Technology scouting—carbon capture: from today's to novel technologies

Concawe has commissioned a new study to evaluate state-of-the-art carbon capture and storage (CCS) technologies, with a focus on commercial/near-term opportunities for CCS that are already in the market or expected to be available in the 2025–2030 time frame, as well as the various emerging CCS techologies that are being developed worldwide. This article provides an overview of the study, the full details of which can be found in Concawe report no. 18/20.[1]

Introduction

Carbon dioxide (CO_2) emissions are a global concern as they are primarily responsible for climate change and global warming. The industrial sector is responsible for around 20% of current greenhouse gas (GHG) emissions worldwide. Technologies for reducing CO_2 emissions already exist, and include swapping fossil fuels for renewable sources, boosting production and energy efficiency, implementing carbon capture and storage (CCS) technologies, and discouraging carbon emissions by putting a price on them. Over the past three decades, several CO_2 capture technologies have been developed in response to the increasing awareness of the importance of reducing carbon emissions. A few of these technologies, such as amine-based CO_2 capture, are already being implemented at the industrial level.

CCS technology involves capturing carbon dioxide at stationary point sources, such as fossil fuel power plants, refineries, industrial manufacturing plants and heavy industrial (iron and steel, cement) plants, as well as mobile sources such as automobiles, ships and aircraft, or directly from the air (direct air capture). The captured CO_2 is compressed and then transported, either for storage in geological formations, or for direct use (non-conversion of CO_2, e.g. for use in enhanced oil recovery, food and beverage manufacture, as a heat transfer fluid, etc.) and indirect use (conversion of CO_2 into chemicals, fuels and building materials), the latter being referred to as carbon capture and utilisation (CCU).

A new study, conducted by FutureBridge at the request of Concawe,[1] focuses on near-term opportunities for carbon capture technologies that are likely to be commercialised in the 2025–2030 time frame, and also on the various emerging carbon capture technologies for power plants and industrial process applications.

In their assessment of near-term and emerging carbon capture technologies, FutureBridge took into consideration various techno-economic factors such as carbon capture efficiency/rates, purity, the cost of CO_2 capture per tonne, the levelised cost of electricity, risks and barriers. They collated information from a wide range of sources, including patents, scientific literature, published techno-commercial reports, white papers, annual reports and sustainability reports to support their assessment of both near-term and emerging carbon capture technologies. In addition, to gauge the potential for near-term commercial carbon capture technologies FutureBridge analysed published front-end engineering and design reports, integrated assessment models, and a techno-economic analysis report for pilot and demonstration plants.

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[1] See Concawe report no. 18/20.
https://www.concawe.eu/publication/technology-scouting-carbon-capture-from-todays-to-novel-technologies

Carbon capture technologies

Carbon capture is a process that involves capturing CO_2 at its point source or from the air, and either storing it underground to avoid its release into the atmosphere (CCS) or using it in a number of direct or indirect applications (CCU). The CCS process includes the following five steps:

- **Source characterisation:** this involves identification of the source location, CO_2 output flow rate, CO_2 purity, and the type of output stream. The Centre for Low Carbon Futures has classified CO_2 sources into four categories, based on the impact of CO_2 concentration on the energy requirements for capture, and the corresponding cost of separating the CO_2 from the gas stream. These categories are: high (>90%); secondary highest (50–90%); moderate (20–50%); and low (<20%).[2]
- **Capture/separation:** CO_2 is separated from the output stream using appropriate technology (chemical solvents, membranes, etc.) based on the type of stream. It is also separated from other gases or air (direct air capture) or from a concentrated source (e.g. industrial flue gases). It should be noted that the different sources have distinct characteristics in the way that CO_2 is produced, and can be further categorised into:
  a) high-purity CO_2 streams (e.g. from production of bioethanol, beer, hydrogen, etc.) with 96–100% CO_2 purity;
  b) medium-purity CO_2 streams (e.g. from production of iron and steel, cement, etc.) with 20–50% purity, and CO_2 streams from hydrogen production (e.g. syngas production, refinery processes) which are considered to be within the 30–45% purity range; and
  c) low-purity CO_2 streams (e.g. from production of paper and pulp, glass, etc.) that directly produce an output stream of <20%. In refineries, process heating and fluid catalytic cracker (FCC) units produce low purity (3–20%) streams of CO_2.
- **Purification:** depending on the source of the carbon emissions, and the type of fuel and capture method used, the CO_2 stream will contain various impurities, such as SO_x, NO_x, O_2, N_2, Ar, H_2, CH_4, CO, H_2S, H_2O and mercaptans, some of which may have a negative impact (e.g. corrosion and formation of liquid slugs in the pipeline) during transportation. The purification requirements of the captured CO_2 vary depending on the final use of the CO_2 stream. Impurities such as O_2 are largely removed by using cryogenic distillation and catalytic oxidation techniques, while H_2O is removed via refrigeration and condensation, and by adsorption using silica gel. Scrubbing and drying techniques are also used to remove impurities from the captured CO_2. A minimum of 96% CO_2 purity is required for pipeline transportation because CO_2 pipelines are susceptible to the propagation of ductile fractures.[3]
- **Transportation:** captured CO_2 is compressed to a pressure ranging from 8–17 MPa at ambient temperature (286 K to 316 K) to reach supercritical form, and the compressed CO_2 is then transported via pipelines, road tankers, railroad tankers (inland transportation) and ships. Each transportation system has its advantages and disadvantages, although pipelines are considered to be the most attractive mode of transportation because they can handle large flow rates effectively. On the other hand, road and rail tankers are more useful for transporting small quantities.

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[2] https://www.ctc-n.org/resources/supporting-early-carbon-capture-utilisation-and-storage-development-non-power-industrial

[3] http://pdf.wri.org/ccs_guidelines.pdf

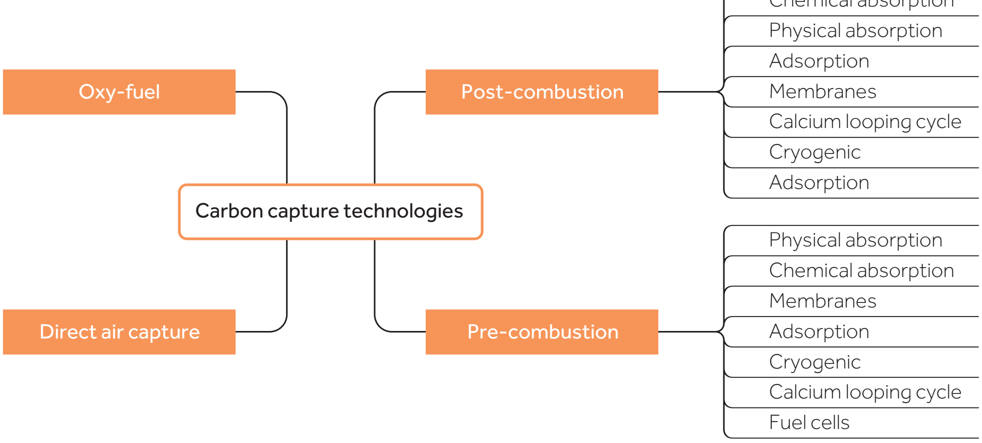
- **Storage:** captured CO_2 is stored by injecting it deep underground where it remains stored permanently. The CO_2 is stored in reservoirs, through the geological storage and oceanic storage routes, whereby CO_2 is directly injected deep into the saline formations of aquifers and depleted oil/gas wells. Three types of geological formations are eligible for storing CO_2: depleted oil and gas reservoirs; deep saline formations; and unminable coal beds.

The most technologically challenging and costly step in the process is the capture step (the main focus of this article). The purification, transportation and storage components of CCS are not nearly as technology-dependent as the capture component.

Currently, the technical approaches available for capturing CO_2 are as follows (see also Figure 1):

- **Post-combustion capture:** involves the removal of CO_2 from flue gas produced after the combustion of fossil fuels or other carbonaceous materials (such as biomass).[4]
- **Pre-combustion capture:** refers to the near-complete capture of CO_2 before fuel combustion or before venting out the exhaust gas or flue gases, and is usually implemented in conjunction with the gasification of coal, coke, waste biomass and/or residual oil or steam reforming/partial oxidation of natural gas to produce syngas.[5]
- **Oxy-fuel combustion:** although not technically a carbon capture technology, this is a process in which combustion occurs in an oxygen-enriched environment, hence producing a flue gas comprised mainly of CO_2 (~89% by volume) and water. [6]
- **Direct air capture:** a technology in which CO_2 is removed directly from the atmosphere as opposed to the capture at point source itself.[7] (Note that the concentration of CO_2 in the air is relatively low, at ~400 ppm.)

Figure 1: Carbon capture technologies



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[4] http://www.zeroco2.no/introduction/AminesNyhetsgrafikk.jpg

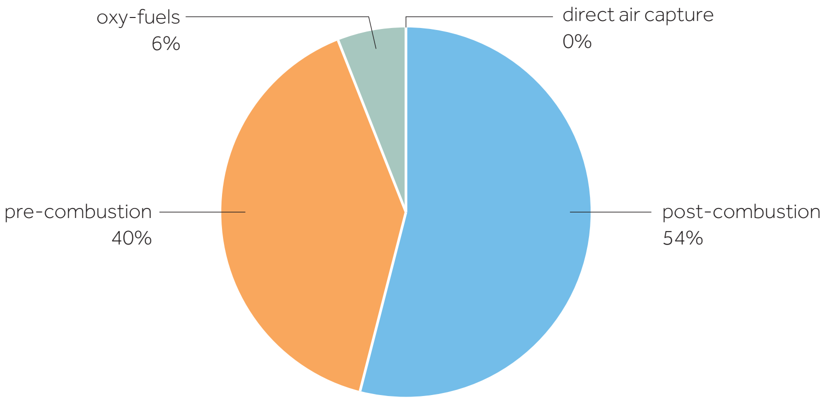
[5] http://www.zeroco2.no/introduction/PrecombustionVattenfall.jpg

[6] https://www.sciencedirect.com/topics/engineering/oxyfuel-combustion

[7] https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Report_on_Negative_Emission_Technologies.pdf

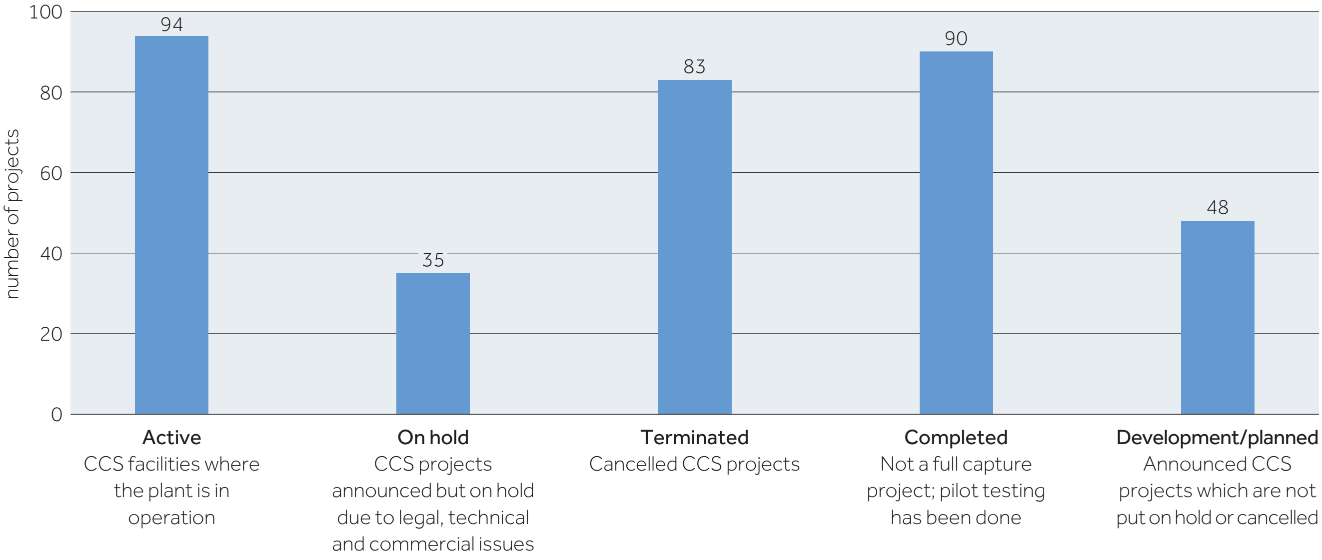
Currently, both pre- and post-combustion capture technologies have been commercialised, and are being used extensively in a variety of CCS projects worldwide, as shown in Figure 2.

Figure 2: Distribution of CCS projects worldwide



In April 2018, there were approximately 150 planned or active CCS facilities worldwide.[8] A total of 118 CCS projects were either on hold or had been terminated, and 90 pilot projects had been realised. The overall status of these CCS facilities is presented in Figure 3.

Figure 3: CCS facilities worldwide as of April 2018



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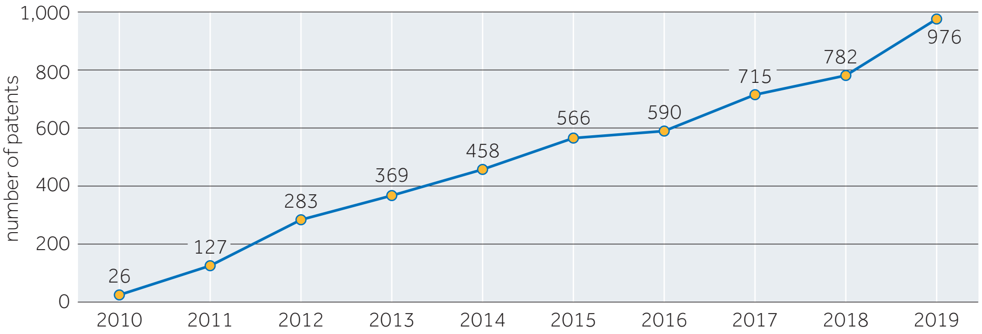
[8] https://www.netl.doe.gov/node/7633

Technology scouting: a deep dive into patent analysis

As part of their scouting assessment, FutureBridge conducted an analysis of patent publications issued since 2010. They identified an increasing trend in the publication of patents relating to carbon capture between 2010 and 2019, as shown in Figure 4.

Figure 4: Worldwide patent publication trend (2010 –2019)



Analysing the trend per country (Figure 5) shows that, as of 2019, China was leading the most active countries in terms of the number of patents on the subject. Currently, China is the world's largest carbon emitter, and a recent push for greener production of goods and energy solutions by the Chinese government and state-owned Chinese companies has propelled the filing of patents related to climate change technologies.

Figure 5: Top 10 countries and their patent filing trends (2010–2019)

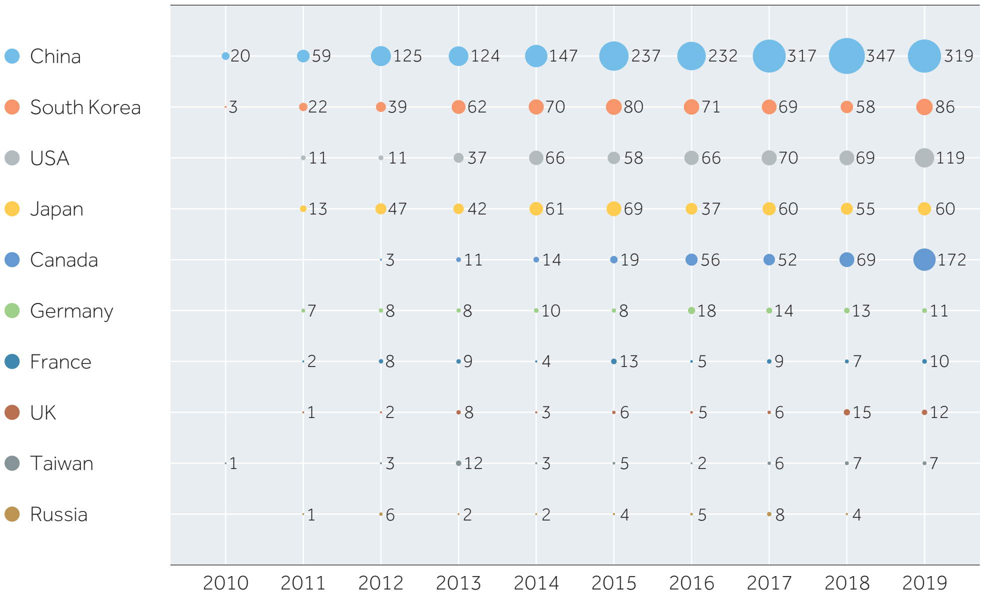
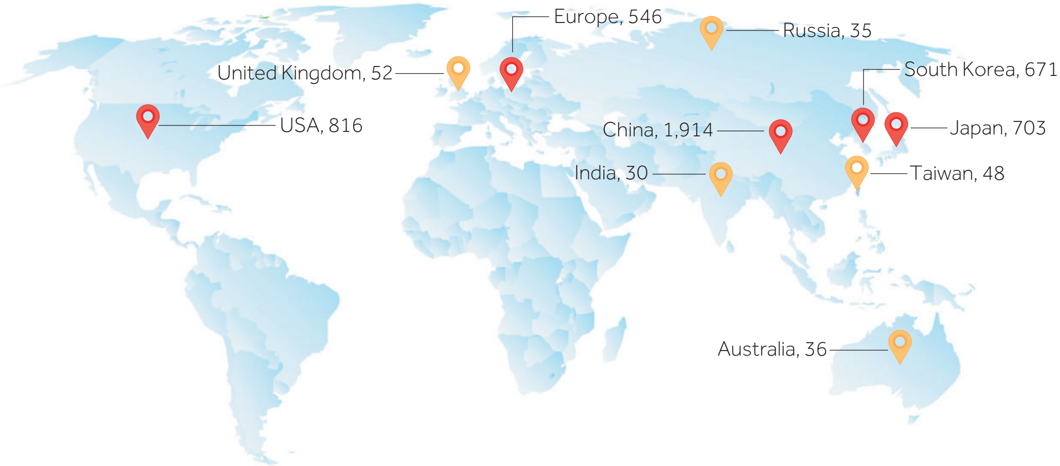


Figure 6: Geographic distribution of patents

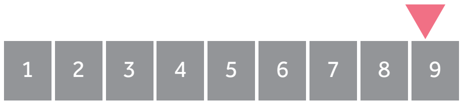
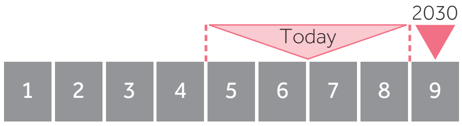
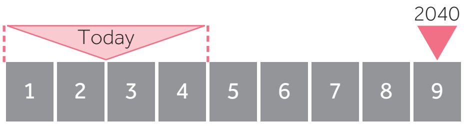


A detailed analysis of patents per type of technology and the main players involved is presented in the full report.

Categorisation of carbon capture technologies

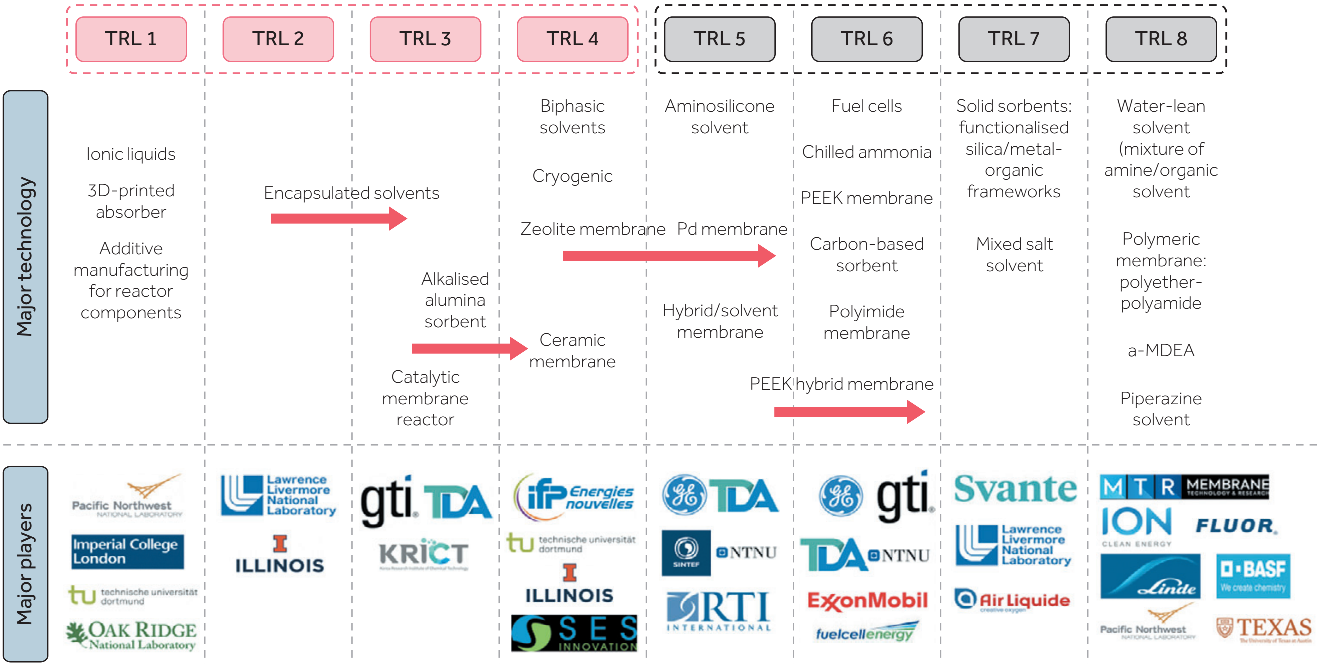
FutureBridge has defined three categories of carbon capture technologies according to their technology readiness level (TRL), i.e. commercial, near-term and emerging technologies (see Figure 7).

Figure 7: Carbon capture technology categorisation

Technology	Technology readiness level	Characteristics
Commercial		First generation technology 85–90% CO_2 capture rate with 95% CO_2 purity Average cost of CO_2 capture is US$50–75 per tonne
Near-term commercial		Second generation technology 90% CO_2 capture rate with 95% CO_2 purity Reduce cost of electricity (COE) by 20–30% Average cost of CO_2 capture is US$40 per tonne
Emerging		Early stages of research and development 95% CO_2 capture rate with 99% CO_2 purity Reduce COE by 30–40% Average cost of CO_2 capture is US$30 per tonne

The major near-term and emerging carbon capture technologies and the major players have been classified as shown in Figure 8.

Figure 8: Overview of the near-term (TRL 5–8) and emerging (TRL 1–4) carbon capture technologies and main players



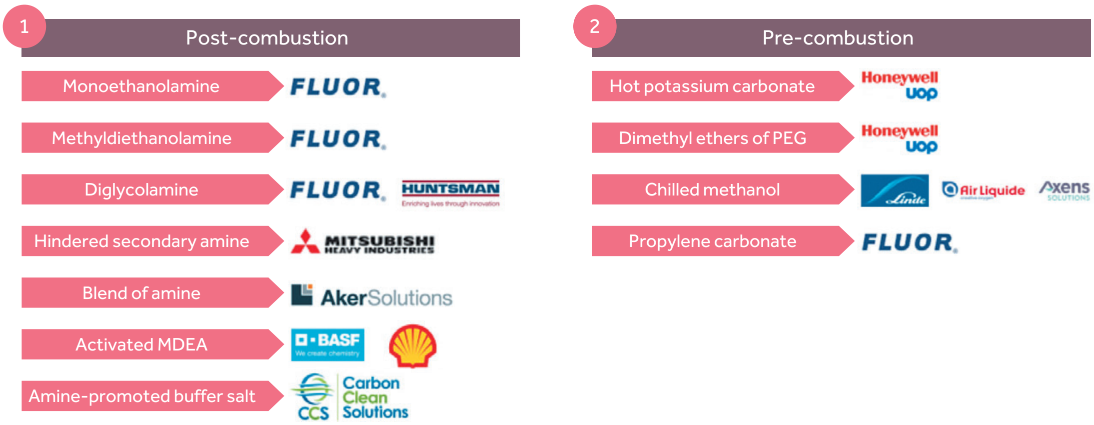
Commercial carbon capture technologies

Commercial technology: first generation technology (TRL 9) with 85–90% CO_2 capture and 95% CO_2 purity.

- Post-combustion capture with chemical absorption is the most proven technique for CO_2 removal from combustion flue gases, and is mostly based on chemical absorption/desorption with the use of liquid absorbent, such as monoethanolamine (MEA) at 30 wt% in water. Chemical absorption is commercialised and used in petroleum, natural gas, and coal-based power plants for separating acid gas (such as CO_2 or H_2S) from natural gas streams. This technique focuses on the reaction (largely exothermic) between the chemical absorbents and CO_2.
- Currently, pre-combustion physical solvent-based technology is used in industrial manufacturing processes, such as syngas, hydrogen, and natural gas production. A few facilities, such as the Enid Fertiliser CCS plant in northern Oklahoma, utilise a high-temperature, high-pressure chemical absorption process in which hot potassium carbonate is employed as a solvent to remove the CO_2 (Benfield process, Honeywell UOP).

Figure 9 summarises the key technologies and main players for both post- and pre-combustion commercial technologies.

Figure 9: Overview of the commercial carbon capture technologies and main players



Near-term commercial carbon-capture technologies

Near-term commercial technology: second generation technologies, currently in the advanced phase (>TRL 5) that are scheduled to become available for demonstration-scale testing around 2020–25 and expected to be available for commercial deployment in 2025–30. These technologies can offer a low overall cost of carbon capture (~US\$40 per tonne of CO_2) and a 90% CO_2 capture rate with 95% CO_2 purity compared to currently available first-generation technologies.

Figure 10 lists some of the technologies that are likely to be commercialised for coal-fired and natural-gas-fired power plants, together with the main players.

Figure 10: Overview of near-term commercial carbon capture technologies and main players

- Research and development work has been ongoing to provide improvements in the membrane technology used for pre- and post-combustion CO_2 capture. Several groups are developing polymeric membrane technology for post-combustion carbon capture. For example, the Norwegian University of Science and Technology patented a polyvinylamine (PVAm) membrane[9] containing amine groups, which has been evaluated in pilot-scale testing at an EDP power plant in Portugal. In addition, Membrane Technology Research Inc. (MTR) has been testing its innovative Polaris™ membranes at various test centres since 2006. MTR is also evaluating a hybrid membrane-absorption process system based on a combination of Polaris™ membranes and an amine solvent-based capture system. Other organisations such as Air Liquide S.A., SRI International, SINTEF Norway, Twente University, Research Triangle Institute, and the New Jersey Institute of Technology are also active in this area.

Emerging carbon-capture technologies

> **Emerging technology:** transformational technologies (<TRL 5) that are in the early stages of research and development and which offer the potential for game-changing improvements in cost and performance (30–40% reduction in the cost of electricity), and have an overall carbon capture cost of ~US$30 per tonne of CO_2, and a 95% CO_2 capture rate with 99% CO_2 purity. These technologies will be available for demonstration-scale testing around 2030–35, and for commercial deployment in the 2035–40 time frame.
>
> These emerging technologies will outperform current technologies for both pre- and post-combustion carbon capture in power plants and refineries, including H_2 generation.

Figure 11: Overview of emerging carbon capture technologies and main players

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[9] https://patents.google.com/patent/US8764881B2/en

The potential for CO_2 storage

The following types of geological structures are available for storing CO_2:

- **Underground sedimentary formation:** CO_2 is stored in porous geological formations underground. These geological formations are located at depths of several kilometres, and have pressure and temperature conditions that allow carbon dioxide to be stored either in the supercritical or liquid state. This is one of the most mature technologies for the storage of carbon dioxide and has been in use for more than two decades.
- **Saline aquifers:** saline aquifers are porous and permeable reservoir rocks that contain saline fluid in the pore spaces between the rock grains. They are found at depths greater than aquifers that contain potable water. Water contained in a saline aquifer cannot be technically and economically exploited for surface uses due to its depth and high saline content. The scientific literature related to carbon dioxide storage states that saline aquifers have enormous potential for carbon dioxide storage. A large proportion of European storage capacity exists in offshore saline aquifers, especially in the North Sea region, around Britain and Ireland, to some extent in the Barents Sea and likely in the Baltic Sea.
- **Depleted oil and gas fields:** these are suitable candidates for geological sequestration of carbon dioxide, although the CO_2 storage capacity is less than that of other structures. This is because of the need to avoid exceeding pressures that can damage the caprock, and because of the significant threat of leakage posed by abandoned wells. The major advantage of this type of storage is its known geology and proven capability to store oil and gas in the formation.
- **Oil and gas wells:** the process of injecting CO_2 into oil and gas wells to enhance recovery has been used for many years. With the right reservoir conditions, the injection of CO_2 can result in permanent storage of the CO_2 in the geological formation. Enhanced oil recovery (EOR) techniques can also involve the use of other gases (e.g. natural gas or nitrogen) as well as thermal or chemical injection; the IEA's new global database of enhanced oil recovery projects shows that around 500,000 barrels of oil are produced daily using CO_2-EOR, representing around 20% of total oil production using EOR techniques.
- **Coal beds/seams:** injecting CO_2 into coal beds/seams allows the CO_2 to be stored in the coal seam while simultaneously enhancing the recovery of coal bed methane. Research into this process—known as enhanced coal bed methane (ECBM) recovery—has been ongoing for the past two decades. The major technical challenges for carbon dioxide storage in coal beds are the low injectivity of coal seams and loss of injectivity as more CO_2 is injected. These challenges significantly limit the opportunity for CO_2 storage.
- **Carbon mineralisation in mafic and ultramafic rock formations:** this is an emerging storage technology and involves storing CO_2 in mafic and ultramafic rocks through mineralisation via carbonation reaction. CO_2 mineralisation can be used in different settings and include the in-situ CO_2 mineralisation of basalts or ultramafic rocks, ex-situ mineralisation of alkaline mine tailings, and reactions that produce other materials that have the potential to be used as mineral resources. Basalt rock has high porosity and permeability which increases its reactivity with CO_2, making it an ideal medium for CO_2 injection and storage.

Technology scouting—carbon capture: from today's to novel technologies

The global CO_2 storage capacity and storage projects across the world are shown in Figures 11 and 12, respectively. A detailed list is provided in the full report.

Figure 12: Global storage capacity ($GtCO_2$)[10]

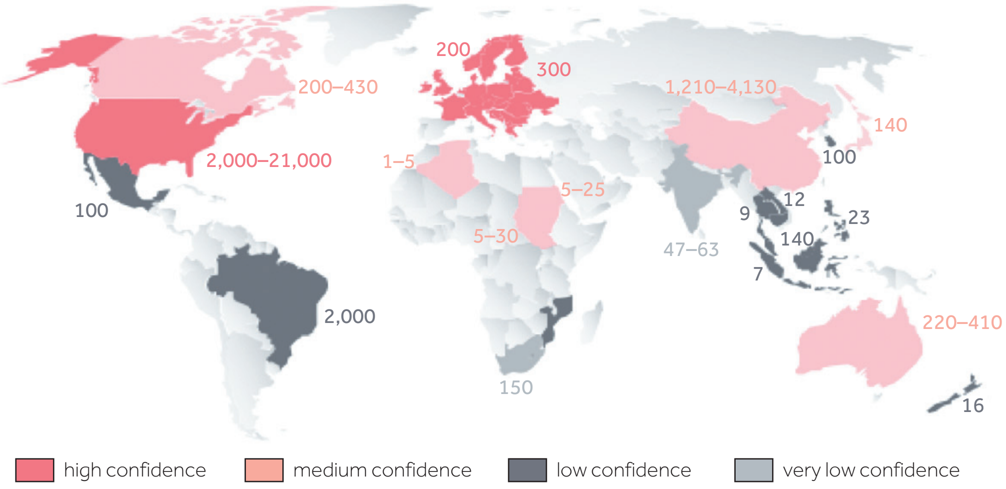

Figure 13: Storage projects across the world[11]

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[10] https://www.globalccsinstitute.com/resources/global-status-report/

[11] https://link.springer.com/article/10.1007/s12182-019-0340-8