Carbon capture: an uncertain outlook despite worldwide interest

28/01/2024

Summary

There is growing commercial, political and regulatory interest in CCS (Carbon Capture and Storage) technologies, which capture the CO_2 emitted by industry or thermal power stations. Manufacturers, who have long presented these solutions as an essential tool for reducing greenhouse gas emissions, are being joined by a growing number of governments and even international organisations such as the IEA and the IPCC.

In addition to the forty or so sites already operational, several hundred projects are under study, and the trend is accelerating. However, there are still major uncertainties surrounding the technical and, above all, financial feasibility of many of these projects. The scenarios for the actual deployment of CCS therefore vary considerably from one source to another. But even under the most optimistic assumptions, CCS will only bring about a very small reduction in CO_2 emissions: at best 550 million tonnes a year by 2030, or around 1.5% of global emissions, and this at the cost of building a large number of capture and transport infrastructures, particularly gas pipelines.

The cost of CCS varies greatly from one project to another, but remains high: from just under $20 per tonne in an ammonia or natural gas processing plant, to over $60 per tonne in a steelworks, cement works or thermal power plant. CCS is also very energy-intensive, causing a loss of efficiency of between 11% and 24% in thermal power stations. The financing of the CCS industry therefore remains heavily dependent on massive public subsidies and the marketing of emission quotas, where current prices are not sufficient for CCS to be self-financing.

As a result, investments to avoid CO_2 emissions - through development of low-carbon energies or electrification of industrial processes - often appear to be more effective than CCS. However, CCS remains the only technical solution for eliminating unavoidable carbon emissions, i.e. from industrial processes that require combustion or a chemical reaction that emits carbon dioxide.

Finally, the utilisation of captured CO_2 in various industrial processes (CCUS) offers interesting prospects for making capture more profitable. However, the two main current uses, urea production and hydrocarbon extraction optimisation, are still net emitters of CO_2. The possibility of producing synthetic fuels from CO_2 and hydrogen is fuelling the hopes of airlines and shipping companies, but this application will require large quantities of "green" hydrogen, and its cost remains high.

1. What is carbon capture and storage?

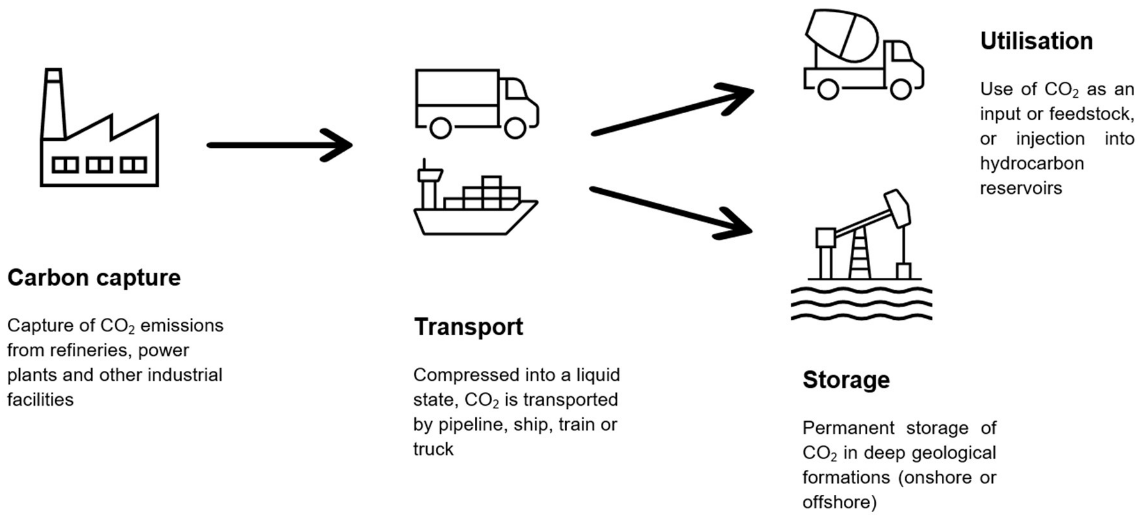
1.1. CCS, CCUS, *Direct Air Capture*: a few definitions

Presented as indispensable solutions for achieving climate objectives by allowing a net reduction in greenhouse gas emissions, CO capture and storage systems2 aim to **capture at source the carbon dioxide (CO_2) produced by the use of fossil fuels**, and present in the smoke released by industrial activities or power stations, in order to **prevent its release into the atmosphere**.

In the case of **CCS** (*carbon capture and storage*), the CO_2 is **sequestered in offshore or onshore subsoils** over very long periods (up to several thousand years).

CCUS (*carbon capture, utilisation and storage*) entails that the **captured CO_2 is reused**, for instance to optimise the recovery of gas or oil or to produce synthetic fuels, plastics, urea or other raw materials (see Chapter 3).

Figure 1: Stages in the CCS and CCUS processes



Source: Global Sovereign Advisory

While CCS (or CCUS) generally involves capturing CO_2 at source, some researchers and manufacturers are also looking to **remove CO_2 directly from the atmosphere**, thereby achieving negative emissions:

- Beyond afforestation, which consists of planting trees in areas that have long remained deforested, **bioenergy with carbon capture and storage** (BECCS) is a more sophisticated process, in that it aims to **extract the CO_2 captured by biomass in order to capture and store it**. When used as a fuel, this biomass releases carbon dioxide which, instead of being released into the atmosphere, is captured and stored along the lines of CCS.
- The use of **direct air capture** (DAC), which involves **filtering atmospheric air in order to extract the CO_2 directly from it**, is also growing. However, the CO_2 present in the air is 200 to 300 times less concentrated in the atmosphere than in flue gases, which complicates the process and significantly increases the costs of DAC.

1.2. A complex but well-known process

1.2.1 CO_2 separation and capture

The first step is to capture the CO_2 released by fuels during the combustion process. According to the IEA (International Energy Agency), current installations equipped with CCS and CCUS technologies are capable **of capturing up to 99% of the CO_2 present in the smoke emitted**[1]. There are several methods of capturing emissions, the main ones being **pre-combustion, post-combustion and oxy-combustion**.

- **Post-combustion involves capturing the CO_2 by separating it from the flue gases produced by combustion using a liquid chemical solvent**. Absorbing the emissions, the solvent binds with the CO_2. The solvent-CO_2 mixture is then heated in a regeneration tower, which separates them while regenerating the solvent. Well mastered, this technique is currently the most widely used, and has the advantage of being able to be applied to existing installations. However, it is costly to set up, and the process is extremely energy-intensive.

- **In pre-combustion**, **the CO_2 is removed from the fuel upstream of the combustion process**. To do this, the fuel is converted into a synthesis gas made up of hydrogen and carbon monoxide. By introducing water vapour into this gas mixture, the carbon monoxide is converted into CO_2, with the additional production of hydrogen. Once separated using a solvent, the CO_2 can be captured while the remaining hydrogen can produce energy without carbon emissions. Although less energy-intensive than post-combustion, this process is nevertheless very costly and **requires specific installations**, which need to be put in place as soon as the industrial site is designed.

- **Finally, oxy-combustion involves burning fossil fuels with pure oxygen, rather than with ambient air, to obtain fumes that are much more concentrated in CO_2** (around 90%). As a result, CO_2 is easier to separate from the water vapour with which it is mixed, and therefore easier to capture. The main obstacle to this technique is the cost of producing and transporting pure oxygen.

1.2.2 Compression and transport

Like other industrial gases, CO_2 can, once captured, be transported in a **gaseous or, more often, liquid state. In the latter case, the gas must be compressed to more than 80 bars**[2]. After this stage, the CO_2 is dehydrated and then sent to the transport system. Although **gas pipelines** are the most commonly used mode of transport, CO_2 can also be transported by train, ship or tanker.

1.2.3 Underground sequestration

In the case of CCS, **the CO_2 is injected into deep geological formations suitable for permanent storage**, generally at a depth of 1km or more. Several storage sites, both onshore and offshore, can be used: **deep saline aquifers**, **depleted hydrocarbon deposits**, **coal seams, etc.** Once introduced into the subsoil, the CO_2 is trapped there by chemical and geological processes: dissolution in rock brine, trapping in the rock, mineralisation, etc.

Some companies are also developing **oceanic storage**, i.e. injecting carbon dioxide into the oceans at a sufficient depth to minimise the environmental impact, such as Iceland's **Carbfix.** The company has demonstrated the feasibility of dissolving carbon dioxide in water and injecting it into deep basaltic formations to transform it into carbonate minerals[3] .

Once injected into geological formations, the CO_2 must be preserved there over the long term, for several hundred years. The subsoil must therefore be hermetically sealed to prevent any risk of escape, and geological formations must be monitored more closely (pressure in the formations, any leaks, etc.). While the

[1] IEA, Carbon Capture, Utilisation and Storage July 2023
[2] ADL Ventures, *Repurposing Natural Gas Lines: The CO2 Opportunity*, consulted on 20 January 2024
[3] Carbon Herald, *Aker And Carbfix Extend Partnership On CCS Project*, May 2023

watertightness of old hydrocarbon deposits has been proven (they have contained gas or oil for millions of years), it can be compromised by new drilling; as for saline aquifers, this is unknown in the long term[4] .

On a global scale, the subsoil suitable for storing CO_2 is much larger than what would be needed to achieve the climate objectives[5]. The countries that emit the most CO2 boast large storage areas; it is estimated that 2,000 and 20,000 billion tonnes of storage capacity are available in North America alone[6] , and 300 billion tonnes in Europe[7] . **The main obstacle to the development of CCS is less the availability of suitable areas than the ability of governments and industry to develop this sector at a controlled cost**.

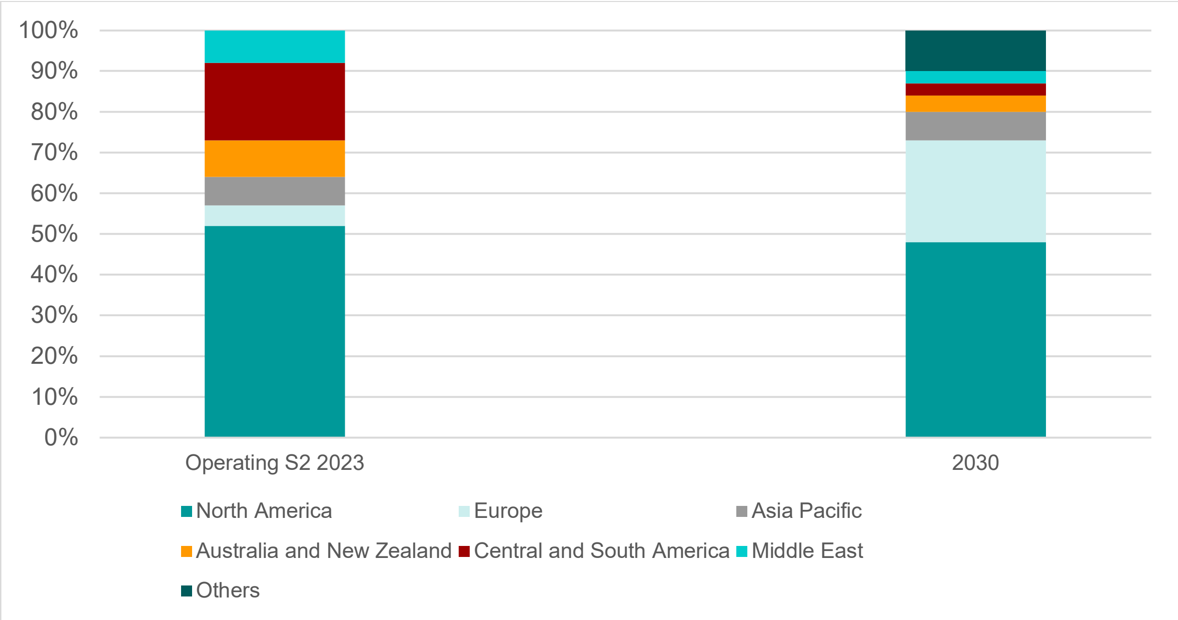
2. Strong growth but an uncertain outlook

2.1. Despite exponential growth, the sector has yet to be built up

The development of the CCS sector is exponential and the number of projects has increased significantly in 2023. **198 new projects were added to the global project pipeline last year, an increase of 102%[8] . In July 2023, out of a total of 392 commercial installations worldwide, 41 were operational** (11 more than in 2022)**, 26 were under construction and 325 were under development (including 121 at the advanced development stage)**[9] .

14 of these operational facilities were in the United States, the first of which, Occidental Terrell, was set up in 1972. The second country is China, with 11 operational sites, all of which will start operating in 2021[10] , followed by Canada. In China, however, these have mainly been demonstrators or small units, so that the United States and Canada very largely dominate world capacity, with 52% of the total (Figure 2).

Graphs 2: operational and forecast capture capacity of CCS installations by region (second quarter 2023 and 2030) (in %)

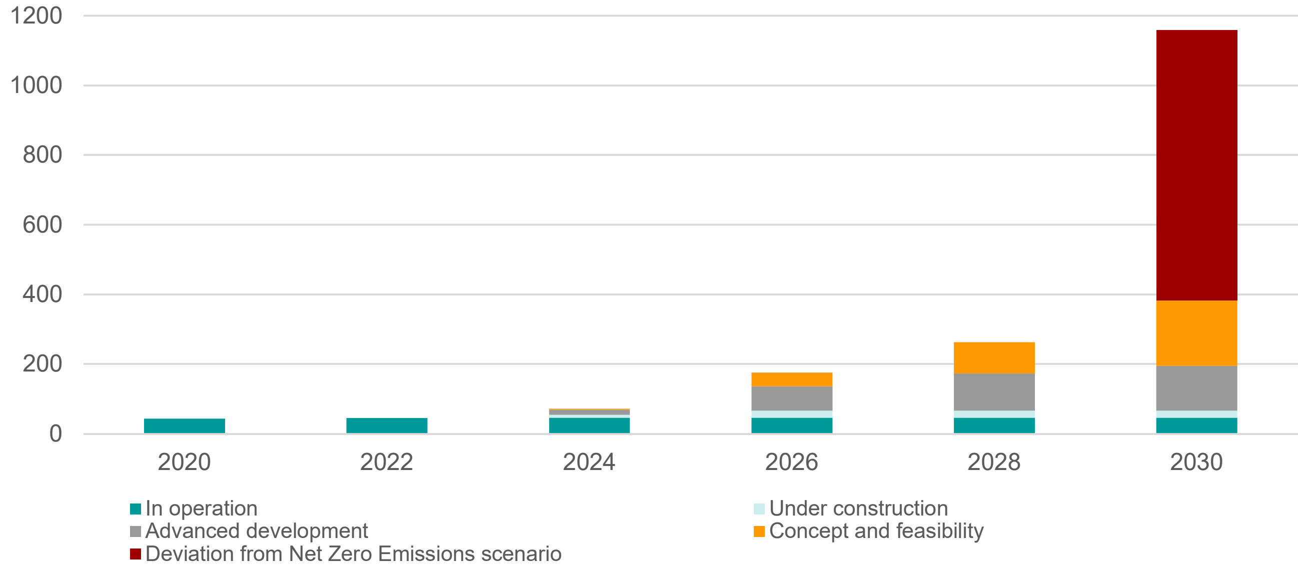


Source: IEA

[4] Polytechnique insights, *Limiting climate change by capturing CO2: dream or reality*, January 2023
[5] Global CCS Institute, *Geological storage of CO_2 : safe, permanent, and abundant*, 2018
[6] *Ditto*
[7] The Conversation, *Carbon capture and storage: how it works*, October 2022
[8] Global CCS Institute, *Global Status of CCS 2023*, 2023
[9] LSE, *What is carbon capture, usage and storage (CCUS) and what role can it play in tackling climate change*, March 2023
[10] Global CCS Institute, *Global Status of CCS 2023*, 2023

However, growth in actual CO_2 capture capacity seems more limited: **at 46 million tonnes per year expected in 2024 according to the IEA, it has barely increased since 2020** (43 million tonnes). And while the cumulative capacity of all CCS projects under development has increased by 48% in one year, to 361 million tonnes per year in July 2023, this **projected growth is subject to considerable uncertainty**: the vast majority of projects, still in the design or advanced development phase, have not yet passed the critical stage of the final investment decision[11], and **may therefore never materialise**.

Figure 3: Capacity of CCS projects in operation and under development, compared with the requirements of the Net Zero Emissions scenario (Mtpa CO_2) (2020-2030)



Source: IEA

2.2. Growth driven by key projects

Most CCS projects, including the most successful, are being carried out in the United States, Canada, Northern Europe, Australia and China. Their characteristics, as well as their capture capacities, vary widely.

One of the largest carbon capture facilities currently in operation is in **Brazil**: the oil platforms operated by **Petrobras** in the pre-salt Santos basin, equipped with CCUS technologies, are estimated to have reinjected almost 10.6 Mt of CO_2 in 2022[12], used to optimise oil production (see chapter 3). A total of 40.8 Mt/CO_2 has been injected since the start of operations.

Other ambitious projects are currently under development. In **the Gulf,** the cumulative capture capacity of projects under development is expected to be 19.5 Mtpa of CO_2. With its CCS project in the industrial city of Jubail, Saudi energy giant **Aramco expects to** capture and store **9 Mtpa** when it comes on stream in 2027[13]. In Asia, **Japan**, in line with its CCS roadmap, has announced its support for seven projects for feasibility studies; the projects should make it possible to store 13 Mtpa CO_2[14].

In **Europe**, projects in the North Sea are multiplying, while construction of the continent's largest CCS facility is due to start in 2024 in the **Netherlands**: the *Porthos* project, with a capture capacity of 2.5 Mtpa, will store emissions from the Rotterdam port area in a depleted gas field in the North Sea from 2027[15] . **Norway**, whose first CCS installation on the **Sleipner** gas field dates back to 1996, is developing a number of projects. *Northern*

[11] IEA, Carbon Capture, Utilisation and Storage, July 2023
[12] Carbon Credit Markets, *Petrobras breaks annual record in CO2 capture, use and storage*, February 2023
[13] MEES, *Saudi Aramco Plans First Phase CCS For 2027*, June 2023
[14] Global CCS Institute, *Global Status of CCS 2023*, 2023
[15] Offshore Technology, *First CCS project in the Netehrlands launched*, October 2023

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Lights, in particular, is set to be the largest CO_2 transport and storage infrastructure in Europe**,** as well as the **first cross-border CCS network in the world**. In practical terms, it will be open to all industries wishing to decarbonise their activities and store their CO_2. *Northern Lights* has signed a commercial agreement with Dutch fertiliser manufacturer **Yara** to capture 800,000 tonnes of CO_2 in the Netherlands, transport it and store it at a depth of 2,600 metres from 2025[16]. *Northern Lights*, a 50/50 joint venture between **Equinor**, **Shell** and **TotalEnergies**, and implemented mainly by **Air Liquide**, is due to come on stream in 2024. The first phase of the project is expected to store up to 1.5 Mtpa of CO_2, with capacity to be increased to 5 Mtpa by 2026[17] .

The proliferation of projects in Europe will enable the Old Continent to significantly increase its carbon capture capacity between now and 2030. **While its installations accounted for just 5% of global capacity in the second quarter of 2023, Europe will have 25% by 2030** (Figure 2). **North America, the CCS pioneer, will maintain its hegemony**: while the capture capacity of the United States and Canada represented 52% of global capacity in the second quarter of 2023, this share will remain at 48% in 2030. Finally, sub-Saharan Africa is still the big absentee.

2.3. Stimulating government policies to accelerate investment

This rapid growth in CCUS projects can be explained by **the growing political support for CCS, which reached an all-time high in 2023[18]** . Long ignored by public policy, the deployment of these technologies is now being accompanied by renewed political attention and the introduction of incentive-based legislative and regulatory frameworks.

In the United States, ***the Inflation Reduction Act* (IRA) adopted in 2022 contains strong incentives for the deployment of CCS installations, through tax credits** (see Chapter 5)[19] . The provisions of the IRA, which should encourage the deployment of these technologies, could **increase US CO capture capacity$_2$ from 200 to 250 Mtpa by 2030**[20] . The 2021 bipartisan infrastructure plan also calls for USD 8.2 billion in government funding for CCS programmes between 2022 and 2026, compared with USD 5.3 billion for research in this area between 2011 and 2023[21] .

In Europe, the objective of reducing greenhouse gas (GHG) emissions by at least 55% by 2030 encourages the deployment of carbon capture, which was included in the European **Green Deal** of 2020. The **Net Zero Industry Act** (NZIA), proposed by the European Commission and approved by the European Council in December 2023, also devotes considerable space to CCS technologies, setting a storage target of 50 Mtpa of CO_2 by 2030[22]. European projects are also supported by the **Innovation Fund**, dedicated to decarbonisation technologies and financed by **the auctioning of carbon quotas**; for example, the "K6" CCS project led by **Air Liquide** and **Eqiom** in the Hauts-de-France region has benefited from this funding[23]. At national level, many European Union Member States have also included CCS in their climate policies; **France**[24] and **Germany**[25] have recently committed to developing carbon management strategies.

In the **UK,** Chancellor **Jeremy Hunt** announced in his *Autumn Statement* in November 2023 that £960 million ($1.2 billion) would be made available for a new programme to accelerate the growth of green industries. This programme, which will focus in particular on the deployment of CCUS[26] , is in addition to existing funding aimed

[16] Yara, *Yara invests in CCS in Sluiskil and signs binding CO2 transport and storage agreement with Northern Lights - the world's first cross-border CCS-agreement in operation*, November 2023
[17] TotalEnergies, *Northern Lights, Norway's first major industrial-scale carbon capture and storage project*, January 2024
[18] Global CCS Institute, *Global Status of CCS 2023*, 2023
[19] Modern Power Systems, *IRA aims to give CCUS a boost, but will it take off?*, February 2023
[20] Global CCS Institute, *Global Status of CCS 2023*, 2023
[21] Congressional Budget Office, *Carbon Capture and Storage in the United States*, December 2023
[22] Clean Air Task Force, *EU moves closer to unlocking carbon capture and storage for industrial decarbonisation*, December 2023
[23] Air Liquide, *Le projet d'Air Liquide et EQIOM dans le nord de la France sélectionné par le Fonds européen d'innovation*, April 2022
[24] French National Industry Council, *CCUS Strategy. Carbon Capture, Storage and Utilization*, June 2023
[25] Energy Post, *Germany is developing a strategy for Carbon Capture and Storage to meet its 2045 net zero target*, February 2023
[26] Power Technology, *UK Autumn Statement: Chancellor pledges £960m for green industry*, November 2023

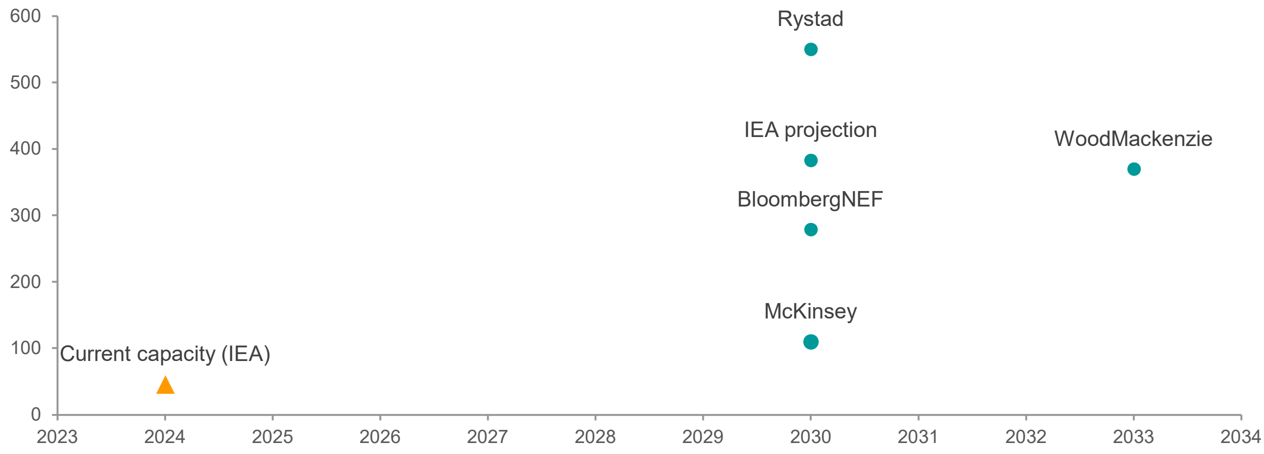
at encouraging oil and gas companies to use this technology[27], while London is targeting the capture of 20 to 30 Mtpa of CO_2 by 2030[28].

Other countries are developing regulations on CCS, such as **Australia**[29], **Indonesia**[30] and **China** (CCS is included in China's 14th five-year plan[31]). Some have also set ambitious carbon capture targets: **Japan**, which published a CCUS roadmap in January 2023[32], aims to store 240 Mtpa of CO_2 by 2050, compared with **Saudi Arabia'**s target of 44 Mtpa by 2035[33].

2.4. Widely divergent growth projections

The growing number of CCS projects, and announcements of political and financial support, mean that we can expect strong growth in capacity over the coming years. However, the **projections made by a number of major consultancies vary radically**, from 110 Mtpa CO_2 for **McKinsey** to 550 Mtpa for Norway's **Rystad Energy** (graph 4).

Figure 4: Projected global CO capture capacity$_2$ by 2030 (million tonnes/year)



Source: Global Sovereign Advisory

The IEA, which forecasts a total cumulative capacity of **383 Mtpa CO_2 in 2030**, nevertheless points out that only 20 Mtpa of additional capacity is actually under construction, with 129 Mtpa at the advanced development stage and 188 Mtpa at the concept and feasibility study stage[34] . **Even if they were all built, the cumulative capacity of this portfolio would only represent a third of the requirements of the IEA's Net Zero Emissions scenario, which calls for CCS capacity of 1159 Mtpa in 2030**[35] .

2.5. Little impact on global CO emissions $_2$

This wide gap highlights the limitations of CCS: even with massive investment and accelerated growth, it will play only a negligible role in achieving carbon neutrality. Even in the most optimistic development scenarios, carbon capture will account for only a very small proportion of total CO_2 emissions. In Rystad Energy's scenario, which assumes the capture of **550 Mtpa in 2030** (see above)**, carbon capture will only represent the equivalent of 1.5% of total emissions in 2022,** or 36.8 billion tonnes[36]. However, in the Net

[27] Le Monde de l'Energie, *Les technologies CCUS (capture, stockage et utilisation du carbone) sont indispensables pour atteindre la neutralité carbone*, December 2023
[28] UK Government, *CCUS Net Zero Investment Roadmap*, April 2023
[29] Norton Rose Fulbright, *Global carbon capture and storage regulations: A driver or barrier to CCS project development*, September 2023
[30] AIE, *Energy Minister Order No.2 2023 on the Utilisation of CCUS in Oil and Gas exploration*, June 2023
[31] Groupe d'études géopolitiques, La puissance écologique de la Chine : analyses, critiques, perspectives, *Le 14ème plan quinquennal dans la nouvelle phase de la réforme chinoise*, September 2021
[32] IEA, *CCS Long-Term Roadmap, Japan*, 2023
[33] Global CCS Institute, *Global Status of CCS 2023*, 2023
[34] IEA, Carbon Capture, Utilisation and Storage
[35] IEA, Carbon Capture, Utilisation and Storage
[36] IEA, *CO2 Emissions in 2022*, March 2023

Zero Emissions scenario, CO2 emissions are expected to fall by 42% in 2030, and to be totally eliminated by 2050.

According to the IEA, if oil and gas consumption evolves as forecast within current policy parameters, 32 billion tonnes of CO_2 will need to be captured by 2050 - a figure that seems out of reach. **CCS technologies would, under this scenario, require 26,000 terawatt hours of electricity generation to operate in 2050, which is more than total global electricity demand in 2022**[37] .

At this stage, the objectives of CCS appear to be out of reach and its impact on CO_2 emissions limited, especially as the sector is coming up against a number of obstacles. In addition to the uncertainties surrounding performance and financing (see chapter 5), projects may also be held back by questions of social acceptance. **Despite this, the rise in carbon prices on certain emission allowance markets, and above all the upward revision of climate targets by many governments, means that the use of CCS should increase, alongside other forms of reducing CO_2 emissions**.

2.6. Criticism is already mounting

Despite the enthusiasm shown for CCS by governments and many industrial companies - particularly the biggest emitters - there are still many reservations about the technology. For example, the IEA, which, in line with the IPCC[38] , sees it as an "indispensable" tool for achieving carbon neutrality, warned in a report published ahead of COP28 **against excessive expectations linked to the deployment of CCS and CCUS, stating that carbon capture must not be a means of maintaining the status quo**[39] .

The technologies are also the target of criticism from many environmental experts and organisations. For instance, the American *Center for International Environmental Law* (CIEL) points out that **most of the CO_2 captured is used to extract new fossil resources** (see chapter 3) and believes that the risks of CO_2 stored underground finding its way back into the atmosphere is not sufficiently taken into account[40] . Similarly, CO_2 reused to produce synthetic fuels will still ultimately be emitted into the atmosphere. Some taxpayers' associations are also pointing to the high cost to the public purse, generally for the benefit of oil groups, for an environmental benefit deemed questionable[41] .

2.7. The only remedy against “unavoidable CO_2” emissions

Despite the above-mentioned limitations of CCS, this technology could prove indispensable in a number of sectors: petrochemicals and refining, cement, steel, etc. While a number of industrial processes could be decarbonised by replacing thermal energy sources with electricity or green hydrogen, **certain stages are bound to generate carbon**, either because they **require combustion** (steel, glass) or because they **involve chemical reactions that emit CO_2** (cement). This is sometimes referred to as **"unavoidable CO_2”**. CCS will, in these cases, the only means of reducing CO_2 emissions.

3. What industrial uses can be made of captured carbon?

The IEA estimates **annual global consumption of CO_2** at an average of **230 million tonnes**, mainly for **urea** production **(around 130 million tonnes)** and **enhanced oil recovery (around 80 million tonnes).** Many other industries use CO_2 as an input, from the food industry (soft drinks, etc.) to metallurgy, and from cooling to chemicals. But these only account for around 10 to 12% of consumption. What's more, some of them need very pure streams[42], and so cannot use CO_2 from CCS processes, preferring CO_2 from biomass[43].

[37] IEA, Carbon Capture, Utilisation and Storage, July 2023
[38] Transitions & Energies, *Carbon capture, "inevitable" according to the IPCC*, December 2023
[39] IEA, *The Oil and Gas Industry in Net Zero Transitions*, November 2023
[40] Center for International Environmental Law, Deep Trouble -The Risk of Offshore Carbon Capture and Storage, November 2023
[41] Taxpayers for Common Sense, Carbon Capture and Storage, consulted on 25 January 2024
[42] National Energy Tecnology Laboratory (NETL), Commercial Carbon Dioxide Uses: Carbon Dioxide Enhanced Oil Recovery
[43] *NB: this estimate of global consumption is much higher than the 46 million tonnes or so captured by CCS each year, because it also includes CO_2 captured directly as part of industrial activities, particularly in the oil industry and urea manufacture.*

3.1. Urea: a closed-circuit process mastered by ammonia manufacturers

Urea, produced by combining ammonia and CO_2, is mainly used to produce fertilisers, but can also be used in the manufacture of animal feed, certain plastics processes, etc. Because of the high CO_2 content of emissions from ammonia plants, and the fact that ammonia and urea production are often co-located and operated by the same operator (fertiliser producer, for example), **this use of CO_2 is relatively inexpensive to implement** (see chapter 4).

But **urea production is not a net consumer of CO_2**: the carbon dioxide used comes directly from the production of ammonia, which in turn comes from the transformation of natural gas. In total, of the 500 million tonnes of CO_2 emitted in the manufacture of ammonia[44], only 130 million tonnes are absorbed in the production of urea. **This industry therefore does not absorb its own CO_2 emissions, and seems unlikely to absorb flows from other sectors**.

3.2. EOR: CO_2 used in oil extraction for a mixed carbon footprint

The other major outlet for captured CO_2 is *Enhanced* Oil Recovery (EOR). The **CO_2 is injected into the oil fields** where it dissolves the oil residue trapped in the rock, making it easier to pump. More recently, the process has been extended to gas production (*Enhanced Gas Recovery*, EGR), where the main purpose of injecting CO_2 is to increase reservoir pressure.

The process, which has been known for a long time, was initially based on local CO_2, escaping from the reservoir brought into production. But the growing extraction of shale oil and gas reserves has increased demand, prompting operators to turn to CO_2 from industry, which now accounts for around 30% of the gas consumed. **This use, which is highly developed in the United States, where it already accounts for 4% of total oil production[45], is also spreading rapidly in the Middle East and Europe**[46].

However, even if the CO_2 injected into the fields is considered to be permanently sequestered, **the process is still a net emitter**: according to the IEA, **oil extracted using EOR processes emits a total of only 37% less CO_2** than conventional oil[47] . In fact, according to the IEA, **0.3 tonnes of CO_2 must be injected to extract a barrel, but using the barrel releases around 0.51 tonnes of CO_2 into the atmosphere**.

The EOR is therefore being **fiercely criticised by environmental NGOs**, who are describing it as a "smokescreen"[48] , and even as a “co-optation” of environmental protection policies by the oil industry. In the United States, **oil companies can receive up to USD 60 per tonne of CO_2 sequestered** as part of their EOR processes[49], compared with USD 85 for simple sequestration. This is considerably more than the cost of purchasing a tonne of carbon, which is estimated at around 40% of the market price of a barrel of oil[50] .

3.3. Greenhouse farming, a little-known Dutch speciality

The last major outlet for CO_2 is greenhouse agriculture, where it is added to the atmosphere to accelerate plant growth by 25 to 30%. **The Netherlands is the undisputed champion of this process, where CO_2 consumption is estimated at between 5 and 6.3 million tonnes a year**[51] , and where 80% of greenhouse crops are grown using this method, at least since the 1990s[52] . However, this use is poorly quantified at global level. In the case of the Netherlands, the CO_2 used in greenhouses generally comes from greenhouse heating systems fuelled by natural gas. To replace this source with CO_2 captured in other industries, and thus achieve a net reduction in emissions, it will therefore also be necessary to supply decarbonised energy to heat the

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[44] Royal Society, Ammonia Policy Briefing, February 2020
[45] Washington Post, Companies capture a lot of CO2. Most of it is going into new oil, October 2023
[46] Energy Transition, Smokescreen for climate inaction: CCS starts to take off in Saudi Arabia and Europe, October 2023
[47] Clean Air Task Force, CO_2 EOR Yields a 37% Reduction in CO_2 Emitted Per Barrel of Oil Produced, 2019
[48] Energy Transition, Smokescreen for climate inaction: CCS starts to take off in Saudi Arabia and Europe, October 2023

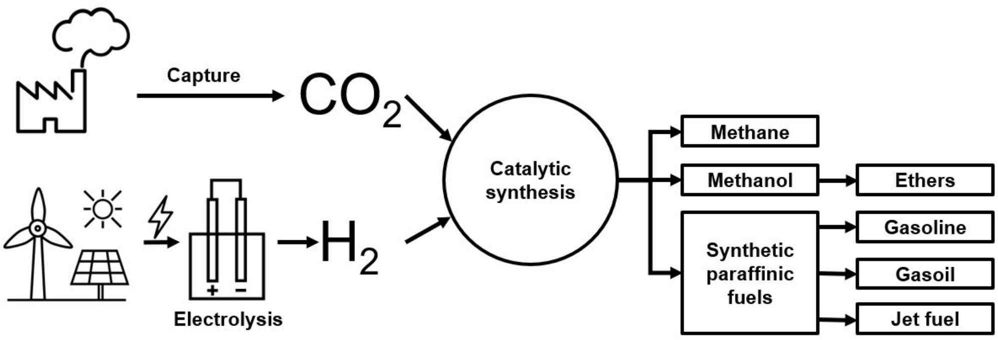
[49] Washington Post, Companies capture a lot of CO2. Most of it is going into new oil, October 2023
[50] Proceedings of the National Academy of Sciences, Infrastructure to enable deployment of carbon capture, utilization, and storage in the US, 2018
[51] IEA, Putting CO2 to Use - Creating Value From Emissions, September 2019
[52] Applied Plant Research, CO_2 in Greenhouse Horticulture, 1999

greenhouses. Furthermore, the carbon dioxide used is not sequestered: it is ultimately released into the atmosphere when the food produced is consumed.

3.4. Synthetic fuels, the hope of the aviation and maritime sectors

Faced with the impossibility of using electric batteries, and the complexity of deploying hydrogen, airlines and maritime charterers are pushing for the development of **fuels synthesised directly from CO_2**. Like the biofuels already partially adopted by these industries, these are compatible with existing distribution infrastructures, but they have the advantage of **not creating conflicts of use with agricultural production**[53].

Graph 5: Main synthesis routes for electrofuels



Source: e-fuels working group, EVOLEN Energies[54]

While the processes differ depending on the type of fuel required (methanol, petrol, kerosene, etc.), they all involve **combining carbon molecules with hydrogen** obtained by electrolysis, **using a catalytic synthesis process** (see also box). These are known as **electro-fuels**, or e-fuels. The development of e-fuels is largely concentrated in Europe, where the vast majority of the 18 projects listed worldwide by the eFuel Alliance[55] are located. In October 2023, the European Union adopted a regulation that aims to increase the share of synthetic fuels to 1.2% of aviation fuel consumption by 2030, rising to 35% by 2050[56] . Several major European shipping companies, including Maersk and CMA-CGM, are also interested in e-methanol.

Strong interdependence with green hydrogen

To be considered decarbonised, electrofuels must use **hydrogen** as a production input, **which itself must come from decarbonised sources**, mainly **electrolysis using renewable energies**.

However, this is still rare, and around three to six times more expensive than the 'grey' hydrogen produced by the oil industry[57]. What's more, many major "green" hydrogen production projects, requiring abundant wind or sunshine and low-cost land, are located in less industrialised regions (Mauritania, Namibia, southern Morocco, etc.)[58] far from readily-available CO_2 sources. This reality, coupled with the high cost of transporting both CO_2 and hydrogen, is likely to **limit the large-scale production of e-fuels to regions with both significant sources of CO_2 emissions and high potential for green hydrogen**.

Alongside e-fuels, companies such as **Lanzatech** in the UK have developed a process for **enzymatically converting CO_2 into ethanol**. Exhaust fumes are fermented in a vat by a **specially selected bacterium**. The main advantage of this process is that it does not necessarily require an external supply of hydrogen: if it is absent from the flues that are being treated, the bacteria are capable of producing it from water[59] . The ethanol

[53] IFP Energies nouvelles, Everything you need to know about synthetic fuels, September 2023
[54] Evolen Energies, Briefing note on electrofuels, February 2023
[55] eFuel Alliance, Selection of announced or already existing production sites, consulted on 25 January 2024
[56] Council of the European Union, ReFuelEU Aviation initiative: the Council adopts a new law to decarbonise the aviation sector, October 2023
[57] Global Sovereign Advisory, The outlook for green hydrogen, June 2023
[58] Ditto
[59] Presentation of the Lanzatech process, 2017

thus produced can be **mixed with petrol, converted into kerosene or diesel, or used as an input in the production of plastics**, detergents or synthetic fabrics. Lanzatech has already equipped three steelworks belonging to the **Shougang** group in China, one belonging to ArcelorMittal in Belgium (see also Chapter IV) and an **IndianOil** refinery in India, for a combined total production of 300,000 tonnes of ethanol per year[60], out of a world ethanol production estimated at 82 million tonnes[61]. Its Freedom Pines e-kerosene plant, which has been delayed until 2024, will produce 37 million litres a year, or, according to the company, around 10% of the world's annual production of sustainable aviation fuel.

There is no precise estimate of the CO_2 consumed by the handful of electrofuel and enzymatic ethanol production plants operating worldwide. However, the IEA predicts that **global production of synthetic fuels could absorb up to 7 million tonnes of CO_2 per year by 2030**[62] .

4. How much does it cost to capture and sequester CO_2 ?

4.1. In thermal power stations, additional costs and loss of efficiency

Electricity generation represents the largest source of net CO_2 emissions, **accounting for 14.2 billion tonnes out of a total of 36.8 billion tonnes (38.5%)** in 2022. Despite the unprecedented installation of new renewable capacity, these emissions continue to rise, driven by the increase in coal consumption in Asia and certain emerging countries, and the growth in natural gas consumption[63]. This sector is therefore, in principle, an ideal candidate for the mass installation of CCS systems. In reality, however, **large-scale deployment would appear to be difficult, given the additional costs and loss of efficiency involved**.

4.1.1 An efficiency loss of between 11 and 24%...

The US Department of Energy's *National Energy Technology Laboratory* (NETL), which periodically carries out in-depth simulations of the operating costs of US thermal power plants, has been measuring the impact of CCS for several years. The results are unequivocal: in 2022, it estimated the loss of efficiency, compared with operation without capture, at **20% for coal-fired power stations**, **11 to 12% for a combined-cycle natural gas power station (NGCC)**, and **15 to 24% for integrated gasification power stations (IGCC)**[64]. As CCS technologies are mature, these penalties have fallen only slightly in recent years.

These losses are explained by the high electricity consumption of CO_2 capture equipment, and by other technical factors, in particular, for some power plants, by the diversion of part of the steam produced for use in the capture process.

4.1.2 ... and additional financial costs of at least 40%.

CCS also generate **significant additional financial costs**, mainly linked to the capital expenditure (CAPEX) required for their installation, and to a lesser extent to their operational costs (OPEX). Again according to the NETL, the **increase in levelized cost of electricity** (LCOE, i.e. the full price of the electricity produced over the entire lifetime of the equipment that generates it) **is very significant: +52 to +60% for gas-fired power stations, +64 to +71% for coal-fired power stations, and 41% on average for IGCC power stations** (table 1).

[60] Lanzatech, Financial results for the 3rd quarter 2023
[61] S&P Global, Ethanol Market Analysis, consulted on 25 January 2024
[62] IEA, Carbon Capture and Utilisation, consulted on 25 January 2024
[63] Our World In Data, Electricity Mix, consulted on 20 January 2024
[64] NETL, Cost And Performance Baseline For Fossil Energy Plants, 2022

Table 1: Loss of efficiency and capture costs in different types of thermal power stations

	Combined-cycle gas (class G turbine), 95% capture	Coal (supercritical), 95% capture	Integrated gasification combined cycle
Loss of efficiency (compared with no capture)	-11% to -12%	-22% to -23%	-15% to -24%
Impact on the levelized cost of electricity (LCOE)	+52% to +60%	+64toà +71%	+41%

Source: Cost and Performance Baseline for Fossil Energy Plants, NETL, 2022

The results of NETL's calculations are consistent with the figures put forward by the sector's professional association, the Global CCS Institute, which also based its estimates on a theoretical installation located in the United States[65]. As CAPEX accounts for the bulk of the additional costs incurred, these orders of magnitude will be found in most regions of the world and under all circumstances.

Such additional costs seem particularly prohibitive for coal-fired or gasification power plants (using coal as a fuel): this type of power plant is favoured by certain countries (emerging countries in particular) precisely because of their low operating costs.

4.2. In industry, costs vary widely from one sector to another

4.2.1 Cement and steel manufacturers, the main emitters, will also have to pay

With 9.15 billion tonnes of CO_2 emitted in 2022 according to the IEA[66] (24% of the total), the industrial sector is the world's second largest emitter after energy. But **the cost of capturing CO_2 varies considerably from one sector to another**, mainly **depending on whether their industrial processes emit a gas that is more or less rich in CO_2: the more diluted the gas, the more expensive the separation process will be.** According to the IEA, the cost of capturing CO_2 from ethanol production or natural gas processing (whose emissions are very rich in carbon dioxide) ranges from $15 to $25/tonne, but it rises to $40 to $120/tonne in the case of a cement plant. NETL made a more detailed estimate for 2022 (Table 2):

Table 2: Cost of capturing one tonne of CO2, by sector of activity

Sector of activity	Capture cost ($/tonne)
Natural gas processing	16,2
Ammonia	19
Ethylene oxide	26,2
Ethanol	32
Cement (99% capture)	62,4
Steelworks (99% capture)	65,4

Source: Cost of Capturing CO2 from industrial sources, NETL, 2022

The cost of capture is therefore **particularly high in steel and cement production**. These two industries are the **two biggest CO_2 emitters, with 2.6 billion tonnes (7% of the total) and 2.3 billion tonnes (6.5%) per year, respectively, worldwide[67]** .

4.2.2 Avoidance less costly than capture: the example of ArcelorMittal

For the manufacturers concerned, it therefore generally seems **more useful to invest in reducing their emissions, wherever technically possible, rather than in capture**. The example of **ArcelorMittal** is particularly telling. At the end of 2022, the world's second-largest steelmaker inaugurated a CO_2 capture and utilisation unit (CCU) at its Ghent plant in Belgium, transformed into ethanol by biocatalysis (Lanzatech

[65] Global CCS Institute, Global Costs of Carbon Capture and Storage, 2017
[66] IEA, CO_2 emissions in 2022, consulted in January 2024
[67] Imperial College London, 'Greening' cement and steel: 9 ways these industries can reach net zero, March 2022

process, see chapter 3). This investment, valued at €200 million, should make it possible to **avoid 125,000 tonnes of CO_2 per year** by producing 80 million litres of ethanol per year: **a drop in the bucket compared with the 6.9 million tonnes produced by 2022 by the Ghent site**, and the **3.9 million tonnes per year that the steelmaker says it wants to eliminate by 2030**. To achieve this, ArcelorMittal is in fact counting mainly on the construction of a direct reduction line (where coal is replaced by gas, and potentially by green hydrogen in the future) - and two new electric furnaces. These latter investments, which will avoid 3 million tonnes of CO_2 emissions per year, are estimated to cost €1.1 billion. In other words, in this example, **the capital costs are clearly in favour of avoidance (€366/tonne) compared with capture (€1,600/tonne).** However, this calculation does not take into account operational costs, income from the sale of ethanol, or the fact that this ethanol will replace 'traditional' ethanol on the market, the production of which emits CO_2.

The steelmaker is continuing to explore the potential of carbon capture, including in Ghent, where it will be testing capture systems on its blast furnaces[68] . But the immediate prospects appear limited. For example, **despite the completion in March 2022 of CCS pilot units at Dunkirk**, **the €1.8 billion of investment recently announced by ArcelorMittal** to decarbonise this site (with up to €850 million from the French government) **will be entirely devoted to avoidance**, in particular through a direct reduction line, where coal will be replaced by natural gas and, in future, by hydrogen.

4.2.3 Transport, a financial and logistical challenge

Large-scale capture of CO_2 also requires the ability to transport it to sequestration or reuse sites, by pipeline, sea transport, etc. The cost of transport varies considerably depending on geographical, industrial and commercial variables. **The cost of this transport varies considerably depending on geographical, industrial and commercial variables**: an emitter located close to industries that consume CO_2, or an underground sequestration site already equipped with a gas pipeline, will face much lower costs.

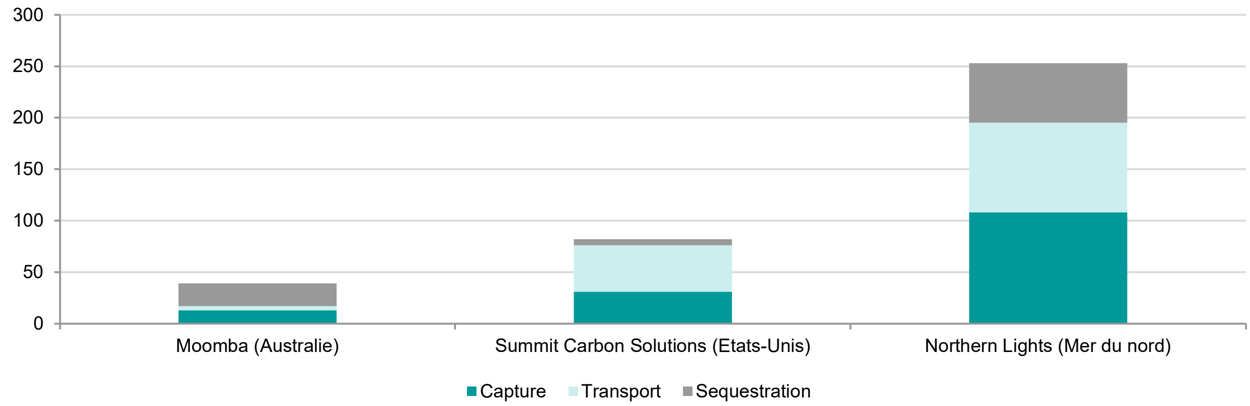
An MIT researcher estimated in 2021 that **the costs of transporting (by pipeline) and storing CO_2 could range from USD 4/tonne to USD 45/tonne**, depending on the context[69] . This large delta is reflected in a comparison of the levelized storage costs of the world's first major CCS projects, drawn up by WoodMackenzie, which shows that the **final cost of CCS varies considerably from project to project**: the ***Moomba* project** in Australia (capturing CO_2 emitted by a single gas-fired power station located in the immediate vicinity of the storage site) cost only **USD 22/tonne of CO_2 sequestered**, but in the ***Northern Lights* project in the North Sea** (see Chapter 2), it would cost as much as **USD 253/tonne**. Indeed, the Northern Lights project calls for the CO_2 to be captured from a large number of customers, transported from continental Europe by ship, compressed, and sent by pipeline to an offshore storage site (Figure 6).

Dedicated pipelines for CO_2, which contribute significantly to lowering transportation costs, are still rare: around 9,500 km worldwide according to the IEA[70] , almost all of them (92%) in the United States, where they primarily supply *Enhanced Oil Recovery* (EOR) activities. However, the geographical distribution of CO_2 emitting industries is rarely optimal from a transport point of view. For example, NETL notes that while a large proportion of US ammonia plants are located close to CO_2 pipelines (serving the oil fields of the American Midwest), this is not the case for ethanol plants, cement works or steelworks.

The cost of maritime transport is still difficult to assess: only a few demonstration vessels built for the first major offshore CCS projects (including *Northern Lights*[71]) are currently operational. However, the shipping brokerage company Maersk Broker estimates them at **between USD 12.9/tonne and USD 31.8/tonne**, depending on the scenarios envisaged[72]. There are many technical constraints, not least the need to compress CO_2 in order to liquefy it, unlike natural gas[73].

[68] ArcelorMittal, 2022 annual report
[69] Erin E. Smith, The Cost of CO2 Transport and Storage in Global Integrated Assessment Modeling, 2021
[70] IEA, CO_2 Transport and Storage, consulted in January 2024
[71] Carbon Herald, Northern Lights To Expand Fleet With A Fourth CO2-Carrying Ship, December 2023
[72] Maersk Broker, Maritime Transport of CO2, October 2022
[73] DNV, Navigating the challenges: Liquid CO2 carriers a vital link in global CCS expansion, consulted in January 2024

Figure 6: Costs of sequestering, transporting and capturing CO_2 in various CCS projects (USD/tonne)



Source : WoodMackenzie[74]

5. How can we put a cost on the CO_2 captured?

The carbon sequestered by CCS projects is of **no economic use: it is a cost item** with no return on investment. The financing of CCS is therefore essentially based on the **sale of emission allowances** - or "rights to pollute" - on carbon credit markets, as well as on incentive mechanisms such as **subsidies** for the construction of infrastructures and **tax credits**. **CCS projects are only economically viable when the cost of sequestering the carbon is less than the price of selling the emission allowance, or the total of the incentives.**

5.1. In the EU, carbon credits are not expensive enough to finance CCS

In addition to the numerous investment subsidies for CCS projects (see Chapter 2), the European Union has opted for a market-based solution. The main mechanism for sequestration activities is **the sale of carbon credits on the Emissions Trading Scheme** (EU ETS), the **world's main emissions exchange**.

The value of these securities, which have historically traded at less than €20/tonne, soared with the presentation of the European Green Deal in December 2019, followed by the European Climate Law proposal in March 2020[75] : in 2022, it reached €80/tonne on average, with a peak of €100/tonne in February 2023.

However, the value of carbon credits has since fallen back due to the economic impact of the war in Ukraine (which caused a reduction in Russian gas imports)[76] and the structural reduction in electricity production from fossil fuels[77]. It stood at **just over €60/tonne in January 2024**[78] , a rate that hardly seems sufficient on its own to support CCS activities. Although, as we have seen (Chapter 4), the cost per tonne sequestered varies greatly from one project to another, **some experts estimate that it is between €70 and €250/tonne for European projects**[79] **.**

However, a number of factors could push prices up in the near future, such as the **end of free allocation of emissions allowances in 2030**[80] or **the arrival of new buyers on the market**. Shipping companies must start offsetting their emissions from 2024; they will be followed, from 2026, by importers of steel, cement, aluminium, fertilisers, etc. covered by the Carbon Border Adjustment Mechanism (CBAM). The EU is also

[74] WoodMackenzie, What's shaping CCUS project costs, May 2023
[75] Global CCS Institute, CCS In Europe Regional Overview, November 2023
[76] Carbon Economist, EU ETS prices fall sharply on Ukraine invasion, 8 March 2022
[77] ING THINK, EU carbon hits year-to-date lows, November 2023
[78] Sandbag.be, Carbon Price Viewer, consulted on 25 January 2024
[79] Clean Air Task Force, Mapping the cost of carbon capture and storage in Europe, February 2023
[80] Euractiv, European legislators vote to end free CO2 quotas by 2030, May 2022

working on setting up a **European certification system for carbon removals**[81], to better differentiate between projects that remove CO_2 from the atmosphere and those that simply reduce emissions. While the text currently under discussion does not provide for a specific trading system[82], these new certificates could lead to the emergence of a **specific and more remunerative market for carbon credits from CCS projects**, particularly "carbon negative" projects, based for example on direct capture from the atmosphere.

In anticipation of a possible sustained rise in prices on the SEQE, some Member States have also begun to set up **carbon contracts for difference** (CCfD), mechanisms that aim to finance the difference between the cost of capturing CO_2 and its price on the SEQE market. For example, the Dutch government has awarded Shell, ExxonMobil, Air Liquide and Air Products a CCfD for their *Porthos* CCS project in the North Sea, which is due to become operational in 2024. **A reference cost of €80/tonne of CO_2 has been adopted, with the government offsetting the difference with the price of carbon on the ETS**.

In mid-2023, Germany launched an initial call for tenders to sign the first CCfDs **with a budget of €50 billion**[83], while France is also looking into the possibility of setting up CCfDs as part of the France 2030 industrial programme[84] .

5.2. United States: the Biden administration opens the floodgates on tax credits

Unlike the European Union, the United States has not imposed emission quotas on its manufacturers. Only California has set up a mandatory market, California CaT (California Cap and Trade), where a tonne of CO_2 was trading at just under USD 40 at the end of 2023[85] .

On the other hand, companies that use CCS to reduce their emissions can benefit from a tax credit, known as a **45Q**, for each tonne of carbon sequestered. According to the US Treasury, this scheme cost **USD 1 billion between 2010 and 2019**[86] , and this figure is set to rise rapidly. In 2022, **the Biden administration substantially strengthened this mechanism as part of the Inflation Reduction Act (IRA)**. Previously capped at USD 50/tonne, the credit can now be up to **USD 85/tonne** for traditional CCS, and even **USD 180/tonne** for CO_2 captured from the atmosphere. The 45Q also covers CCUS: the emitter can obtain up to 60 USD/tonne of CO_2 reused (compared with 35 USD previously) and even 130 USD/tonne, if the CO_2 comes from direct atmospheric capture (DAC)[87]. The scheme has been criticised, however, as a substantial proportion of the tax credits awarded do not comply with the US Environmental Protection Agency's (EPA) requirements for reporting sequestered carbon[88] . It also mainly benefits oil companies using the CO_2 for enhanced oil recovery (EOR). This scheme is in addition to major investment subsidies (see chapter 2).

5.3. China

In China, CCS regulation is still in its infancy and subject to the influence of a multitude of decision-making bodies, such as the State Council, the National Development and Reform Commission, the Ministry of Science and Technology, the Ministry of the Environment, etc.[89] . There is therefore no incentive framework at national level, and the capture and storage sites that have already been launched are, for the most part, small-scale[90]. **In January 2021, China launched a mandatory emissions trading market**, in addition to two voluntary markets (the Beijing Green Exchange and the China Hubei Carbon Emissions Exchange). Covering around 40% of national emissions, it mainly concerns the energy sector, although other industries are due to join gradually. Three years after its launch, the results are mixed: **emissions allowances are trading at around USD 10/tonne of CO_2, a price that is far too low to** support **investment in CCS**.

[81] European Parliament, Carbon phase-out: Parliament calls for EU certification scheme to encourage uptake, November 2023
[82] ERCST, The Carbon Removal Certification Framework: what is next, November 2023
[83] Usine Nouvelle, Germany unveils its financial instrument for decarbonising its industry, June 2023
[84] France 2030, Decarbonisation of industry (public consultation), February 2022
[85] California Air Resources Board, Cap-and-Trade Program Data Dashboard, consulted on 25 January 2024
[86] Congressional Budget Office, Carbon Capture and Storage in the United States, December 2023
[87] Clean Air Task Force, Carbon Capture Provisions in the Inflation Reduction Act of 2022, August 2022
[88] Taxpayers for Common Sense, Hot Air and High Costs: The Carbon Capture and Sequestration Credit, February 2023
[89] Qiao Ma et al, China's policy framework for carbon capture, utilization and storage: Review, analysis, and outlook, February 2023
[90] Global CCS Alliance, Facilities Database, consulted on 25 January 2024