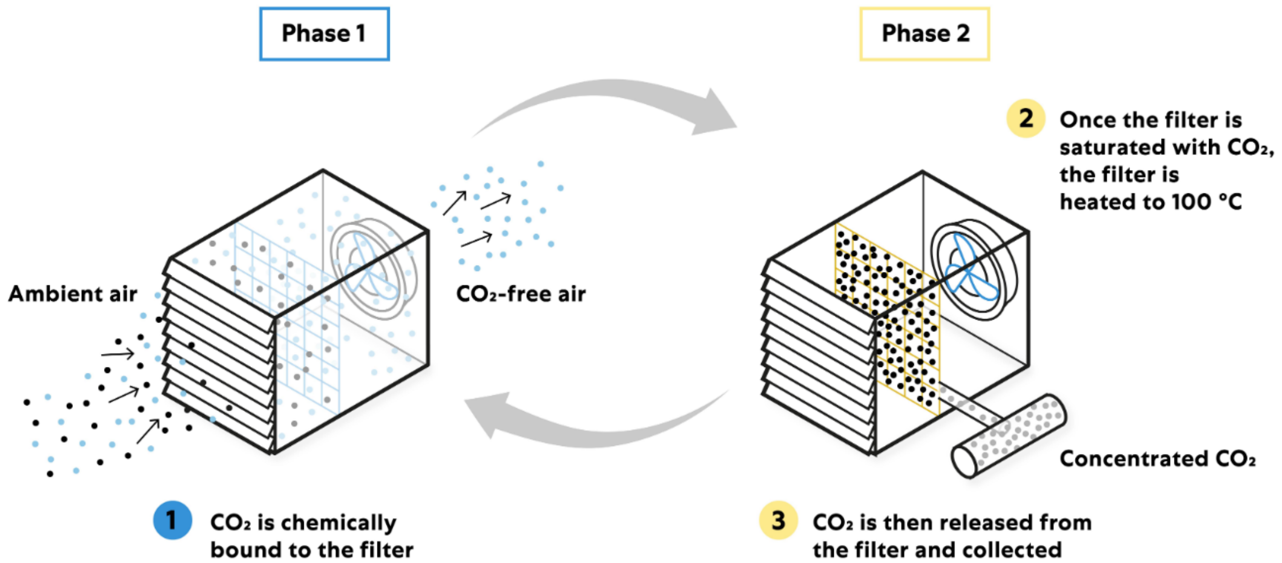

Figure 6. "How the Climeworks technology works" /16/.

3.2.2 Carbon Engineering

Carbon Engineering Ltd. is a Canadian-based clean energy company focusing on the commercialization of Direct Air Capture technology that captures carbon dioxide (CO_2) directly from the atmosphere /17A, 17B/.

The process starts with an **air contactor –** a large structure modelled off industrial cooling towers. A giant fan(s) pulls air into this structure, where it passes over thin plastic surfaces that have potassium hydroxide solution flowing over them. This non-toxic solution chemically binds with the CO_2 molecules, removing them from the air and trapping them in the liquid solution as a carbonate salt. The CO_2 contained in this carbonate solution is then put through a series of chemical processes to increase its concentration, purify and compress it, so it can be delivered in gas form ready for use or storage. This involves separating the salt from solution into small pellets in a structure called a **pellet reactor**, which was adapted from water treatment technology. These pellets are then heated in a third step, in a **calciner,** in order to release the CO_2 in pure gas form. This step also leaves behind processed pellets that are hydrated in a **slaker** and recycled back into the system to reproduce the original capture chemical. In Figure 7 the principle of this DAC process is shown.

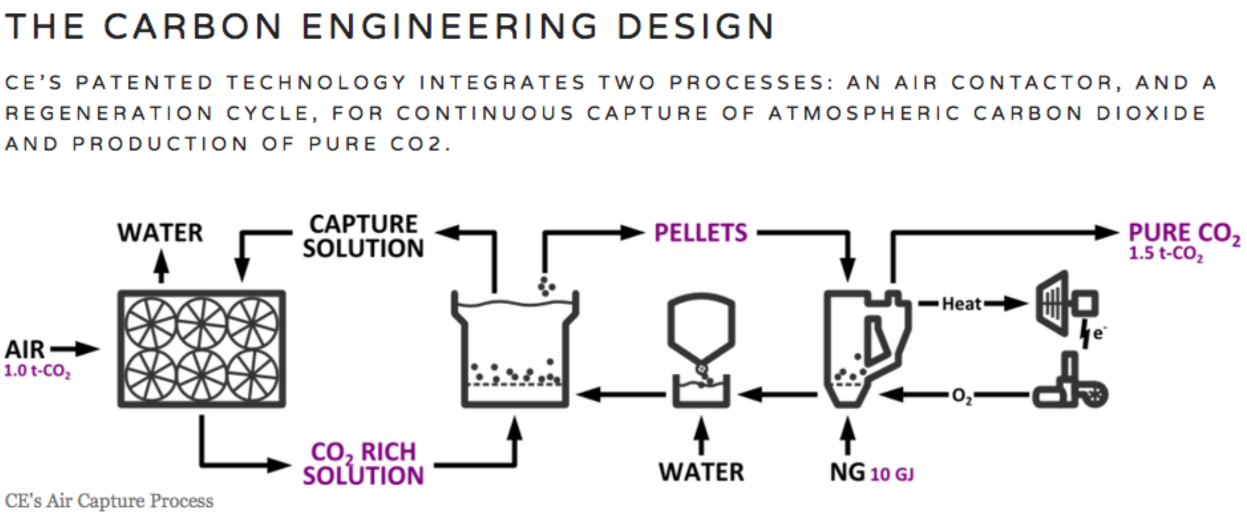

Figure 7. Carbon Engineering process principle /18A/.

3.3 Storage and Utilisation of CO_2

3.3.1 General

Today, 35% of today's consumption of CO_2 is used for EOR, 55% for urea and methanol production and 6% for the food industry. /18B/

CCS is the process of capturing as a typical target almost 90% of the CO_2 emitted during the burning of fossil fuels for electricity generation or industrial processes, followed by transporting it by pipeline or ship for safe and permanent storage several kilometers below the earth's surface. CCU differs from CCS in that CCU, instead of permanent geological storage,/18C/ the captured CO2 is converted into/utilized as valuable commercial products ranging from concrete and plastics to reactants for various other chemical synthetic processes including synthetic fuels or as an inert/carbonation gas in the food industry. CO_2 utilization technologies such as enhanced oil recovery (EOR) are already successfully commercialized and others are at various stages of development. See below Figure 8 for CCS/CCU difference. In /19/ some further CCU options are described.

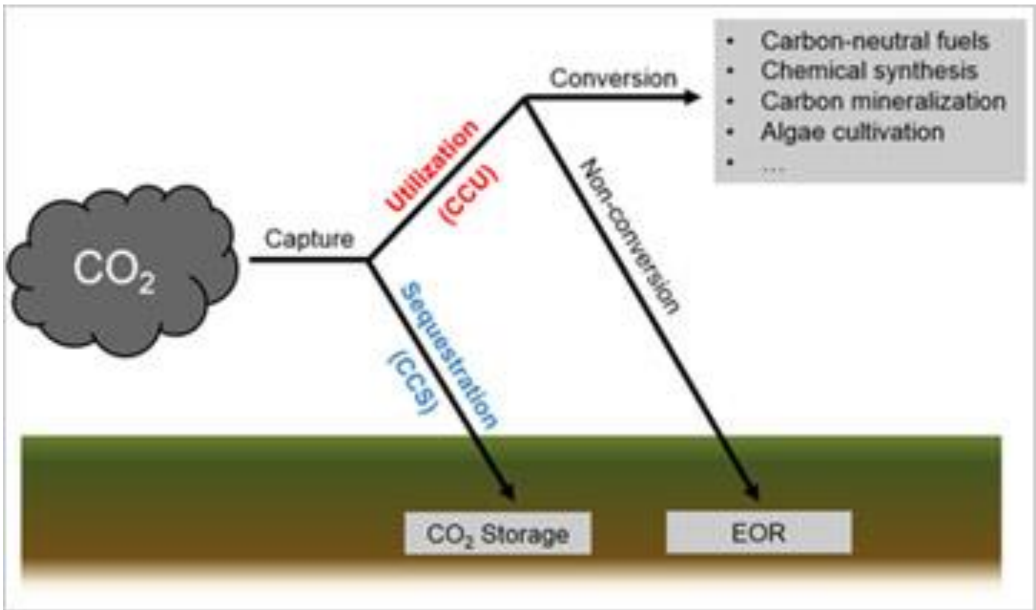

Figure 8. Geological sequestration and utilization of captured CO_2 /19/.

In the following chapters (3.3.2 and 3.3.3) the focus is on Carbon Capture and Storage.

3.3.2 Mineral carbonation

Carbon, in the form of CO_2 can be removed from the atmosphere by chemical processes and stored in stable carbonate mineral forms. This process (CO_2-to-stone) is known as “carbon sequestration by mineral carbonation or mineral sequestration” /20A/. The process involves reacting carbon dioxide with abundantly available metal oxides–either magnesium oxide (MgO) or calcium oxide (CaO)–to form stable carbonates.

$CaO + CO_2 \rightarrow CaCO_3$

$MgO + CO_2 \rightarrow MgCO_3$

Basaltic rocks, which primarily consist of magnesium and calcium silicate minerals, provide alkaline earth metals necessary to form solid carbonates. Calcium and magnesium are found in nature typically as calcium and magnesium silicates (such as forsterite (olivine) /20B/ and serpentinite /20C/) and not as binary oxides. For forsterite and serpentinite the reactions are:

$Mg_2SiO_4 + 2\ CO_2 \rightarrow 2\ MgCO_3 + SiO_2$

$Mg_3Si_2O_5(OH)_4 + 3\ CO_2 \rightarrow 3\ MgCO_3 + 2\ SiO_2 + 2\ H_2O$

In the Hellisheiði geothermal power plant in Iceland the captured CO_2 is dissolved in water – “sparkling water” – then the “mix” is injected into the subsurface where it reacts with rock formations to form solid carbonate minerals (takes about 2 years). See Figure 9 for overview of the process.

Figure 9. Three requirements for mineral carbonation: favourable rocks, water and carbon dioxide source. (CarbFix) /21A/.

Basalt is the most common rock type on the surface of earth, covering about 5% of the continents and most of oceanic floor /21A/.

3.3.3 Geological Sequestration

Geological sequestration refers to the storage of CO_2 underground in depleted oil and gas reservoirs, saline formations, or deep, un-minable coal beds.

Once CO_2 is captured from a point source, it needs to be compressed to ~100 bar so that it becomes a supercritical fluid. In this fluid form, the CO_2 can easily be transported via pipeline to the place of storage. The CO_2 will then be injected deep underground, typically around 1 km, where it would be stable for hundreds to millions of years. At these storage conditions, the density of the supercritical CO_2 is 600 to 800 kg/m^3.

The important parameters in determining a good site for carbon storage are: rock porosity, rock permeability, absence of faults, and geometry of rock layers. The medium in which the CO_2 is to be stored ideally has a high porosity and permeability, such as sandstone or limestone. Sandstone can have a permeability ranging from 1 to 10^{-5} Darcy /21B/ and can have a porosity as high as ≈30%. The porous rock must be capped by a layer of low permeability which acts as a seal, or caprock, for the CO_2. Shale is an example of a very good caprock, with a permeability of 10^{-5} to 10^{-9} Darcy.

Once injected, the CO_2 plume will rise via buoyant forces, since it is less dense than its surroundings. Once it encounters a caprock, it will spread laterally until it encounters a gap. If there are fault planes near the injection zone, there is a possibility the CO_2 could migrate along the fault to the surface, leaking into the atmosphere, which would be potentially dangerous to life in the surrounding area.

Another danger related to carbon sequestration is induced seismicity. If the injection of CO_2 creates pressures that are too high underground, the formation will fracture, potentially causing an earthquake. While trapped in a rock formation, CO_2 can be in the supercritical fluid phase or dissolve in groundwater/brine. It can also react with minerals in the geologic formation to precipitate carbonates as described in above chapter 3.3.2 Mineral carbonation.

Worldwide deep saline formations have the largest storage capacity, which is estimated to be 1,000–10,000 Gt CO_2.

The first large-scale CO_2 sequestration project is called Sleipner began in 1996 and it is located in the North Sea. In the plant, carbon dioxide is stripped from natural gas with amine solvents and the concentrated carbon dioxide is disposed of in a deep saline aquifer /22/. Sleipner is located in the Utsira formation in Norway.

The 2005 Special Report on CCS by the Intergovernmental Panel on Climate Change concluded that appropriately selected and managed geological reservoirs are 'very likely' to retain over 99% of the sequestered CO_2 for longer than 100 years and 'likely' to retain 99% of it for longer than 1000 years /23/. The European Union (EU) has established "... a legal framework for the environmentally safe geological storage of carbon dioxide CO_2 ..." in regulation 2009/31/EC /24/.

However, in many regions significant further assessment work is required to convert theoretical storage capacity into "bankable" storage, assessing the maximum amount of CO_2 that can ultimately be stored, the maximum rate of injection, how the gas is contained in the formation and the risk of leakage. The identification and development of CO_2 storage will also need to be supported by a robust legal and regulatory framework, as well as effective communication with local communities and the broader public /5A/.

Importance of above assessment work is further illustrated by following a reported case - Article: "Faulty Geology halts project" /25A/ - see text below Figure 10. When oily water injection began on Tordis, only a relatively limited volume was probably stored in these sands before the pressure rise caused fracturing of the overlying shales. The fractures eventually reached the surface, allowing the injected water to escape. The oil company had thought the injected water would be held in the Utsira formation, which it assumed was present as a large structure with a big storage capacity – NPD ("Norwegian Petroleum Directorate") found that the formation does not exist where the Tordis injector was drilled.

Source /25B/ contains more information on the case – "The leakage occurred on May 14th 2008 when 175 cubic meters of oily water escaped from the intended underground storage site. The oily water was surplus production water injected as waste at approximately 1 km beneath the earth's surface, but subsequently migrated upwards to the sea bottom. Seabed surveillance equipment detected a sinkhole (a depression on the sea floor) that was 30-40 meters wide and 7 meters deep … The sinkhole was located about 60 meters from the nearest oil production installation where the oil-contaminated water leaked out. … In 2007 a similar accident happened at the Visund oil field when an accumulation of sediments at the sea bottom was linked to an injection of cuttings and drilling mud...".

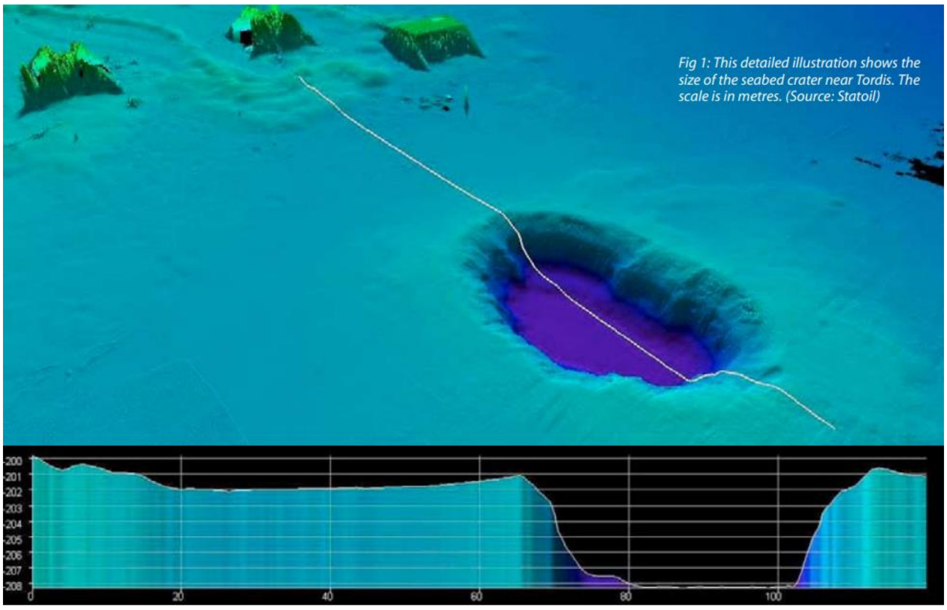

Figure 10. Stratigraphic studies by the NPD ("Norwegian Petroleum Directorate") in the wake of an oil leak on Tordis showed that the Utsira formation is not present where an injection well (Tordis) was drilled for this North Sea field /25A/.

Based on these findings, confidence in the availability of safe, secure and adequate CO_2 storage must be a prerequisite for investment in both transport and storage infrastructure and capture facilities /5A/.

3.4 Dynamics of energy production and (amine) CC process

Already today and more frequently in the future, existing and new power plants must face the challenges of the liberalized electricity market, predictability issues regarding renewable sources and the requirement to cover intermediate and peak load constraints, to be able to respond to the variation of the electricity load demand.

The flexibility requirements have further enhanced over the last years due to the increasing share of intermittent renewable electricity generating sources (such as solar and wind) connected to the grid.

Quote /26/: "*Increasing penetration of renewable energy sources presents challenges for transmission grid operators to maintain electric reliability despite the intermittency of wind and solar power. This variability is managed with redundant generating capacity that can quickly respond to fluctuations in demand and has predominately been served by coal and gas fired units that are synchronized to the grid but operating at part load. Flexible power generation that can be rapidly brought online reduces the inefficiency of relying on part load operation. System operators, such as PJM, California ISO and ERCOT define such "quick start" or "non-spinning" reserve as generation capacity that can be synchronized to the grid and ramped to capacity within 10 minutes*".

In modern power purchase markets flexibility is thus a key factor for the grid balancing plants. The reciprocating engine plants´ start up time ("hot start" conditions) is typically 2 - 10 minutes dependent on engine type. Shut down time of the engine (100% - 0% load) is within less than 1 minute /26/. Flexibility of the reciprocating engine plant can be enhanced further by integration with a BESS (Battery Energy Storage System – i.e. hybrid generation) /27A/.

Boilers and power plants in general equipped with today's reference CCS technology have a long start up time are thus to be kept on-line (at part load) all the time in order to be flexible enough and thus at the same time curtailing production of renewable electricity in times with excess "green power" generation. From Annex 3 can be seen that the CCS ramp rates are similar as those for a CCGT and boiler plant. It appears from Annex 3 that the CCS equipped power plant has a rather long start up time. E.g. for a boiler/CCGT plant equipped with CCS a "hot start-up" condition is around 1 – 2 h and a "warm start-up" requires an even longer time span. Fast dynamic/flexible reciprocating engine plants can however be shut down in times with enough/excess intermittent renewable electricity generation and thus fuel is saved and associated CO_2 emissions avoided. As a consequence, the share of intermittent renewable electricity penetration into the grid can be increased - average greenhouse gas intensity of the produced grid electricity is thus further reduced.

It is expected in the future that the grid balancing thermal power plants will ***run less and more infrequently*** when the amount of intermittent renewable energy is further increased in the power grid. During this decade the fuel of the grid balancing plants will largely be based on natural gas, which will be gradually replaced by cleaner renewable fuels when availability increases after the years 2030/2035 and thus the average grid GHG intensity will decrease further. In Annex 4 the expected operational trend of the grid balancing thermal power plant in Europe is shown. Especially the forecasted sharply decreasing annual operating hours of the thermal power plants and the "peaker gas" type increased share of the capacity additions require flexible operation.

Membrane technology for CSS could be a promising concept for these more infrequently operated power plants, as the gas separation process can cope with dynamics equally well as the exhaust generation. However, promising reference CCS processes today are more designed for the base load (continuous operation) plant – not flexible enough for todays´ / future flexible power market needs**.** Besides the gas separation process' sensitivity to a change in operating conditions of the power plant, also the downstream processing systems for local CO_2 storage and further transport must be designed for the intermittent operation which creates technical and economic challenges.

However, CCU (mostly in EOR applications) is today applied in industrial sectors with long (or continuous) yearly operational periods such as natural gas processing plants. Steel, cement and chemical industrial sectors have also a (potential) high future interest in CCUS. In Annex 1 large-scale commercial CCUS projects in operation year 2020 are listed.

4 Transport Sector – Marine

The IMO (International Maritime Organisation) agreed to the initial GHG strategy in MEPC 72, 2018. The Strategy sets targets for reaching at least 50% reduction of marine transportation GHG emissions by 2050. In addition, EU's Green Deal and Fit for 55 climate packages includes instruments to set the course for decarbonizing maritime transport. In July 2021, the Commission presented its key tools for driving the green transition in the sector. These include the extension of emissions trading to shipping and the FuelEU Maritime initiative to promote alternative fuels.

To meet these new requirements, the shipping sector is looking at different solutions to make the vessels more climate friendly. Technological development is taking place to improve the energy efficiency of the vessels as well as utilizing new, less carbon intensive fuels and on-board carbon capture. According to DNV's Maritime Forecast to 2050, carbon capture onboard ships has the potential to reduce shipping's fleetwide GHG emissions by more than 30% /27B/. In terms of actual emissions figures, such an implementation of maritime CCS would reduce CO_2 emissions by more than 300 million tonnes per year.

Current development efforts towards maritime carbon capture are focused on pairing experience from land-based technologies with knowledge in the maritime equipment industry of how to make innovative solutions work in a maritime environment. These concepts seem largely based on the CC technologies described in earlier chapters of this document, e.g. the amine-based CC process and the Cryogenic Carbon Capture.

An optimised carbon capture systems onboard could achieve capture rates typically above 90%. The main challenges to overcome are the energy consumption, size of the capture plant and finding ways to store the captured CO_2 until it can be unloaded. About three tons of CO_2 is generated in combustion of 1 ton (oil) fuel, and that needs to be stored on-board. As storing gaseous CO_2 is not viable due to space requirements, it needs to be stored in liquified or solid state. Port reception facilities for the disposal of the ship stored CO_2 are also needed on a technical side, and international legal frameworks how CO_2 disposal from international shipping is to be set up. The below figure outlines the main challenges of onboard carbon capture, many of which are under active research and development.

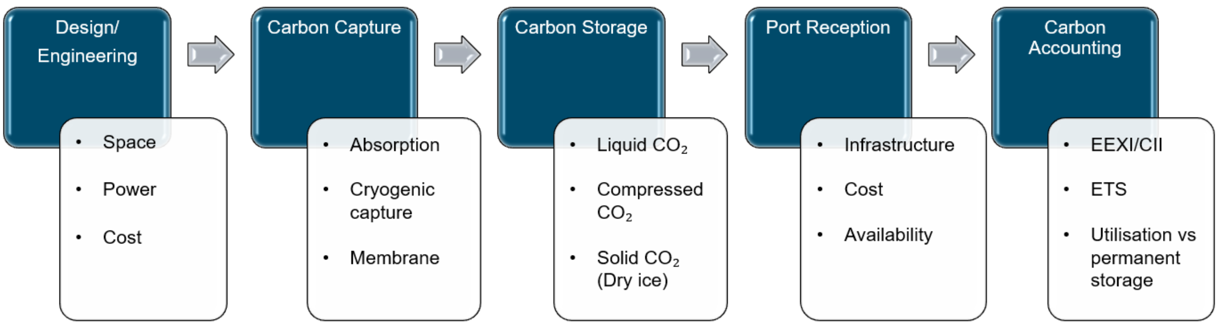

Figure 11. Main challenges of marine on-board carbon capture.

The maritime industry needs consistent and simple rules that are possible to both live by and be enforced. In order to stimulate innovation and technological development, policies and their subsequent rules should aim to set targets based on tangible factors like carbon intensity and emissions, and let vessel owners or operators choose the technologies, including maritime CCS, that they want to use to reach those targets. It is therefore critical that key policy instruments take all feasible technologies into account. The EU ETS already contains a mechanism that allows for

CCS adoption and use. Due to the international nature of the shipping industry, similar consistent mechanisms shall be ultimately implemented on a global level.

Concepts to combine SO_X scrubbing with CO_2 removal or utilizing energy needed for LNG evaporation to cooling needs of the carbon capture process have been proposed several times, however, past announcements of pilot installations have not realized to provide detailed technical data so far. Generally, there is frequent media coverage about CC technology also for marine applications, and several announcements from equipment manufacturers, operators and publicly funded projects have been published recently /28/. However, due to the unavailability of confirmed data, no detailed evaluation of marine CC applications was possible in this document.

4.1 Piloting plans in the maritime industry

In recent news, equipment manufacturers, operators and publicly funded projects have reported first steps of the development on marine CC solutions /28, 29/. Many of these studies are still early phase considerations and design studies, but pilots and commercial scale installations are being planned in the near future.

Wärtsilä is currently developing a solvent-based carbon capture system that will be suitable for commercial shipping, particularly in terms of size and cost. Initial testing reveals CO_2 capture rates of more than 65% while maintaining a footprint that enables the technology to fit into funnel casings. The tank size for captured CO_2 will be vessel-specific, based on operational profiles. In addition to a 1 MW research prototype in an engine laboratory in Norway, a pilot installation of Wärtsilä's CCS system onboard a tanker vessel with a 7 MW main engine is planned in 2023. /32A/.

Alfa Laval has executed a CCS test with Japan's National Maritime Research Institute (NMRI) providing real-world validation of results achieved in the lab. The tests showed that a scrubber could perform the CO_2 capture on board. The modified PureSOx system was able to absorb CO_2 from the auxiliary diesel engines in port, while operating in a closed loop. The shipowner, who had installed Alfa Laval PureSOx, arranged with Alfa Laval and a local shipyard to include the testing during the vessel's sea trials. However, according to Alfa Laval more development is needed before CCS can be deployed at sea, but the progress of the carbon removal technology and recent successful testing showed clear potential in the approach. /32B/

Samsung Heavy Industries has reported receiving approval in principle (AIP) from the Korean Register of Shipping regarding the onboard carbon capture system developed together with Panasia for vessels that run on LNG. The system uses an amine-based liquid absorbent to separate and recover CO_2 from the exhaust gas. Companies have been working on CCS technology since 2020 and are currently conducting a technology performance test at a demonstration facility of Panasia in Jinhae. Their plan is to commercialize the CCS technology for LNG-fuelled ships by 2024. /33A/

Daewoo Shipbuilding & Marine Engineering (DSME) reported in April 2022 that they have obtained basic approval for a liquified carbon dioxide carrier from ABS. The carrier would have an LNG propulsion engine and a carbon dioxide capture unit using ammonia-water sorbent and mineral carbonation technology. Mineral carbonation technology (MCT) is a process whereby CO_2 is chemically reacted with minerals containing calcium or magnesium to form stable carbonate materials which do not incur any long-term liability or monitoring commitments. The technology is developed by Hi Air Korea. The LNG tanker company GasLog is also involved in the development and could install the technology on their new carriers delivered by DSME from 2024. /33B/

Mitsubishi Shipbuilding has been piloting their CCS solution together with K-line and Class NK. The three parties have conducted tests on a small-scale demonstration plant, which has been installed on the K-Line bulker Corona Utility since August 2021. /34/

Value Maritime has introduced a concept of exhaust gas "filtration" for engine sizes of 3-15 MW, where SOx, particulates and CO_2 are captured. In this process CO_2 is captured in a CO_2 storage ("battery") which can be discharged in port. Value Maritime has installed a pilot system capable to reduce the carbon emissions by 70% on the Visser Shipping's containership Nordica. Value Maritime is also working together with the company Carbon Collectors to introduce full scale capture units on new MGO fuelled tugs in 2024 and the vessels are announced to be operational by 2026. /35/

5 Conclusions

In this document, an overview of technologies that have reached the industrial piloting phase or seen as promising developments, for CCUS (main focus on CCS in the power production context), related historical development trend and technological descriptions are presented. Some Direct Air Capture alternatives are also briefly described.

In source /5A/, following Technology Readiness Level rating for the technologies in the CCUS chain is presented:

- CO_2 ***capture* in power generation**:
  - Natural gas - chemical absorption is still in the "demonstration phase"
  - Coal – chemical absorption is in an "early adaptation phase"

- CO_2 ***transport***:
  - Pipeline – "mature"
  - Ship (port to port) – "demonstration phase"
  - Ship (port to offshore) – "large prototype phase"

- CO_2 ***storage***:
  - EOR (Enhanced Oil Recovery) – "mature"
  - Saline Formation – "early adaption phase"
  - Depleted oil & gas reservoirs – "demonstration phase"

- CO_2 ***use***:
    - Urea – "mature"
    - Concrete – "early adaptation phase"
    - Synthetic methane – "demonstration phase"
    - Synthetic liquid hydrocarbons – "large prototype phase"

Many advancements have been made on CCUS technology during the last 10 years, but not all parts of the CO_2 value chain are currently operating at a proven/mature commercial scale. Many key technologies are still at the demonstration or the large prototype stages. In addition to technology readiness of the capture processes also the confidence in the availability of safe, secure and adequate CO_2 storage is a prerequisite for investment in both transport and storage infrastructure and capture facilities.

Most current carbon capture processes are a "base-load" type technology with rather long start-up time and thus not ideally suitable for flexible thermal natural gas fired power plants needed in todays´ or future power markets for stabilizing the electrical grid due the increased power generation of variable renewables like wind and sun. A high "plant availability" of the power plant equipped with CC is a key to keep the overall costs down. The power generation flexibility demands will set limitations for CC utilization in this sector.

CCU is today applied in sectors with a stable and continuous operational profile such as natural gas processing plants. Other industrial sectors with a future growing interest in CCU and CCS are steel, cement and chemical industries.

CCU and CCS are not merely of interest for land-based applications, also the transport sector (marine) is investigating the technologies and new developments and several piloting plans have been announced recently.

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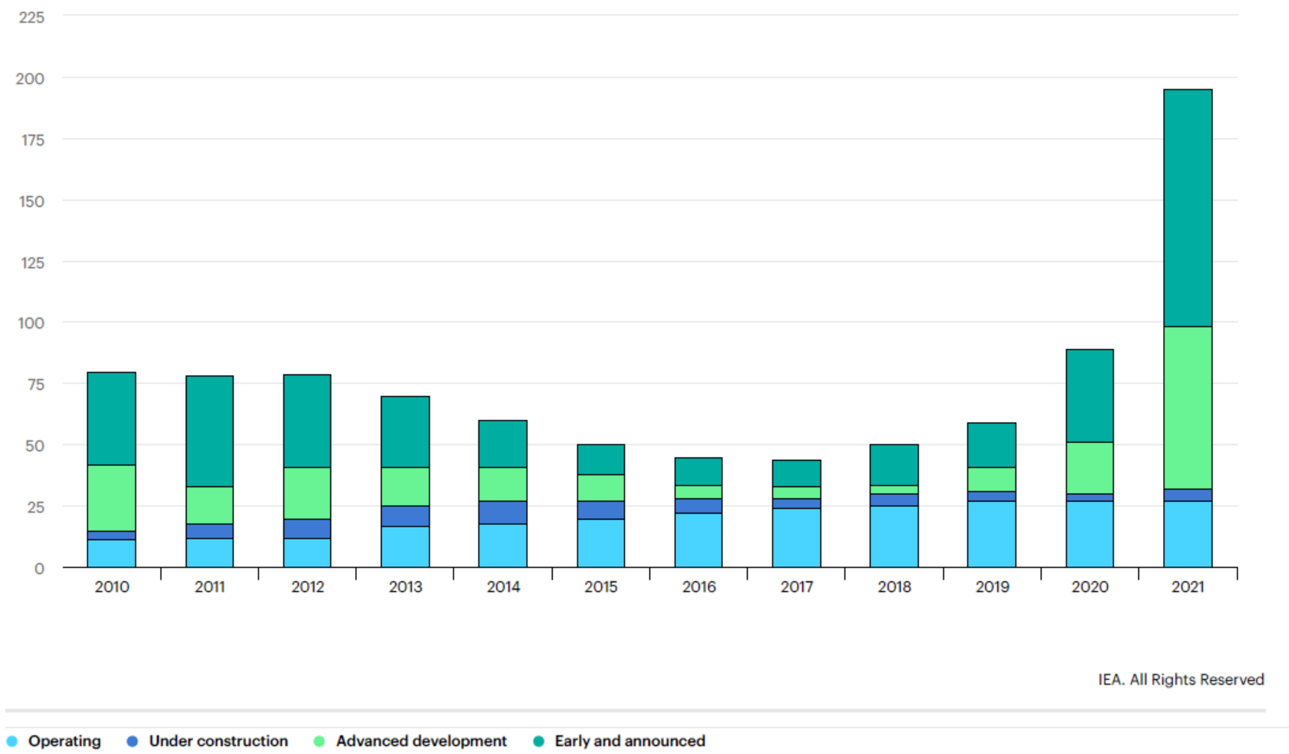
Annex 1: Large-scale commercial CCUS projects in operation 2020 /5A/

Country	Project	Operation date	Source of CO_2	CO_2 capture capacity (Mt/year)	Primary storage type
United States (US)	Terrell natural gas plants (formerly Val Verde)	1972	Natural gas processing	0.5	EOR
US	Enid fertiliser	1982	Fertiliser production	0.7	EOR
US	Shute Creek gas processing facility	1986	Natural gas processing	7.0	EOR
Norway	Sleipner CO_2 storage project	1996	Natural gas processing	1.0	Dedicated
US/Canada	Great Plains Synfuels (Weyburn/Midale)	2000	Synthetic natural gas	3.0	EOR
Norway	Snohvit CO_2 storage project	2008	Natural gas processing	0.7	Dedicated
US	Century plant	2010	Natural gas processing	8.4	EOR
US	Air Products steam methane reformer	2013	Hydrogen production	1.0	EOR
US	Lost Cabin Gas Plant	2013	Natural gas processing	0.9	EOR
US	Coffeyville Gasification	2013	Fertiliser production	1.0	EOR
Brazil	Petrobras Santos Basin pre-salt oilfield CCS	2013	Natural gas processing	3.0	EOR
Canada	Boundary Dam CCS	2014	Power generation (coal)	1.0	EOR
Saudi Arabia	Uthmaniyah CO_2-EOR demonstration	2015	Natural gas processing	0.8	EOR
Canada	Quest	2015	Hydrogen production	1.0	Dedicated
United Arab Emirates	Abu Dhabi CCS	2016	Iron and steel production	0.8	EOR
US	Petra Nova	2017	Power generation (coal)	1.4	EOR
US	Illinois Industrial	2017	Ethanol production	1.0	Dedicated
China	Jilin oilfield CO_2-EOR	2018	Natural gas processing	0.6	EOR
Australia	Gorgon Carbon Dioxide Injection	2019	Natural gas processing	3.4-4.0	Dedicated
Canada	Alberta Carbon Trunk Line (ACTL) with Agrium CO_2 stream	2020	Fertiliser production	0.3-0.6	EOR
Canada	ACTL with North West Sturgeon Refinery CO_2 stream	2020	Hydrogen production	1.2-1.4	EOR

Note: Large-scale is defined as involving the capture of at least 0.8 Mt/year of CO_2 for a coal-based power plant and 0.4 Mt/year for other emissions-intensive industrial facilities (including natural gas-based power generation).
Source: GCCSI (2019), The Global Status of CCS 2019: Targeting Climate Change.

Annex 2: Global pipeline of commercial CCUS facilities operating and in development, 2010-2021 /1A/



Annex 3: Flexibility of CCGT, boiler plants with/without CCS /30/

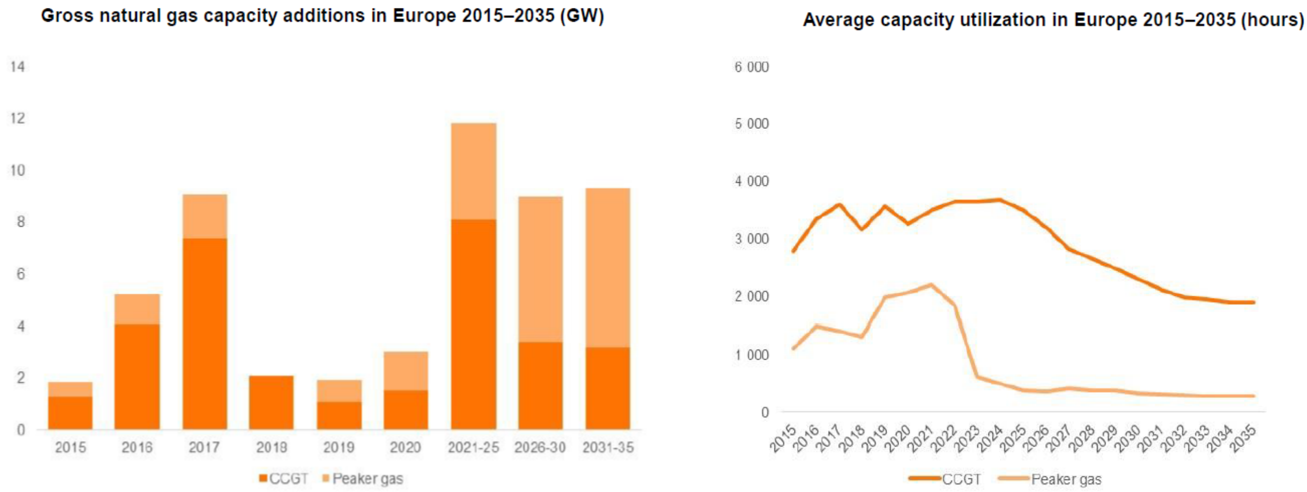
Table 1. Flexibility features of power plants with and without CCS

	Turndown	Cycling capability		Part load efficiency
		Start-up to full load	Ramp rates	
NGCC	Low load operation: 15-25% CC load (10-20% GT load) Min. environmental Load: 40-50% CC NPO (30-40% GT load)	Hot start-up: 45-55 min Warm start-up: 120 min Cold start-up: 180 min	35 - 50 MW/minute max Hot start-up load change rate: - 0-40% GT load: 3-5%/min - HRSG press.: 1-2%/min - 40-85% GT load: 4-6%/min - 85-100% GT load: 2-3%/min	Approx. constant efficiency down to 85% GT load 2-3 percentage points less @ 60% CC load
with CCS	Post-combustion unit min. load: 30% CO_2 compressor min. efficient load: 70%	Regenerator preheating: - hot start-up: 1-2 h - warm start-up: 3-4 h	Same as plant w/o CCS	Same as plant w/o CCS
IGCC	Min. env. GT Load: 60% PO. Process unit /air separation unit (ASU) cold box min. load: 50% ASU compr. min. load: 70%	Cold start-up: 80-90 h Gasification hot start-up: 6-8 h ASU hot start-up: 6 h	Gasification ramp rate: 3-5%/min ASU ramp rate: 3%/min	Gross electrical efficiency: 2 percentage points less @ 70% CC load
with CCS	CO_2 compressor min. efficient load: 70%	Same as plant w/o CCS	Same as plant w/o CCS	Same as plant w/o CCS
USC PC	Min. boiler load: 25-30%	Very hot start-up: < 1h Hot start-up: 1.5-2.5 h Warm start-up: 3-5 h Cold start-up: 6-7 h	30-50% load: 2-3%/min 50-90% load: 4-8%/min 90-100% load: 3-5%/min	Subcritical boiler: -4 perc. point @ 75% load Supercritical boiler:- 2 perc. point @ 75% load
with CCS	Post-combustion unit min. load: 30% CO_2 compressor min. efficient load: 70%	Regenerator preheating: - hot start-up: 1-2 h - warm start-up: 3-4 h	Same as plant w/o CCS	Same as plant w/o CCS
Oxy fuel				
Air-firing mode	Min. boiler load: 25-30%	Very hot start-up: < 1h Hot start-up: 1.5-2.5 h Warm start-up: 3-5 h Cold start-up: 6-7 h	30-50% load: 2-3%/min 50-90% load: 4-8%/min 90-100% load: 3-5%/min	Subcritical boiler: -4 perc. point @ 75% load Supercritical boiler: -2 perc. point @ 75% load
Oxy-firing mode	Cold box min. load: 40-50%. ASU compressor min. efficient load: 70% CO_2 compressor min. efficient load: 70%	Start-up in air-firing mode, ASU start-up completed in approx. 36 h	ASU ramp rate: 3%/min	Same as plant in air-firing mode

For NGCC and USC-PC with post-combustion capture, Table 1 shows that the introduction of the capture unit may impose additional constraints on the turndown, start-up and fast load changing of the plant. For oxy-combustion plants, the main constraint on flexibility is the ASU, which has a minimum operating load of the cold box of around 50% and a maximum ramp rate of 3% per minute (a boiler can typically ramp at 4-5%).

Annex 4: Current and Future Trends in Power Generation – Flexibility a Key Aspect /31/

1) Increasing amount of intermittent renewables in power system require additional flexible thermal capacity, which will be based on Natural gas during this decade. 2) Future natural Gas plants will run less and more infrequently. 3) If climate ambitions are increased the need for thermal balancing capacity increases even further. Then natural gas would be largely replaced by cleaner fuels after 2030 or emissions are abated in some other way.



Source: BloombergNEF New Energy Outlook 2020 & 2021

CCGT = Combined Cycle Gas Turbines (intermediate and baseload gas)
Peaker Gas = Open Cycle Gas Turbines and Reciprocating Engines (peaking operations)

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