CO_2 capture and storage

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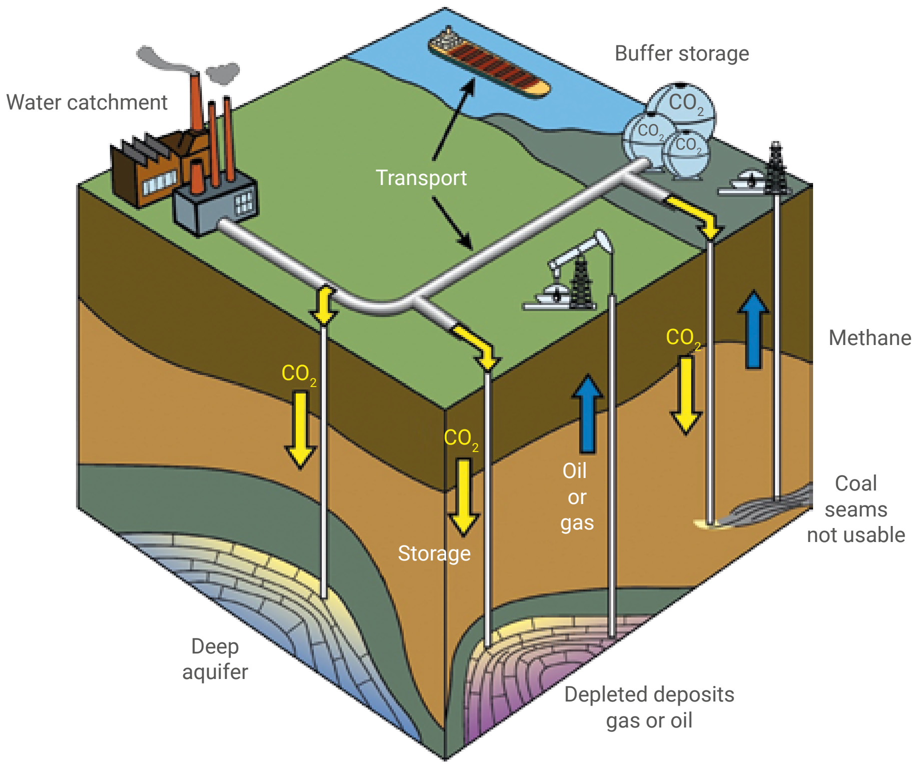
Carbon dioxide capture and geological storage are not new technologies: CO_2 capture and separation has been used in industry for decades, and CO_2 injection has been used since the 1970s for enhanced oil recovery. However, a number of obstacles still need to be overcome before they can be deployed on a large scale.

This article reviews existing technologies, both mature and under development, and discusses the issues to be addressed: reducing the cost and energy penalty for CO_2 capture, pooling infrastructures for transport, demonstrating the feasibility of mass storage, and the outlook for use.



1. Capture and storage of CO_2

Scenarios for reducing greenhouse gas emissions on a global scale highlight the role of geological CO_2 capture and storage (CCS) in the energy mix to reduce emissions associated with the energy and industry sectors. Not only could this technology be implemented rapidly, but many industries (steel, cement, refining, chemicals and petrochemicals) do not currently have alternative technologies that would enable them to massively reduce their emissions. This is why achieving energy and climate objectives requires a rapid increase in the deployment of CCS: 2 300 Mt (megatonnes) of CO_2 per year need to be captured by 2040, whereas today only 40 Mt are captured each year .

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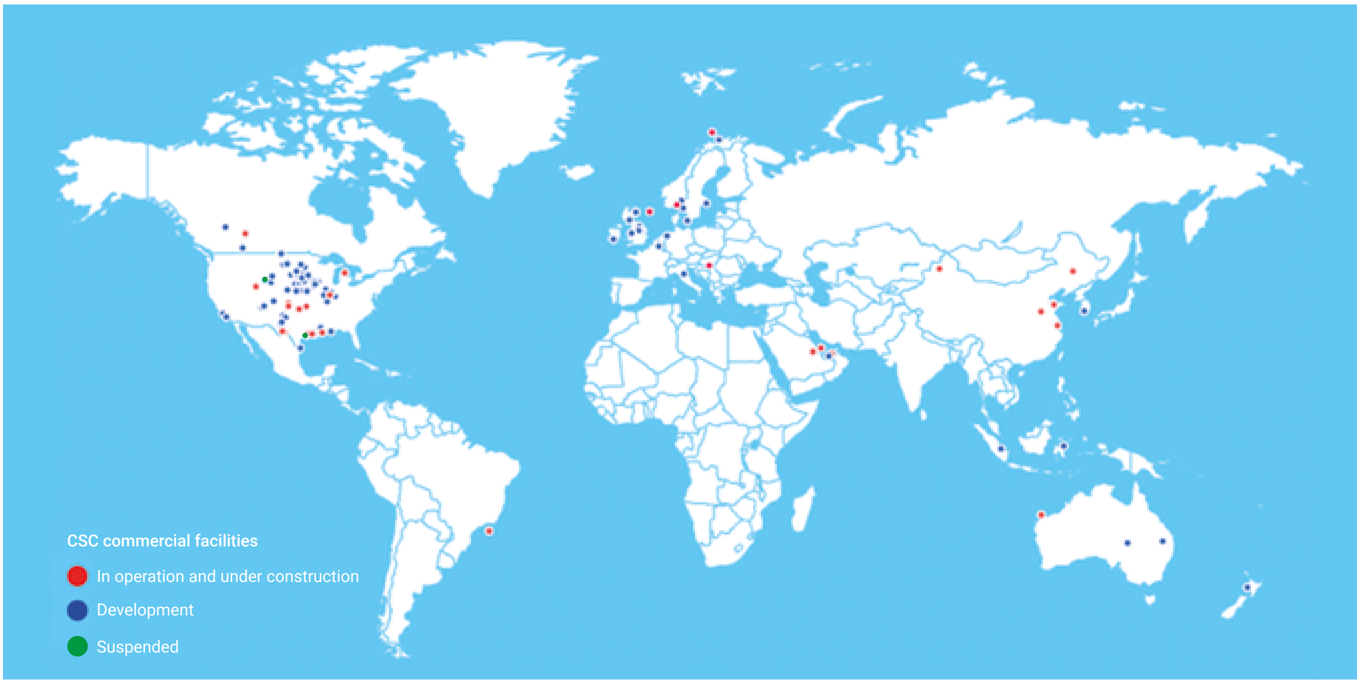

2. Major CO_2 capture and storage facilities worldwide in 2021.
"Global Status of CCS 2021", https://cutt.ly/globalccsinstitute-pdf

The issues

To keep global warming below 2°C, or even 1.5°C by the end of the century, we need to control man-made greenhouse gas emissions. The European Commission, in its Green Deal for Europe [1], and France, in its National Low-Carbon Strategy (SNBC2 [2]), have set themselves a target of carbon neutrality by 2050, while supporting a competitive, clean and circular economy.

Achieving these objectives requires the implementation of a portfolio of solutions to reduce greenhouse gas emissions, including energy efficiency, the development of renewable energies... and CO_2 capture, utilisation and storage (CCUS). The CO_2 capture and storage (CCS) involves capturing it at the source of production and storing it permanently in underground geological formations to isolate it from the atmosphere (fig. 1). In the International Energy Agency's (IEA) "Sustainable Development" scenario, CCUS would help to avoid CO_2 emissions of emissions by 850 Mt/year in 2030, 5 Gt/year in 2050, and 10 Gt/year in 2070, which in the latter case would correspond to almost 15% of the cumulative reduction in emissions [3].

This technology is being considered as a means of decarbonising the energy and power generation sectors, as well as the industrial sector, particularly cement, iron and steel production, and the chemical industry. For these heavy infrastructures, which are generally designed to operate for at least thirty to forty years, CCUS offers the advantage of being able to be implemented without the need to completely replace industrial installations or upgrade the entire energy distribution network. In addition, a large proportion of the emissions from these industries are 'difficult to reduce', because they result from chemical reactions that are inherent in the production process (in cement manufacture, for example), or are associated with a need for high-temperature heat (currently supplied almost exclusively by the combustion of fossil fuels). CCUS is therefore the only solution to date for reducing these emissions. In addition, this technology makes it possible to produce, at reasonable cost, some of the hydrogen needed to decarbonise certain sectors, such as long-distance transport, the chemical industry and iron and steel production. Lastly, CCUS provides solutions for removing carbon from the atmosphere and thus offsetting the CO_2 emissions of certain sectors, such as transport and agriculture.

Of course, for this technique to have an effect on the climate, it needs to be able to be deployed on a very large scale. That's where the current developments come in.

Capture-storage and use of CO_2

CCUS is a mature technology that has been used in industry for decades. Worldwide, around 40 Mt of CO_2 are currently being captured each year, and by 2021 there will be 135 large-scale projects: 27 in operation, 2 suspended, 4 under construction, 58 in the advanced development stage and 44 in the preliminary development stage (fig. 2).

Today, the value chain is based on CO_2 capture by the emitting industry

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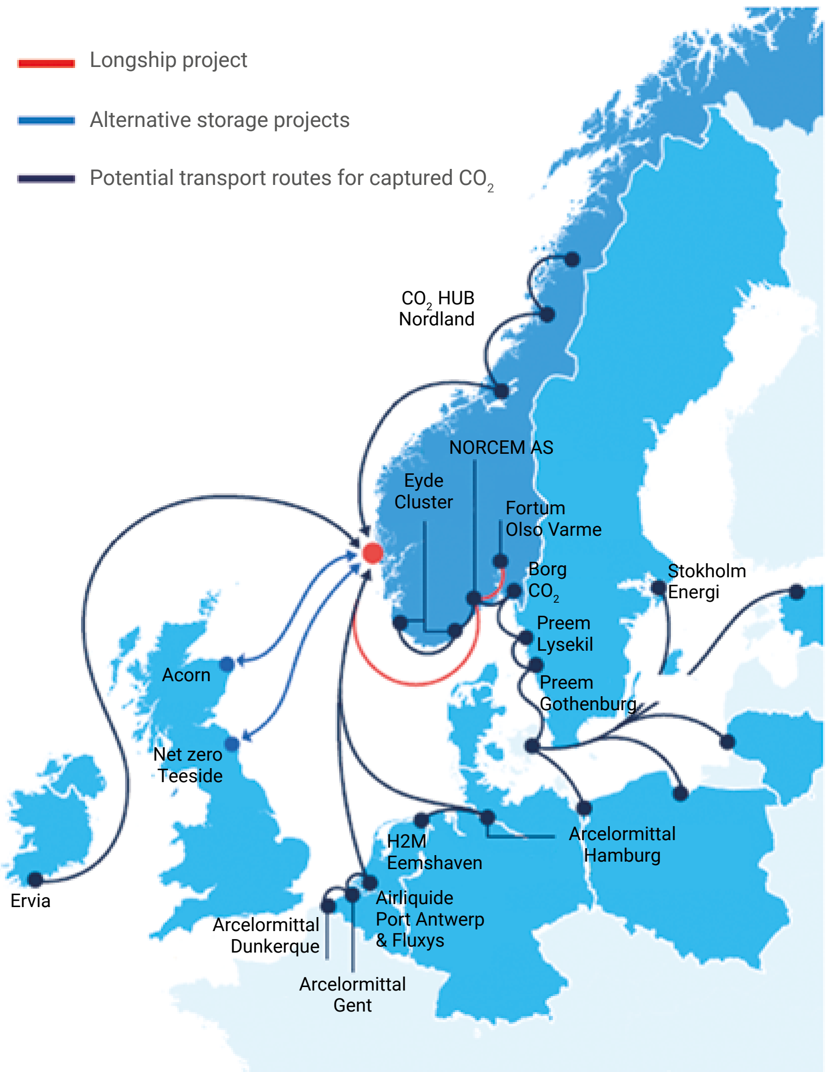

3. The Northern Lights project in the North Sea.
●: Catchment sites. ●: Alternative storage sites. ●: Storage site in Norway.
(Source : *Global Status of CCS 2020*, The Global CCS Institute).

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and a shared infrastructure for transporting and storing CO_2, enabling economies of scale to be achieved. One of the most advanced projects in Europe is the Longship/Northern Lights infrastructure, developed by Equinor, Shell and Total, which is due to come on stream in 2024 with an initial storage capacity of 1.5 Mt CO_2/year, which could be increased to 5 Mt/year at a later date (fig. 3).

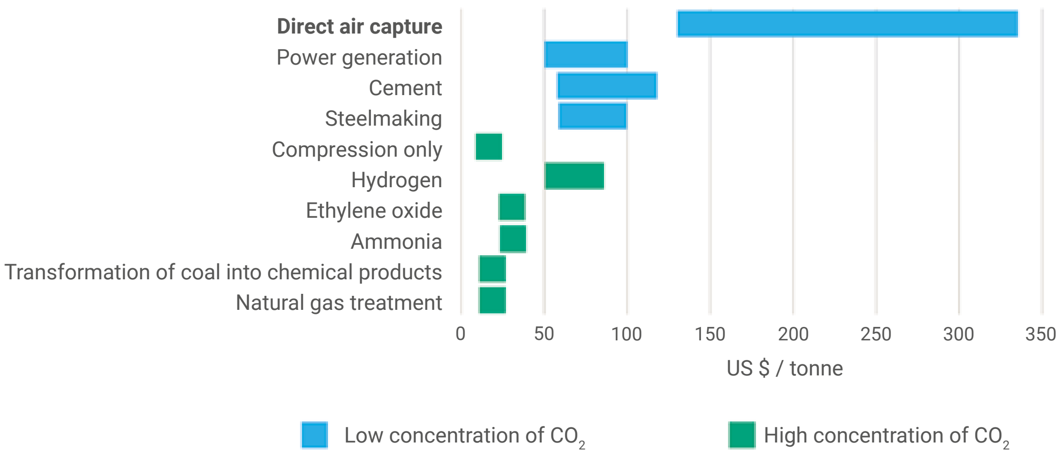
CO_2 capture

Capturing CO_2 involves separating it from the smoke emitted by industry and the energy sector, by adding a specific separation unit to an industrial installation and/or by modifying existing industrial processes. CO_2 is extracted in gaseous or liquid form, mixed with other gaseous species that are generally in a very small minority. After separation, the CO_2 stream may need to be purified and then compressed for transport.

There are three main approaches [4] to capturing CO_2, which can be combined to create hybrid methods.

1 - **Post-combustion capture** consists of extracting it from the flue gases, which contain mainly nitrogen (since combustion takes place in air), oxygen, water, nitrogen oxides (NO_x) and sulphur oxides (SO_x)... The most commonly used capture process is an absorption process: the CO_2 is extracted from the combustion fumes using a solvent, generally amine-based, which has an affinity for the CO_2 molecules. The CO_2 captured by the solvent is then separated from the solvent by thermal regeneration. While solvent capture is the most mature process, other technologies are being developed, such as calcium cycle capture (capture of CO_2 by quicklime to produce limestone which, once heated, releases the CO_2), cryogenics (solidification of the CO_2 by icing), membranary separation or contact with a solid adsorbent. Post-combustion processes generate a stream of CO_2 with a concentration generally greater than 99%, with the flue gases released into the atmosphere containing mainly nitrogen, water and oxygen.
In addition to its maturity, post-combustion capture has the advantage of being able to be implemented on existing installations without requiring major modifications, as long as the space required to install the equipment is available. It can also be applied to the treatment of flue gases from various industries (power stations, steelworks, cement works, etc.). On the other hand, this type of process has a high energy penalty and therefore a high implementation cost.

2 - **Oxycombustion capture** involves combustion in the presence of (almost) pure oxygen rather than air, producing a gas made up almost exclusively of water vapour and CO_2, which is easy to extract. Part of the combustion gas is recycled to the combustion chamber, while the rest is dehydrated to obtain a high-purity CO_2 stream.
Oxygen is generally produced by air separation (cryogenic distillation or membrane separation), but this technology requires high energy consumption. A second option is to supply oxygen in the form of metal oxides, which will rotate in a loop between an oxidation reactor and a reduction reactor. In the "*air*" reactor, the material is oxidised in contact with the air, transporting the oxygen; in the "*fuel*" reactor, the material is reduced in contact with the fuel, giving up its oxygen. This solution, known as "chemical loop *combustion*", has virtually no energy penalty for oxygen production, but is still in the development phase.



4. Cost of CO_2 capture by sector, including CO_2 compression
"Energy Technology Perspectives 2020, Special Report on Carbon Capture Utilisation and Storage", IEA (2020). www.iea.org/reports/ccus-in-clean-energy-transitions

3 - Finally, **pre-combustion capture** consists of extracting the CO_2 upstream of combustion, by transforming the initial fuel by partial oxidation into a H_2 + CO mixture which is treated to increase hydrogen production. Once the CO_2 has been extracted using a post-combustion process, the hydrogen is burnt in an appropriate thermal plant, which releases only water into the atmosphere. As the synthesis gas is produced under pressure, the CO_2 can be separated using a physical solvent (methanol, for example), without the need for heat to desorb the acid gases.

CO_2 capture is generally the most expensive stage in the capture and storage value chain, due to the investment costs and energy requirements of the processes. Of course, the benefit of implementing a CO_2 capture process at an installation is quantified not in terms of CO_2 captured , but in terms of "CO_2 avoided", i.e. including the additional emissions resulting from the implementation of CO_2 capture.

The cost of CO_2 capture is estimated at between €10 and €130 per tonne of CO_2 avoided. They depend heavily on the characteristics of the industrial process under consideration (CO_2 concentration, pressure, flue gas composition, etc.), energy consumption and the financial assumptions made (Fig. 4). As well as separating the CO_2 from the flue gas, the capture stage includes conditioning the CO_2, which must be compressed for transport. Given the low level of deployment of the technology, there is still a great deal of uncertainty surrounding these costs. They are highly sensitive to a number of underlying assumptions, such as the composition of the gases treated, the purity of the CO_2 captured, the capture process used, the lifespan of the installations, the price of natural gas or electricity, and the discount rate...

The cost of CO_2 capture can in fact represent up to 70% of the total cost of the CCS chain, with transport and storage each accounting for around 15%. Against this backdrop, the challenges for research and innovation lie in developing high-performance, low-cost technologies. The aim is thus not only to carry out incremental research with a view to optimising existing technologies, gaining in maturity and enabling economies of scale and learning, but also to prepare new-generation capture processes, making it possible to significantly reduce costs.

Transporting CO_2

There are no major technological obstacles to transporting CO_2. It is already practised on an industrial scale by ship and gas pipeline. Gas is transported by pipeline in the supercritical phase (pressure in excess of 74 bar) or liquid phase (10 bar, -40°C), and by ship in the liquid phase at moderate pressure and low temperature (7 bar and -50°C, for example).

Transport costs depend on the volumes of CO_2 transported, the distance travelled, the diameter of the pipeline and the size of the vessels. The costs associated with transporting gas by pipeline are mainly determined by CAPEX (capital investment expenditure) and are approximately proportional to the distance covered. They are very sensitive to the amount of CO_2 transported. Those associated with transport by ship are less dependent on distance but, below a certain distance, transport by ship is no longer economically viable.

The challenge for CO_2 transport is more of a logistical nature, although, particularly in the case of pipeline transport, innovations may be needed to detect and remediate any leaks. The transport network needs to be mapped, developed and optimised according to the location of capture facilities in relation to storage sites.

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CO_2 storage

Geological storage of CO_2 must be safe and permanent, thanks to natural trapping phenomena. Reservoirs of CO_2 several million years old exist underground, demonstrating that certain natural formations are capable of storing it safely and effectively over very long periods. However, CO_2 cannot be injected just anywhere underground. Its storage (fig. 1) is envisaged mainly in two types of formations, *onshore* and *offshore*:

(a) depleted oil or gas reservoirs, the properties of which are well known as a result of oil exploration and production, even if studies are required to confirm the properties of the reservoir and its cover at the end of production ;

(b) deep saline aquifers, which offer greater storage potential but are generally less well known.

The selection of a CO_2 storage site depends on a number of criteria:

- a depth of more than 800 m, in order to reach temperature and pressure conditions (greater than 31°C and 754 bar respectively) in which the CO_2 is in a supercritical state, thereby maximising the quantity stored;
- porosity and permeability of the reservoir rock, allowing sufficient storage capacity;
- the presence of an impermeable rock cover (clay, salt, etc.) preventing CO_2 from rising;
- the presence of trap structures, controlling the lateral migration of CO_2;
- the absence of drinking water or, more generally, any potential conflict with other possible uses of the subsoil.

While the overall capacity for underground CO_2 storage worldwide remains uncertain, particularly for deep saline aquifers, the availability of geological formations suitable for storage is not a barrier to the development of the sector. Total global storage capacity is estimated at between 8,000 and 55,000 Gt (gigatonnes), while the amount of CO_2 to be stored is around 220 Gt over the period 2020-2070. However, most of this capacity (between 6,000 and 42,000 Gt) is located *onshore*, and CO_2 storage is therefore encountering problems of social acceptability in some countries. *Offshore* storage is limited to geological formations located less than 300 kilometres from the coast, at water depths of less than 300 metres, and excluding the Arctic and Antarctic, storage capacity is estimated at between 2,000 and 13,000 Gt [5].

Reservoir rocks are usually filled with brine. The CO_2 is therefore injected into the geological formation at a pressure significantly higher than that of the reservoir, so as to push the fluid back into place. Geomechanical studies are used to identify the maximum pressure that must not be exceeded to avoid damaging the formation. CO_2 injection can also be affected by chemical processes. Depending on the reservoir rock, the composition of the fluids in place and the pressure and temperature conditions, mineral dissolution or precipitation reactions can occur, particularly in the vicinity of the injection well, affecting the porosity of the rock and the ability of the CO_2 to flow. Dissolution of carbonates can increase the porosity of the rock, while precipitation of carbonate minerals can cement the formation around the well. Reservoir engineering studies, coupled with geochemical analyses, are therefore needed to manage injection rates, in order to anticipate these complex interaction phenomena and avoid any phenomenon likely to reduce the quantities of CO_2 that can be injected.

The costs of CO_2 storage are estimated at between €1 and €20/t CO_2 [6]; they vary according to the rate of CO_2 injection and the characteristics of the storage reservoirs, as well as the location of the storage sites. *Onshore* storage is less expensive than *offshore* storage, and storage in depleted oil and gas fields is *a priori* less expensive than in deep saline aquifers. The cost of developing new sites remains uncertain, however, and is likely to be a major factor in the deployment of CCS in certain regions over the coming decades.

Beyond demonstrating the feasibility of massive storage in deep saline aquifers, the main challenge lies in ensuring that storage projects, particularly *on shore ones*, are acceptable to society. The deployment of this technology also requires the rapid introduction of incentive regulations to encourage the emergence of a market for CO_2 and offset the extra cost of CCS, border mechanisms to keep industries competitive, and a legal framework authorising the cross-border transport of CO_2.

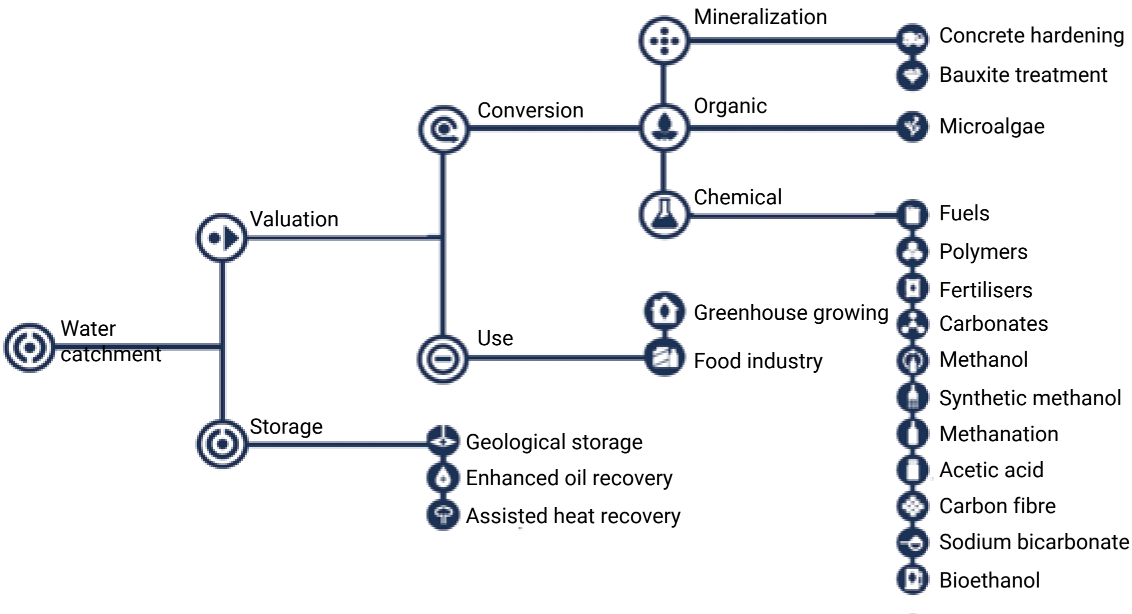
Beyond CO_2 capture and storage

CO_2 use and conversion

Rather than being permanently stored underground, CO_2 can also be considered as a resource that can be used directly or converted into a product (CCU, Carbon Capture and Utilization). According to the IEA [7], around 230 Mt of CO_2 are used every year in the world, the biggest consumer being the fertiliser industry (130 Mt of CO_2 used in the manufacture of urea), followed by oil exploration (70 to 80 Mt of CO_2 used for enhanced oil recovery). While most commercial applications today are associated with the direct use of CO_2, value-adding processes involving the chemical and biological conversion of CO_2 into chemical products and construction materials in particular are being developed (fig. 5).

The future market potential for these products is difficult to assess because of the slow development, or even lack of maturity, of the technologies, the high need for hydrogen or low-carbon electricity whose direct use for other applications could be more profitable, and uncertainties over regulatory aspects. The volume of conversion of CO_2 into a given product must also be analysed, in view of the risk of flooding the market and destroying any value of the product resulting from this conversion.

However, the use of CO_2 can only be an instrument in the fight against climate change if it allows it to be stored in the product resulting from the transformation. This is the case with the production of building materials from CO_2 and minerals or



5. Main ways of recovering CO_2
"Global Status of CCS", GCCSI 2019. https://cutt.ly/globalccsinstitute-status-of-ccs-report-2019

waste: using CO_2 in the manufacture of concrete also improves the performance and durability of the material. On the other hand, converting it into fuel would immediately re-emit the CO_2 used. These approaches are therefore considered as possible complements, not alternatives, to CO_2 storage, with a view to reducingCO_2 emissions on a large scale. In the IEA scenario, of the 10 Gt of CO_2 captured in 2070, more than 90% is stored; 8% is used, mainly to produce fuels.

Negative emissions

Finally, CCS technologies can not only reduce CO_2 emissions, but also remove CO_2 from the atmosphere. This is the case with bioenergy with CCS (BECCS): the substitution of biomass in an industrial process for a raw material or energy of fossil origin, combined with capturing the CO_2 produced by combustion and storing it in geological reservoirs, is a way of reducing the amount of CO_2 in the atmosphere. In addition, work is underway to develop Direct Air Capture (DAC) processes, with the first pilots already underway.

These technologies are now appearing in all the sustainable development scenarios to offset CO_2 emissions in sectors where it is difficult to reduce them. In the IEA's "Sustainable Development" scenario, BECCS accounts for 45 Mt of CO_2 between 2030 and 2070, and DAC for 2.8 Mt of CO_2. The term "negative emissions" is used to illustrate the fact that these technologies remove CO_2 from the atmosphere.

CO_2 capture, storage and utilisation in France

CCS is a building block in the portfolio of technologies identified in the national low-carbon strategy for reducing CO_2 emissions, with a CCS-related reduction target of 15 Mt CO_2/year , including 5 Mt CO_2/year in the industrial sector from 2030 and 10 Mt CO_2/year associated with BECCS. The French Environment and Energy Management Agency (ADEME) [8] has estimated the potential for CO_2 capture and storage at 24 Mt CO_2/year based on 2017 emissions, taking into account the technical and economic feasibility of CCS. Of the chain, the availability of transport infrastructure and societal opposition to *onshore* storage. This potential is driven by three regions: Hauts-de-France (15 Mt CO_2/year, with storage in the North Sea off Dunkirk), Normandy (6 Mt CO_2/year with storage in the North Sea off Dunkirk) and New Aquitaine (3 Mt CO_2/year with storage in old gas reservoirs). Facilities for collecting the captured CO_2 and transporting it are being studied in these three regions. One of the obstacles to the deployment of this technology will be the availability of operational storage sites in the very short term. While there is capacity to store emitted CO_2 in France and Europe, in practice the storage projects currently under advanced development are insufficient to store the volumes of CO_2 that industrial emitters have announced they want to capture by 2030.

Conclusion

CO_2 capture and storage is one of the technologies needed to combat global warming. Without it, it will be impossible to achieve carbon neutrality by 2050. The challenge now is to create the conditions that will enable large-scale deployment from 2030: efficient and economically viable capture technologies, infrastructures for transporting CO_2 and storage sites that are accessible to

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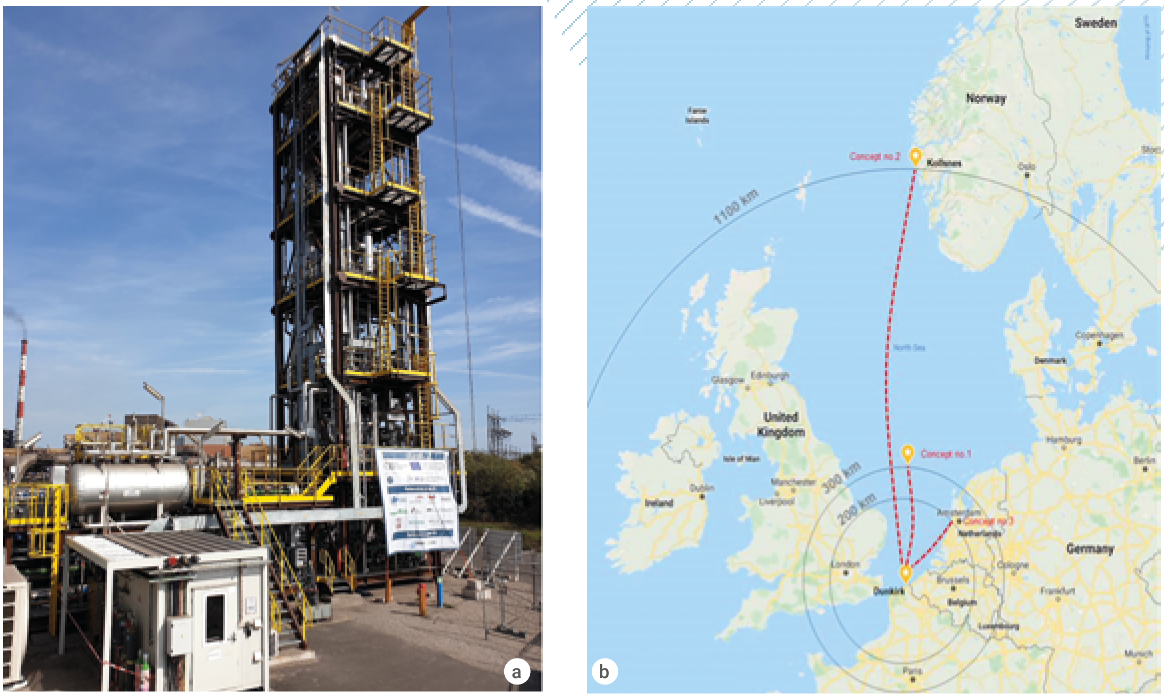
➲ THE 3D PROJECT "DMX™ DEMONSTRATION IN DUNKIRK"



E1. 3D project.
(a) DMX process demonstrator in Dunkirk.
(b) The future European Dunkirk-North Sea CO_2 capture and storage hub on an industrial scale (https://3d-ccus.com/). The CO_2 captured at Dunkirk will be transported by pipeline or ship to three deep saline aquifer storage sites in the North Sea (fig. E1): off the south-east coast of England (300 km), at Kollsnes near Bergen in Norway (transport by ship only), or near the west coast of the Netherlands.

Launched in May 2019, the "3D" project ("DMX Demonstration in Dunkirk") is part of the European Union's Horizon 2020 research and innovation programme. Coordinated by IFPEN, it brings together ten other partners from research and industry, from six European countries: ArcelorMittal, Axens, Total Energies, ACP, Brevik Engineering, CMI, DTU, Gassco, RWTH, Uetikon.

This project has a threefold objective. The first is to demonstrate, on an industrial pilot scale, the performance of a CO_2 capture process developed by IFPEN. This process, using a DMX™ solvent, is more efficient than reference processes using amines, which consume a lot of energy to regenerate the solvent. The IFPEN solution is based on a solvent with a very high cyclic capacity that decants into two phases, with only the phase that is richer in CO_2 being regenerated. The chemical stability of the DMX™ solvent also enables this regeneration to be carried out at temperature and therefore CO_2 to be produced at pressure, resulting in a saving of two compression stages compared with conventional processes. Finally, thanks to the recovery of the heat produced on the ArcelorMittal site, this process should enable a significant reduction in the total cost of capture.

The pilot plant for demonstrating the process, designed by Axens (fig. E1a), was built in 2021.

It has now been installed at the ArcelorMittal steelworks in Dunkirk and was inaugurated on 21 March 2022. Its capacity is 0.5 t CO_2 captured per hour. At the end of the "3D" project, in 2023, this process will be marketed by Axens.

The second objective of the 3D project is to prepare the setting up of an initial industrial unit on the ArcelorMittal site in Dunkirk, which could be operational from 2026. This unit should capture more than 125 tonnes of CO_2 per hour, or more than 1 Mt (million tonnes) of CO_2 per year.

Finally, the "3D" project is part of a more global ambition, that of developing a future European CO_2 capture and storage hub at Dunkirk-North Sea (fig. E1b). The third objective is therefore to design this future centre, which could capture, condition, transport and store 10 Mt of CO_2 per year, and which would come into being by 2035. This hub would be based on the conditioning and transport infrastructures for CO_2 storage in the North Sea, which have been put in place *through* other projects. Pipeline and ship transport solutions are being studied, taking into account the CO_2 compression required for pipeline transport, pipeline dimensions, logistics (size and number of ships) and intermediate storage requirements.

DIRECT AIR CAPTURE

Box 2

Direct Air Capture (DAC) refers to technologies that separate CO_2 from the atmosphere. Coupled with a stockage of CO_2 in geological formations (direct capture and storage of carbon in the air - DACCS), it makes it possible to generate negative emissions. This solution is used in transition scenarios towards carbon neutrality to offset CO_2 emissions from certain sectors, such as agriculture, which are sometimes at very high levels. Compared with negative emission solutions such as reforestation or soil carbon storage, DACCS has the advantage of not requiring a large amount of water and arable land, and ensures a lasting reduction in the amount of CO_2 in the atmosphere. What's more, the modularity of the DAC means that it can be deployed easily and relatively quickly.
Current processes require large fans that carry ambient air through a filter where a chemical captures the CO_2, which is then released and collected for treatment. Current technologies use either a liquid sorbent (Carbon Engineering) or a solid adsorbent (Climeworks and Global Thermostat) to separate the CO_2 from the atmosphere.
The major stumbling block lies in the very low concentration of CO_2 in the air - 0.04%, around 300 times lower than in industrial combustion gases - which significantly increases energy requirements and the associated costs. The costs of the first projects are estimated at between €400 and €700/t CO_2 and could fall to €200/t CO_2*. However, given the lack of large-scale units to date, the uncertainties are considerable.
The advantage of this technology, compared with capturing CO_2 from industrial flue gases, lies in the possibility of installing the capture unit next to a storage area, thereby limiting transport and the associated costs. This is the case with the Orca project in Iceland, which takes advantage of the availability of a storage site close to abundant geothermal renewable energy. Inaugurated in September 2021 by the Swiss company Climeworks, Orca is currently the largest direct capture plant in the world (see photo, p. 76). It is expected to capture 4,000 tonnes of CO_2 per year. The plant is equipped with twelve fans that mix the ambient air and suck it in, bringing it into contact with chemical solvents that capture the CO_2. This is then filtered, heated to around 100°C to separate it from the air, and recovered in concentrated form. The CO_2 is then dissolved in water and injected into basaltic rock at a depth of around 1 km using a process developed by Carbfix. The CO_2 reacts with the minerals in the basalt and turns to stone in a few years. To finance the operations, Climeworks offers companies and individuals the opportunity to offset some of their CO_2 emissions by buying captured CO_2 for around €500/t CO_2. More than 8,000 customers, including Microsoft (investor and customer), Shopify, The Economist Group and Swiss Re, have already signed up to the scheme.
There are currently fifteen DAC plants in operation worldwide, with a total capacity of 11.3 kt CO_2/year. The CO_2 captured by these plants is either stored in geological formations or used in the food industry. However, various applications are currently being considered in demonstrators, such as the use of CO_2 for greenhouse fertilisation and the production of chemicals and fuel.

* "Global Assessment of Direct Air Capture Costs", IEAGHG Technical Report 2021-05 (2021) https://cutt.ly/ieaghg-report-global-assessment

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the various emitters. Financial and regulatory support mechanisms are also needed to accelerate the development of the industry. Over and above these technical and financial issues, the main obstacle to the deployment of CCS lies in the reluctance of civil society. There are many questions, including the risk of accidents or environmental damage, and the associated nuisance, real or imagined, which could affect the quality of life of local residents. The implementation of pilots and demonstrators is a crucial point for collective reflection (involving industry, academics, research institutes, representatives of civil society, etc.) and informed debate. ▮

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