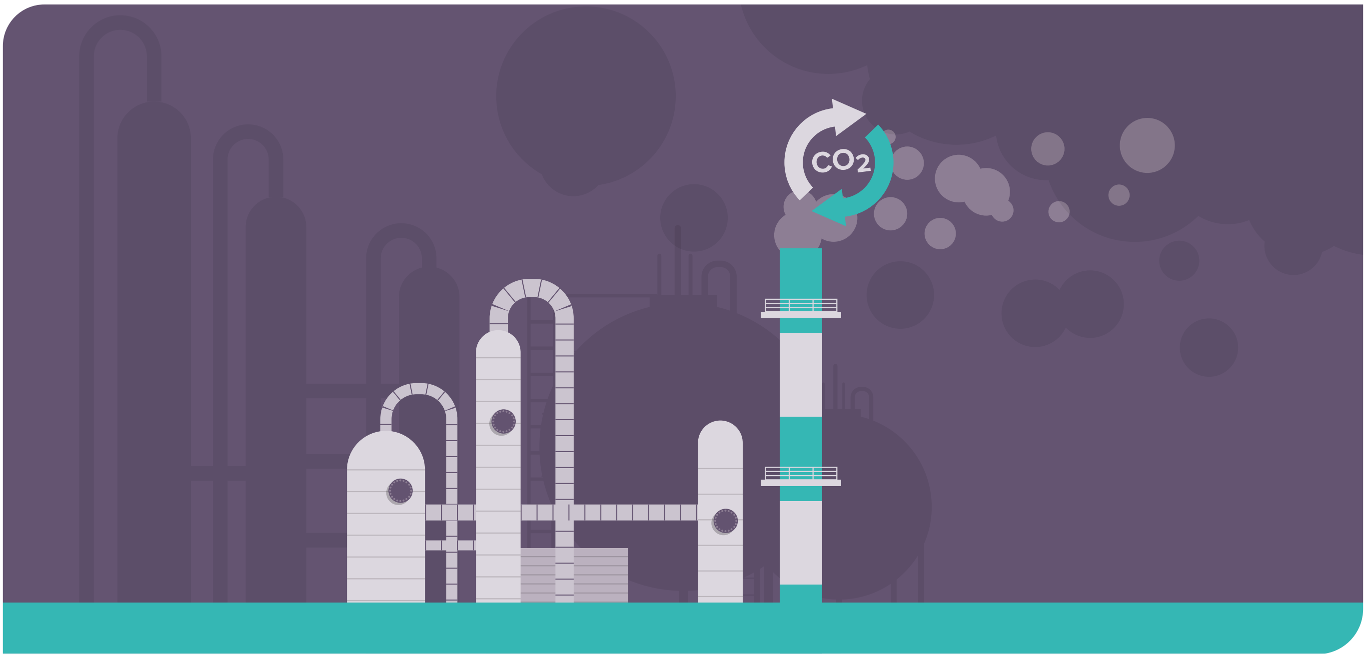


Carbon Capture and Storage, a necessary tool to fight climate change

Solution for hard-to-abate emissions

Morgane PIGEAUX
Strategic Marketing Engineer

Clément SALAIS
Low Carbon Solutions Technology Manager

Christian STREICHER
Gas Development Director

Jeanne TOURDJMAN
Customer Training Engineer

CONTENTS

EXECUTIVE SUMMARY

Carbon Capture, Utilization and Storage (CCUS) covers all technologies dedicated to removing CO_2 from flue gas, industrial gases, natural gas and the atmosphere, recycling this CO_2 for utilization (U) in chemical applications, for instance, and/or storing (S) it in geological cavities. Carbon Capture and Storage (CCS) is a subset of CCUS, as its name suggests. Both are part of the equation for reducing GreenHouse Gas (GHG) emissions, improving energy efficiency, increasing renewables use and promoting a fuel switch. Anthropogenic GHG emissions, mainly composed of CO_2 largely from the power, industry and transport sectors, need to be reduced drastically to meet the targets of the 2015 Paris Agreement, which are currently being tightened to limit the rise in temperature this century. Since CCS has a vital role to play in all the anticipated scenarios, the development of CCS projects is growing significantly worldwide, but not quickly enough. Clearly, CCS is expected to show a significant contribution to achieving net-zero emissions around the mid-century mark by removing emissions from industries that are hard to decarbonize. Moreover, accelerated CCS is one of the COP26 Mission Innovation targets.

COP 26 was held in Glasgow from 31 October to 12 November 2021
“UNITING THE WORLD TO TACKLE CLIMATE CHANGE”

On January, 20th, 2021, the very day that President Joe Biden was inaugurated, the USA reintegrated the Paris Agreement, four years after their withdrawal. Following this announcement, a lot was expected from the COP26 dedicated to bring parties together to accelerate action towards the goals of the Paris Agreement and the UN Framework Convention on Climate Change.

Since then, what has COP26 done to keep 1.5 alive?

- Countries agreed the Glasgow Climate Pact.
- They committed to real actions bound to CO_2 production reduction and to its capture when produced. These actions include:
  - Methane emissions reduction by 30% in 2030
  - Coal faster phasing out
  - Switch to electric vehicles speeding up
  - Deforestation ending

At the end of the COP26 UN Climate Conference, it has been stated that “COP26 resulted in the completion of the Paris Agreement rulebook and kept the Paris targets alive, giving us a chance of limiting global warming to 1.5 degrees Celsius.”

Learn more ›

At the closing plenary, the COP26 president added: “... it emphasises the urgent need to accelerate our efforts to turn targets into action to keep 1.5 within reach. That work must start now.”

Learn more ›

Among the numerous carbon capture technologies, the dominant two are pre- and post-combustion. These technologies are discussed below.

New, more cost-effective CO_2 capture technologies are, however, required. IFPEN and Axens are addressing this situation through the development of the DMX™ process technology, for instance.

After the capture stage, transport to storage and the storage solution itself are key to accelerating decarbonization. Carbon dioxide will preferably be stored in the form of clusters, as is the case with the **Northern Lights project in Europe**.

The paper concludes with some hints on the way forward for large-scale CCS rollout.

Go to the top of the document

Make the net zero future a reality

OIL AND GAS CLIMATE INITIATIVE

The Oil & Gas Climate Initiative (OGCI) is an international organization combining the forces of 12 member companies from the oil & gas industry to knock down the technological barriers and, thus, accelerate the industry response to climate change. To deliver a low-carbon future, collaborative work is essential to address the challenges of climate change. Among the "new technologies and approaches that catalyze low-carbon ecosystems", OGCI supports deployment of carbon capture technology "to help decarbonize industrial regions" and meet the target of a net zero future.

More information

INTRODUCTION

The Paris Agreement adopted at the Paris Climate Conference (COP21) in December 2015, intends to limit global warming to well below 2°C and to pursue efforts to 1.5°C. In late 2018, the Intergovernmental Panel on Climate Change (IPCC) published a special report on the impacts of global warming of 1.5°C to 2°C above pre-industrial levels. Their analysis shows that climate change impacts do not vary proportionally with temperature in the 1.5 to 2°C range – far from it. The effects of 2°C of warming would, in fact, be far worse than those of 1.5°C. To fight against this global warming, carbon neutrality should be achieved by 2050.

All sources agree that society must urgently break with the unsustainable way energy is currently consumed to tackle climate change linked to anthropogenic GHG emissions. All scenarios anticipating carbon neutrality by 2050 or after, led by those of the International Energy Agency (IEA), confirm the need to shift to cleaner energy systems to achieve the net-zero emissions through a wide range of solutions (energy efficiency, renewables and fuel switch), and to move even further towards negative emissions.

To meet the net zero target, a mix of radical transformations is urgently required, the main ones being improving the energy efficiency of our economies, developing non-fossil fuel-based energy sources and, last but not least, implementing CCUS on existing and future facilities. Indeed, among the radical transformations proposed for the energy sector, heavy industries and transport, Carbon Capture and Storage is ranked among the top solutions to reach this vital goal. As stated in IEA's 2020 Global Status of CCS report, "Without CCS, net-zero is practically impossible."

Deep decarbonization of those sectors where GHG emissions remain hard to abate is, therefore, a priority. Meanwhile, more and more CCS projects are emerging worldwide, with varying degrees of maturity and with a tendency for grouping in clusters and hubs for reasons of efficiency and economies of scale. The two main carbon capture technologies are post- and pre-combustion comprising a range of technical solutions developed in recent years by way of capturing the CO_2.

Go to the top of the document

1. THE ROLE OF CCUS

1.1. Level of CO_2 emissions per segment

Since all sources agree with the urgent need for action to mitigate climate change and, consequently, the top priority of reducing GHG emissions, it is important to examine the origin of these emissions. First, CO_2 represents around 75% (in CO_2 equivalent) of GHG which also contains methane and nitrous oxide (both of which have a much higher global warming potential than CO_2), to name the most important ones. Anthropogenic CO_2 emissions, caused by human activities, account for some 35 Gt CO_2 per year (except for anthropogenic emissions due to agriculture, forestry and other land use change). As can be seen in Figure 1, the amounts of anthropogenic CO_2 emissions have continuously increased over the last century and more sharply in recent years. Total GHG emissions, taking into account agriculture, forestry and other land use change, amount to around 50 Gt of CO_2 equivalent. (Source : https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf)

“Recycling CO_2: Transforming Climate Risk Into Opportunity And CO_2 Into Valuable Products”

CO₂ VALUE EUROPE

Axens is a member of this “European think-and-do-tank dedicated to Carbon Capture and Utilization (CCU)”.
This association brings together “partners from the complete CO_2 value chain, from the largest CO_2 emitters to the technology developers and to the CO_2 users with a focus on 3 pillars: CO_2-to-Chemicals, CO_2-to-Fuels and CO_2-to-Materials”.
The goal pursued is to “better address key issues faced by the nascent CCU industry”.
More information

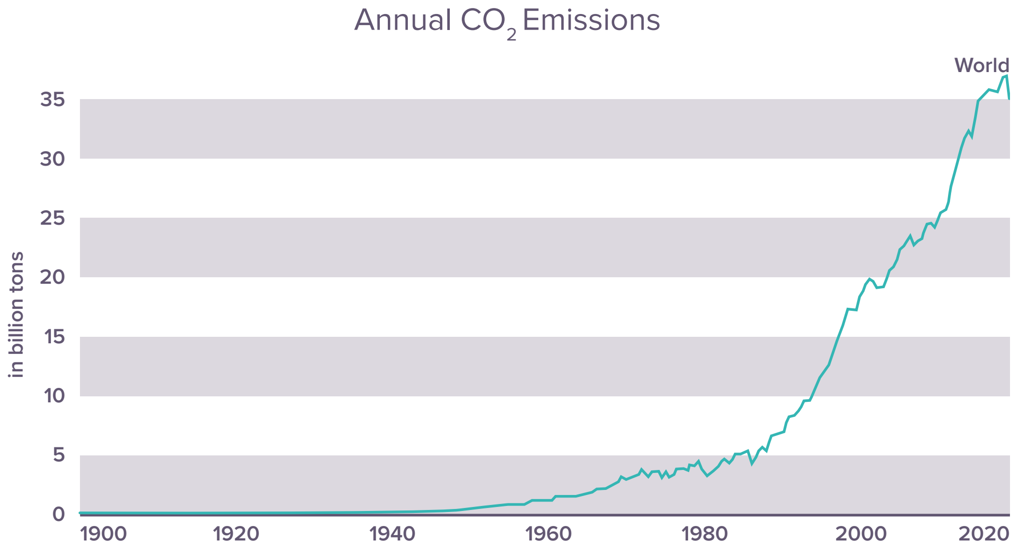
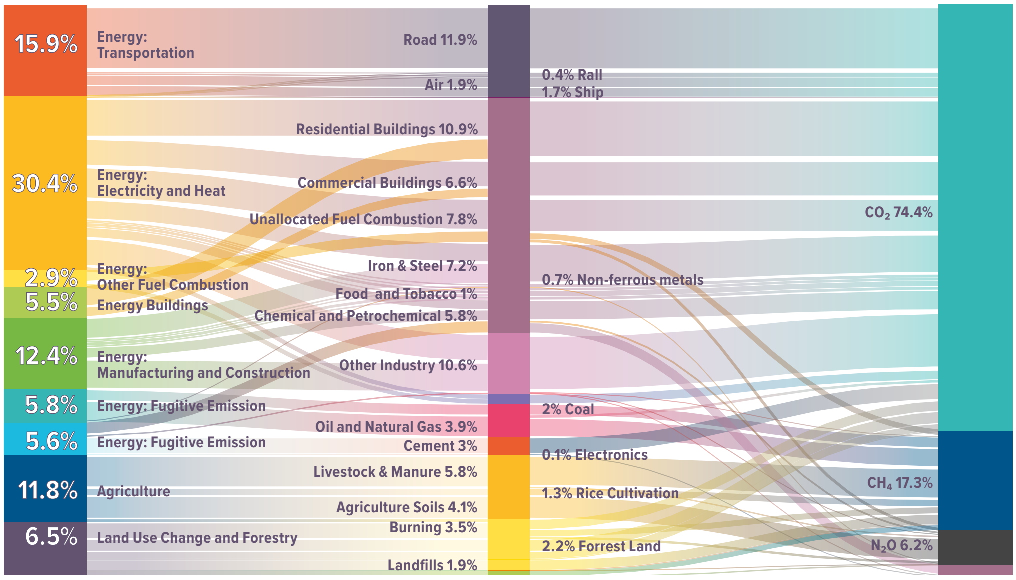


Figure 1: Overall anthropogenic CO_2 emissions resulting from fossil fuels and cement production (Source: https://ourworldindata.org/co2-emissions)

Moreover, the breakdown of global GHG emissions shows (Figure 2) that nearly half of the emissions is caused by energy used in industry, thus reinforcing the need to deploy and retrofit CCS projects accordingly.

In this graph, the first column shows a breakdown per sector (sources of emissions) whereas the second one lists the activity causing the release. The third column gives the type and volume of gas (in percentage), associated with each activity.



↑ Figure 2: World greenhouse gas emissions (Source: World Resources Institute, 2016)

Upon closer inspection, it appears that in 2018 the power sector was the largest carbon emitter, accounting for 40% of global energy-related emissions with coal-fired plants alone representing 29% of the total. Transport and Industry take second place with 23% each (Figure 3).

Within the industry sector (23%), cement, iron and steel plants represent approximately 53% of the emissions and are among the hardest to decarbonize. Their high level of carbon emissions is due to the industrial processes and high temperatures involved.

Refining is the fourth largest contributor to industrial CO_2 emissions, responsible for 2% of total anthropogenic energy-related emissions (~ 35 Gt CO_2). (Source: Concawe report no. 18/20 (September 2020))

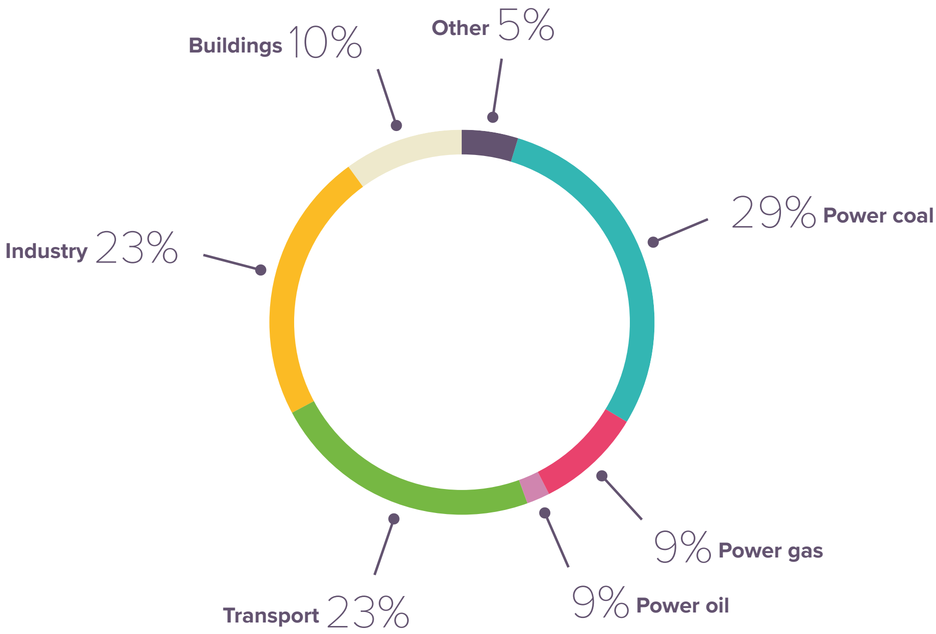


Figure 3: Global energy-related CO_2 emissions by sector (Source: IEA – The role of CCUS in low-carbon power systems, 2020)

It must also be considered that CO_2 emissions from some industrial sectors cannot be easily reduced or eliminated simply by switching fuel type. It is therefore evident that CCUS has a crucial role to play in the world economy, as stated by the IPCC, by providing a sustainable pathway in line with global warming limitations, as underligned in Concawe report no. 18/20 (September 2020).

1.2. Impact of solutions on emissions reduction

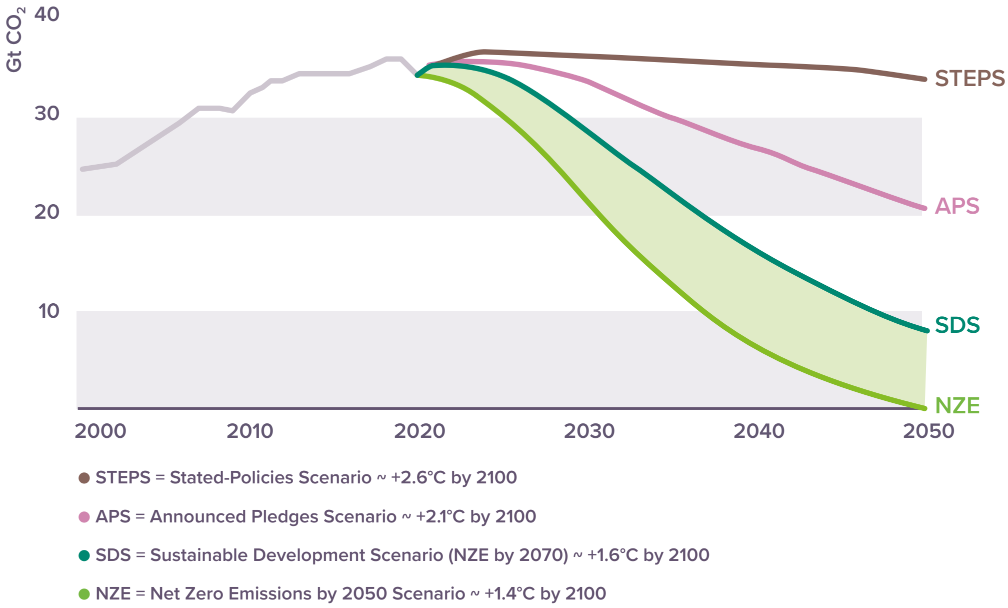
Several third parties have analyzed CCUS impact. The scenarios of the International Energy Agency (IEA) provide benchmarks to underline how the different energy policy choices and technological solutions affect emissions reduction.

The IEA has recently introduced new scenarios in the 2020 and 2021 versions of the World Energy Outlook (WEO). They include Net-Zero Emissions by 2050 (NZE2050) and the Announced Pledges Scenario (APS), as well as the well-known STEPS and SDS scenarios.

Understanding World Energy Outlook Scenarios

	NET ZERO EMISSIONS BY 2050 SCENARIO	ANNOUNCED POLICIES SCENARIO	STATED POLICIES SCENARIO	SUSTAINABLE DEVELOPMENT SCENARIO
DEFINITIONS	A scenario which sets out a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. It doesn't rely on emissions reductions from outside the energy sector to achieve its goals.	A scenario which assumes that all climate commitments made by governments around the world, including Nationally Determined Contributions (NDCs) and longer-term net zero targets, will be met in full and on time.	A scenario which reflects current policy settings based on a sector-by-sector assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.	An integrated scenario specifying a pathway aiming at: ensuring universal access to affordable, reliable, sustainable and modern energy services by 2030 (SDG 7); substantially reducing air pollution (SDG 3.9); and taking effective action to combat climate change (SDG 13).

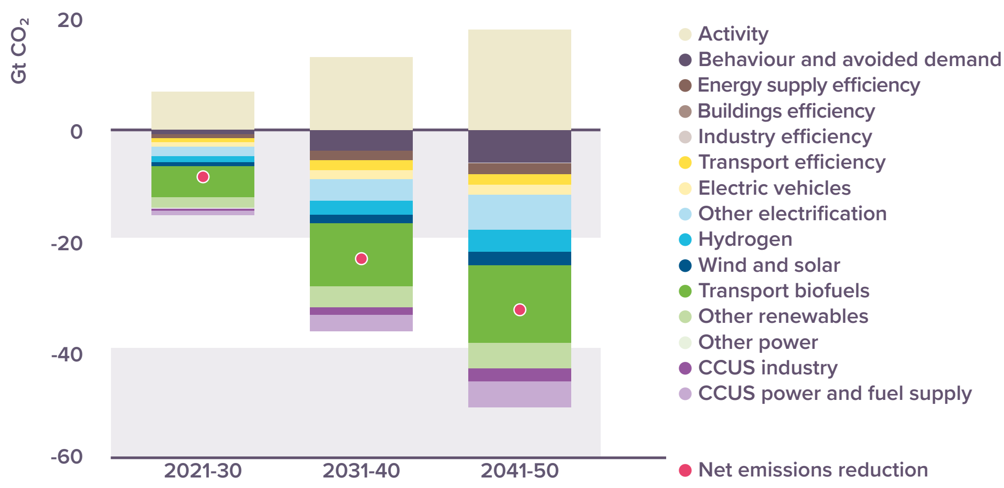
In 2020, following the economic impact of the Covid-19 pandemic, the IEA estimated a 7% decrease in CO_2eq emissions from the energy sector. This decrease due to the lock-down of many countries and the slowdown of economic activity represents what would be necessary in the NZE 2050 scenario (shown by the light green curve – Figure 4) although the solutions to be implemented are very different in a situation with higher economic growth and GDP.



↑ Figure 4: Global energy-related CO_2 emissions in the 2021 WEO scenarios (Source: IEA – World Energy Outlook, 2021)

In the STEPS, global energy-related and industrial process CO_2 emissions bounce back quickly in 2021 and rise to 36 gigatonnes (Gt) by 2030. In the APS, emissions peak in the mid-2020s and return to just under 34 Gt, close to current levels, by 2030. In contrast, NZE shows emissions falling to 21 Gt in 2030, marking a decisive change of direction.

Therefore, compared to the STEPS or even the APS scenario, significant additional GHG emission reduction efforts are clearly required to achieve NZE expectations (net zero emissions by 2050). This target could be attainable through a wide range of solutions and decarbonization technologies, besides CCUS deployment, including energy efficiency, renewables (solar, wind, biofuels, etc.), fuel switching and others, such as transport electrification or population behavior change. Application of a combination of solutions will depend on government policies, incentives and technology development to limit environmental impact and meet climate targets. Figure 5 shows the range of solutions that should be put in place to reduce CO_2eq emissions from the energy sector and industrial processes with the corresponding average annual CO_2 reductions from 2020 in the NZE scenario.



↑ Figure 5: Average annual CO_2 reductions from 2020 in the NZE Scenario (Source: Net Zero by 2050: A Roadmap for the Global Energy Sector (International Energy Agency – IAE, May 2021))

Among the range of solutions, CCUS, adding the 'Utilization' component to the CO_2 captured and stored, will deliver further emissions abatement. Chemical fertilizers, polymers manufactured with recycled carbon feedstock, concrete manufacturing, clean hydrogen, Enhanced Oil Recovery (EOR), and food and beverage applications are some of the many examples of CO_2 utilization pathways that are still under development. In that respect, CCUS offers a key opportunity to accelerate the reduction of GHG emissions in the transition period. In the SDS scenario, IEA anticipates that a cumulative emissions reduction of around 5.4 billion tonnes per annum of CO_2 captured and permanently stored by 2050. This forecast highlights the need to retrofit and deploy carbon capture technologies together with low-carbon technologies. In all the scenarios developed by the IEA and other entities to keep the global temperature rise well below 2°C, CCUS plays a substantial role in achieving the ambitious goals of GHG emissions reduction.

Go to the top of the document

1.3. Current status of CCS facilities around the world

In 2021, the number of existing CCUS facilities worldwide is far below that planned within the SDS scenario. Currently, 135 large-scale CCS facilities are at various stages of development:

- 27 in operation (with an annual capture capacity of 36.6 $MtCO_2$, so less than 1% of the 5.4 GT CO_2 expected in 2050)
- 4 under construction
- 58 in advanced development using a dedicated front end engineering design (FEED) approach (compared to only 13 in 2020)
- 44 in early development (compared to 21 in 2020)
- 2 are on hold.

Figure 6 shows the progress of commercial CCS facilities from 2010 to September 2021. Capacity decreased year on year between 2011 and 2017, probably due to factors such as public and private sector focus on short-term recovery after the global financial crisis. Since 2017, there has been growth at the early and advanced development stages. Importantly, Figure 6 does not include ten early development or five advanced development projects in the pipeline, for which no capacity has been announced. Consequently, it underestimates potential. The large increase in commercial CCS facilities in the first half of 2021 has led to project pipeline capacity levels not seen since 2011 – 149.3 Mtpa, with a 30% average annual growth rate since 2017.

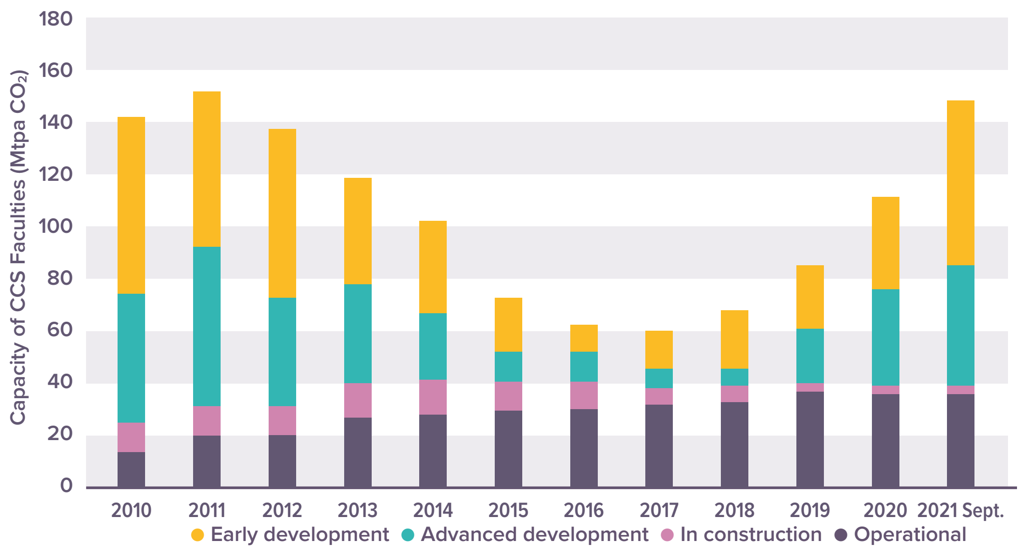


Figure 6: Pipeline of commercial CCS facilities from 2010 to September 2021 by capture capacity (Mtpa CO_2) (Source: Global status of CCS, 2021)

The global geological storage capacity is by no means the limiting factor in what is required for CCS to achieve net-zero emissions under any scenario. However, to reach the levels expected in the SDS, the number of industrial-scale facilities needs to increase from 26 in operation now to more than 2,000 by 2050 – and more for the NZE2050 case. According to Axens, this figure could easily be doubled based on current average capacities of CCS facilities. Consequently, it is particularly important to reduce the capital and operating costs (mainly energy requirements) of carbon capture technologies.

Beyond accelerating emissions abatement, the requested rapid scaleup of CCS technology provides a number of economic benefits, such as the creation of highly qualified jobs, the support of economic growth through new net-zero industries and innovation, and possible infrastructure reuse and the deferral of shutdown costs related to existing facilities.

The full picture of CCS projects (Figure 7) comprises three main components: CO_2 capture, achieved through a number of technologies and available at various levels of maturity, CO_2 transport mainly by pipelines or ships (in liquefied form) up to the storage facility.

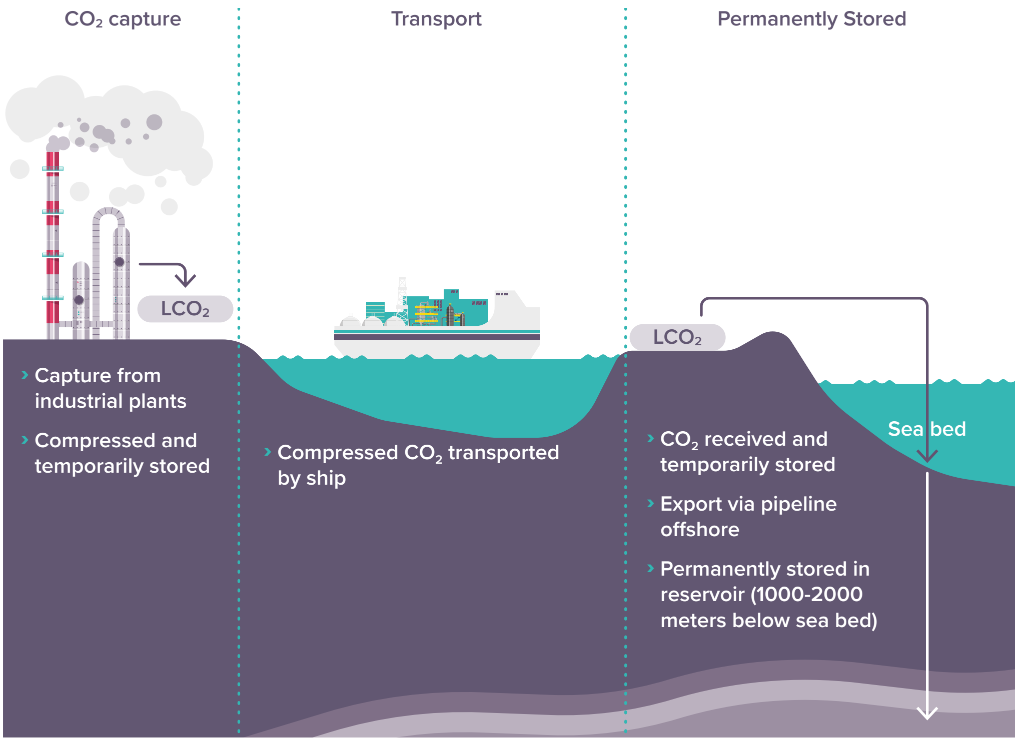


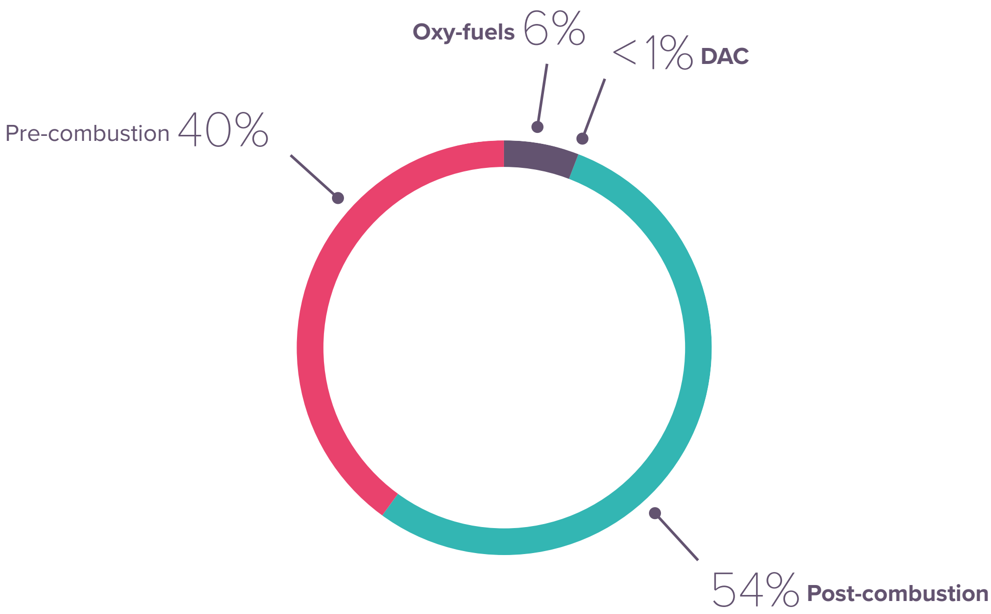
Figure 7: The whole CCS value chain (Source: https://3d-ccus.com)

Go to the top of the document

2. CARBON CAPTURE TECHNOLOGIES

2.1. Mature pre- and post-combustion technologies

The two main carbon capture technologies, according to the distribution of CCS projects worldwide, are pre- and post-combustion (Figure 8). Due to the low figures involved, the other two technologies – oxy-fuel combustion and direct air capture (DAC) – will not be detailed below, although they are currently attracting significant development.



↑ Figure 8: Distribution of CCS projects worldwide (Source: Concawe report no. 18/20 - September 2020)

Pre- and post-combustion carbon capture solutions (Figure 9) involve a wide range of technical processes with chemical and physical absorption at the top, but also adsorption on selected solids, membrane or cryogenic processes. They represent the most numerous and the most advanced technologies, with a Technology Readiness Level (TRL) of over 5 on a scale ranging from 1 for the initial idea (basic principles observed) to 11 for mature technologies (proof of stability attained). To meet the aforementioned Sustainable Development (SDS) deadlines, sufficient maturity levels and further developments are required.

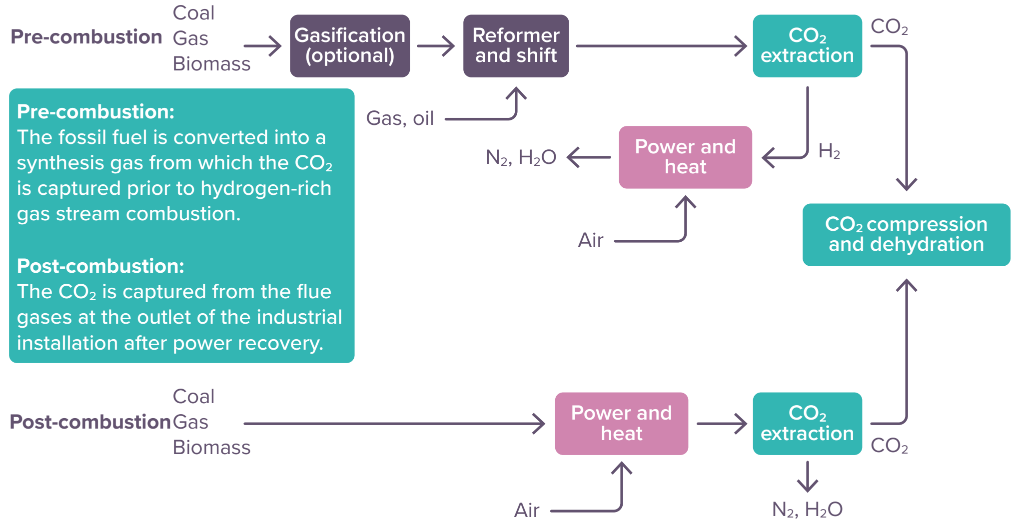


Figure 9: Pre-combustion and post-combustion CO_2 capture routes

Today, the most common process technology for either pre- or post-combustion applications is based on absorption in solvents that will selectively pick up the CO_2 present in the gas. This process is illustrated in Figure 10. The feed gas is washed in a counter-current in an absorption column with the solvent. The CO_2-rich solvent at the bottom of the absorber is then thermally regenerated to release the absorbed CO_2.

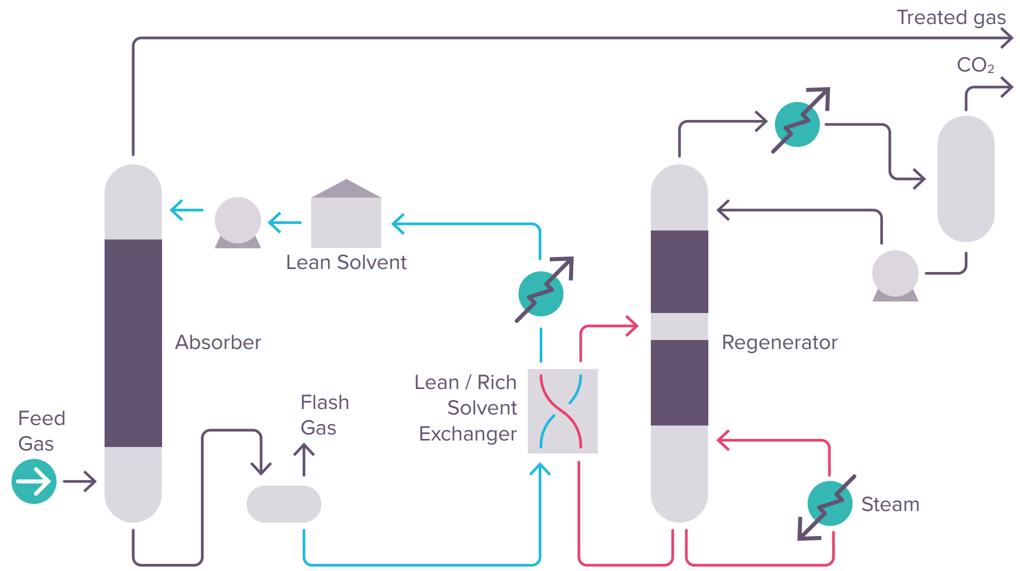
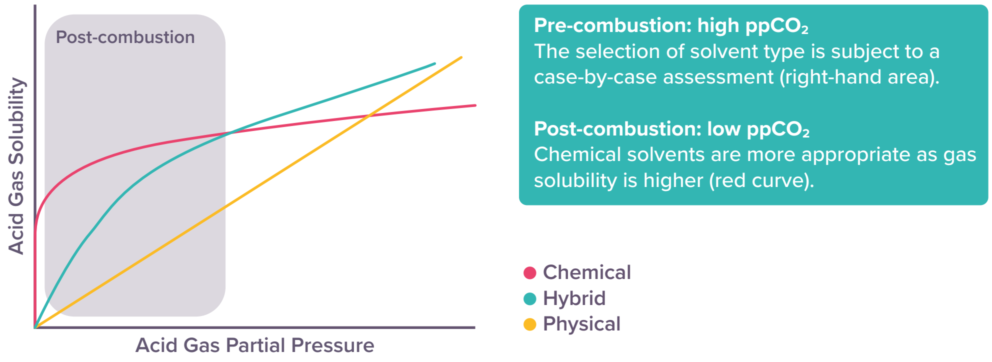


Figure 10: Typical absorption process for CO_2 removal

As a rule, acid gas solubility reflects the ability of the CO_2 to dissolve in the solvent. The higher the gas solubility, the more gas can be treated in the same amount of solvent. The choice of solvent type (chemical, physical or hybrid) for a given application will mainly depend on CO_2 partial pressure in the gas to be treated. As illustrated in Figure 11, chemical solvents are clearly more suited to gases with low CO_2 partial pressure as encountered in post-combustion applications. CO_2 solubility will indeed be higher at low partial pressure in chemical solvents than in physical solvents leading to lower solvent circulation rates and lower overall energy consumption.

The selection of solvent type at higher CO_2 partial pressure (ppCO_2) will be case-dependent and driven by many parameters such as the level of impurities in the gas, energy consumption, the treated gas specification, quantity of equipment, utilities available at the site, and others.



↑ Figure 11: CO_2 solubility trends in solvents versus CO_2 partial pressure

Some typical conditions of industrial gases for post-combustion and pre-combustion applications are summarized below:

Industrial process	Gas pressure (bar)	CO_2 content (%vol)	CO_2 partial pressure (bar)	Type
Aluminum production	Atm	1-2	0.01-0.02	Post-combustion
Natural gas combined cycle	Atm	3-4	0.03-0.04	
Coal-fired power plant	Atm	13-15	0.13-0.15	
Cement production	Atm	14-33	0.14-0.33	
Steel production (blast furnace	1-3	20-27	0.2-0.6	
Hydrogen production	20-30	15-20	3-6	Pre-combustion
Natural gas processing	9-80	2-65	0.5-44	

Go to the top of the document

Steam Methane Reforming (SMR)

As a rule, the process involves two reactions in parallel where methane in the presence of steam is converted into hydrogen and carbon monoxide (reaction 1), the latter participating in the equilibrium reaction – water gas shift (reaction 2) – to form CO_2 and additional hydrogen, thus resulting in the balanced chemical equation (reaction 3). A number of side reactions take place which are responsible for detrimental coke formation.

- reaction 1: $CH_4 + H_2O \rightleftharpoons CO + 3H_2$
- reaction 2: $CO + H_2O \rightleftharpoons CO_2 + H_2$
- reaction 3: $CH_4 + 2H_2O \rightleftharpoons CO_2 + 4H_2$

The synthetic gas (syngas) produced is a mixture that contains mainly hydrogen, but also carbon monoxide and dioxide as well as non-converted methane. This gas mixture is at medium to high pressure, close to ambient temperature and has a relatively high CO_2 partial pressure (>3.5 bar). It is lean and contains almost no impurities, a small quantity of carbon monoxide and no oxygen: ideal conditions for "easy" CO_2 capture!

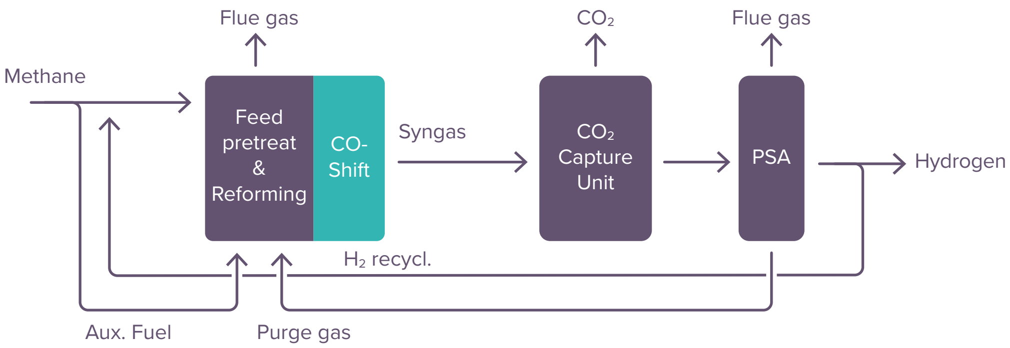
Other types of syngas production process such as autothermal reactor (ATR) or partial oxidation (POX) processes will produce the same kind of syngas. However, this syngas may contain additional impurities (mainly H_2S, HCN, NH_3 and COS) when feedstock other than gas, such as heavy oil, coal and biomass, are processed.

More information

a) Pre-combustion

Pre-combustion consists in removing the CO_2 from the synthetic gas (syngas) before combustion for power generation. This pre-combustion system is applicable to many industrial processes such as fertilizer manufacturing, refineries, hydrogen production, etc. It can also be extended to natural gas that shares most of the characteristics of the syngas. In this context, the various solvents (either physical or chemical or hybrid) could be suitable depending on the application and the drivers of the project.

A typical pre-combustion carbon capture process is illustrated below in the example of a Steam Methane Reformer (SMR) unit (Figure 12) used to produce hydrogen from methane (the main component of natural gas). The CO_2 capture unit is typically installed upstream of the Pressure Swing Adsorber (PSA) dedicated to stringent purification of H_2 (>99.9% purity).



↑ Figure 12: Typical Steam Methane Reformer (SMR) process diagram and location of pre-combustion CO_2 capture unit

?

LEARN MORE ABOUT

- Axens Advamine

Several pre-combustion technologies can be used for CO_2 capture on syngas:

- Pressure Swing Adsorption, usually used when high-purity hydrogen is required. PSA will produce a purge gas with a large amount of carbon monoxide and hydrogen, which is generally recycled as an additional fuel stream to the Reformer furnace.
- Physical solvents such as Rectisol, Purisol or Selexol, to name but a few. Such solvents will have low sensitivity to contaminants and low heating demand but may require high chilling duty.
- Chemical solvents such as activated amines (OASE™ from BASF, ADIP Ultra from Shell, AdvAmine™ from Axens) or potassium carbonate (Benfield from UOP).

All these technologies are mature, widely sold and readily available to perform carbon capture on syngas and natural gas in pre-combustion. The term “blue hydrogen” corresponds to hydrogen produced from steam reforming of fossil fuels (typically natural gas) where CO_2 is captured for downstream reuse or permanent storage.

b) Post-combustion

The post-combustion carbon capture technology consists in treating exhaust gas from fuel combustion (such as coal, fuel oil, gas, biomass or waste). Such flue gases are encountered in many industrial sectors such as power generation, steel manufacturing, cement plants, waste incinerators, crude oil refineries and chemical plants. In the case of a SMR as illustrated above, a post-combustion CO_2 capture unit can alternatively be installed on the flue gas from the SMR furnace.

All the gases are at low pressure and high temperature, contain several impurities and, for most of them, several percent of oxygen. The impurities and oxygen are usually detrimental to the solvents used, giving rise to degradation reactions of these solvents. Carbon capture conditions are therefore much more severe than for pre-combustion.

These gases will also generally require a more complex treatment chain that can include, depending on flue gas conditions, a waste heat recovery unit, a blower to overcome the pressure drop of the treatment units, a filtration step to eliminate any dust present, a SO_x removal unit, and a NO_x removal unit before it enters the carbon capture unit.

Apart from the required pretreatment to condition the gas for capture, the main characteristic of the gas is its low CO_2 partial pressure. The gas contains from 5 to 30% CO_2 at near-atmospheric pressure and its CO_2 partial pressure is frequently lower than 1 bar. Unlike pre-combustion, chemical solvents are most suitable here as illustrated by the blue area in Figure 11 above.

Monoethanolamine (MEA) is generally considered to be the first-generation solvent for post-combustion carbon capture. It is highly reactive to CO_2 even at very low partial pressure and is efficient at removing carbon from flue gas. It is, however, sensitive to oxygen, subject to thermal degradation and highly energy intensive. It requires about 3.5 GJ of heat input per tonne of CO_2 captured. The accumulation of degradation products in the solvent loop generates corrosion issues that are mitigated by selecting high-grade steel extensively on the unit and by reclaiming the solvent through a dedicated unit.

One of the main limitations of the various CO_2 capture processes considered is their relatively high energy requirement. As an illustration, it has been calculated that for high-efficiency coal-fired power plants (45% net electricity), the implementation of a conventional MEA-based carbon capture unit would decrease the net electricity yield by about 10-11% (so dropping down to 34-35%) (Source: P. Broutin & al.; GHGHT13 Conference “Benchmarking of the DMX™ CO_2 Capture Process”). For this reason, considerable R&D has been dedicated in recent years to developing less energy-intensive CO_2 capture processes, including second-generation chemical solvents.

Go to the top of the document

2.2. Emerging Carbon Capture technologies: example of DMX™

LEARN MORE ABOUT

- 3D CCUS
- Axens CO_2 Capture solutions
- IFPEN Capture, Storage and Use

New generations of chemical solvents have emerged in recent years reducing the energy used in carbon capture and offering strong resistance to the presence of oxygen and contaminants. They will therefore bring benefits in terms of design and operating costs of the carbon capture unit.

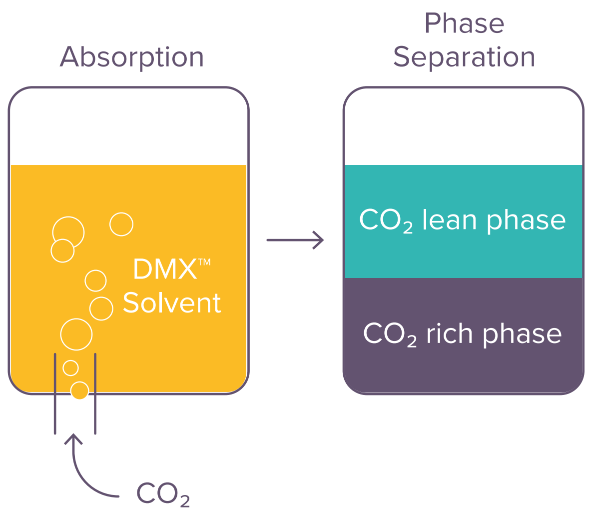
Solvent-based technologies can be further segregated based on the type of solvent used for carbon dioxide capture, including activated amines, amine blends, ionic liquids and biphasic solvents. A biphasic solvent is used in the case of the DMX™ technology developed by both IFPEN and Axens based on the use of an amine blend which forms two immiscible liquid phases under certain temperature and pressure conditions when loaded with CO_2.

Figure 13: IFPEN mini-plant in Solaize (France)

The **DMX™ technology** is built on very solid foundations since it benefits from over 60 years' experience in CO_2 removal on natural gas acquired by **Axens** and **IFPEN** through the licencing of the Advamine™ processes. Benefiting from prior developments through the Octavius and Valorco projects, including several laboratory experiments and pilot-scale testing (Figure 13), the DMX™ technology is now being demonstrated at laboratory scale and is ready to test industrially.

- The Octavius project, launched in 2012, was dedicated to reducing post-combustion CO_2 emissions of fixed sources such as coal-fired power plants. For this project, the DMX™ solvent has been compared to the MEA (monoethanolamine) reference solvent diluted at 30wt% in water.
- The Valorco project coordinated by ArcelorMittal and funded by ADEME is aimed at reducing and reusing CO_2 emissions from the steel industry. In this project, IFPEN evaluated the performance of the CO_2 capture process comparing MEA solvent at 30wt% with the DMX™ process, for different potential steel mill applications.

The DMX™ technology (Figure 14) represents a real breakthrough for post-combustion CO_2 capture based on absorption by a demixing solvent.

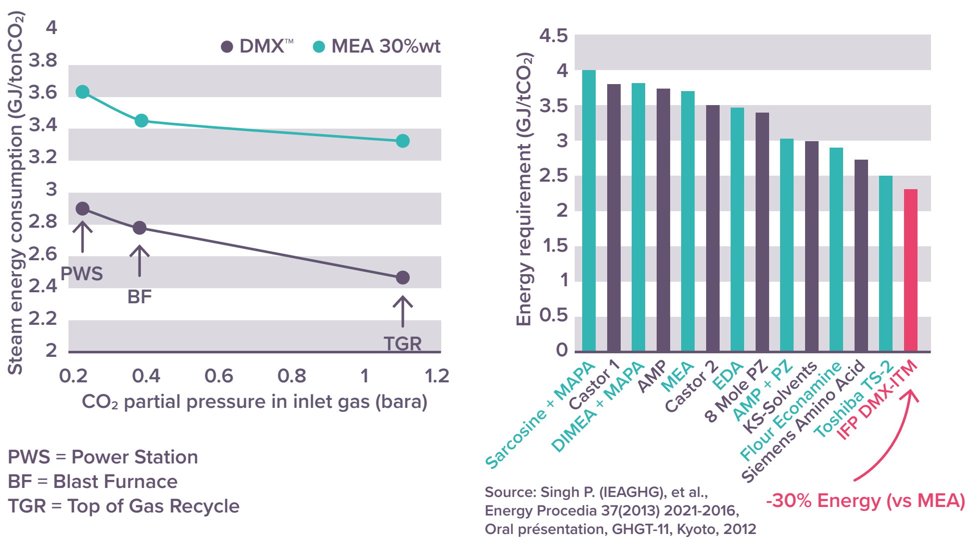


↑ Figure 14: The demixing principle

Advantages of the DMX™ technology

This second-generation process has several benefits:

- A regenerable solvent with a much higher cyclic capacity than commercially available solvents
- High solvent thermal stability with low degradation rate, making regeneration possible at higher temperature, and therefore producing CO_2 directly under pressure, leading to significant CO_2 compression cost savings for downstream sequestration or liquefaction
- Solvent stability also induces lower corrosion risks and therefore allows cheaper steel to be used
- A high capture rate (>90%) is achievable with high purity of produced CO_2 (>99%)
- Low steam energy consumption
- All these solvent properties lead to a 30% reduction in the energy penalty and in the total CO_2 capture cost (Figure 15)



↑ Figure 15: Reduction of energy penalty with DMX™ solvent

Go to the top of the document

DMX™ Technology Development Status

The first application of the DMX™ technology is expected to be CO_2 capture on blast furnace gas. Further applications will concern the decarbonization of flue gas from different origins, such as cement plants, coal power stations, waste incinerators, and petrochemical and refining units.

Currently, the DMX™ technology demonstration is part of the EU-funded **3D (for DMX™ Demonstration in Dunkirk)** Project. A pilot CO_2 capture unit will be installed in ArcelorMittal's steel mill in Dunkirk to treat gases from the plant with a capacity up to 0.5 tCO_2 captured/hr. This demonstration in Dunkirk is one of the objectives of the 3D project and will be the last step before the process is put on the market by Axens.

Axens constructed the demonstration facility (Figure 16) as a modular unit delivered at site. The operation of the demonstration plant starts in 2022 and lasts 14 months.

↑ Figure 16: The DMX™ demonstration unit under construction

Other applications are also being studied through the DinamX ("Demonstration and innovative applications of the DMX™ process") project funded by ADEME including a lime production plant case study with Lhoist and a Waste-to-Energy case study with Suez.

Go to the top of the document

DeCARBON'us

Axens proposes to assess the CCS full value chain through its Decarbonization consulting offer "DeCARBON'us". Performing technical and economical feasibility study on CCS full value chain and taking into account all technological blocks such as flue gas collection, heat integration, CO_2 capture, CO_2 post-treatment, CO_2 compression or liquefaction, CO_2 transport and CO_2 injection in storage as far as taxation and regulations aspects, DeCARBON'us offers support to identify the most appropriate CCS scenario and assess the full viability of CCS project.

LEARN MORE ABOUT

- Axens Consulting

3. LARGE-SCALE CCS ROLLOUT

Large-scale CCS rollout represents many challenges, the main ones being:

- **The costs** (CAPEX and OPEX) associated with carbon capture units. As discussed above, this issue is addressed mainly through the development of improved capture technologies.
- **Transport of CO_2:** CO_2 is typically transported either by pipeline over shorter distances or by boat for the liquefied gas. The latter option is especially suitable for offshore permanent storage sites.
- **Permanent storage of CO_2:** this is generally considered as reinjection into a suitable geological formation such as saline aquifers or depleted oil/gas fields, although alternatives such as sequestration by mineralization are also being studied. In the majority of current CCUS projects, the captured CO_2 is injected into an oil field for Enhanced Oil Recovery (EOR). Although the potential of suitable geological sites would appear to increase the need for CCS deployment considerably in the coming decades, social acceptance of such geological storage sites can be an issue in some places. In Europe today, the main CO_2 storage sites are being developed offshore in the North Sea by the UK, the Netherlands and Norway. They include the Norwegian Northern Lights project which will accept up to 1.5 MT CO_2/year in its first phase.
- **Taxation & Regulations:** last but not least, CCS comes at a cost. Suitable taxation or incentive schemes therefore need to be put in place in countries implementing GHG emission reduction policies. Tax incentives have been put in place in the US under the 45Q tax credit scheme. In Europe, allocated CO_2 quotas can be exchanged within the EU Emissions Trading System (ETS). For many years, prices on the ETS market remained well below typical CO_2 capture and storage costs announced between €50 and €150 per tonne. However, the situation is changing rapidly today (Figure 17), due to a tightening of the EU's CO_2 emission allowances. Some experts estimate that CO_2 prices may reach €80-90 per tonne by 2030.

Figure 17: ETS official prices (Source: https://sandbag.be/index.php/carbon-price-viewer)

Go to the top of the document

3.1. Hubs and clusters, a possible answer to large-scale CCS challenges

It is anticipated that large-scale CCS will take the form of hubs and clusters (Figure 18). In such an industrial ecosystem, multiple CO_2 suppliers are either located far from available storage facilities or are too small to economically justify having their own CO_2 capture, compression, transport and permanent storage facilities.

Hubs are networks of infrastructures connecting CO_2 emitters relatively close to storage (or export) zones. The hubs serve clusters – groups of several manufacturers, together emitting large amounts of CO_2 into the atmosphere – that are located close to geological sites appropriate for CO_2 permanent storage (and/or zones from which large amounts of CO_2 could be exported for storage). The purpose of clustering is therefore to centralize and pool CCS infrastructure for several industrial facilities, creating a network to collect the captured CO_2 and transport it to a storage hub.

The result is the reduced unit cost of CO_2 transport and storage, in particular for compression, liquefaction, transportation and storage on a larger scale, thus leading to:

- economies of scale
- commercial synergies
- reduced risk of investment
- synergies between multiple CO_2 sources and storage sites

This industrial ecosystem of CCS services also helps reduce the operational risk.

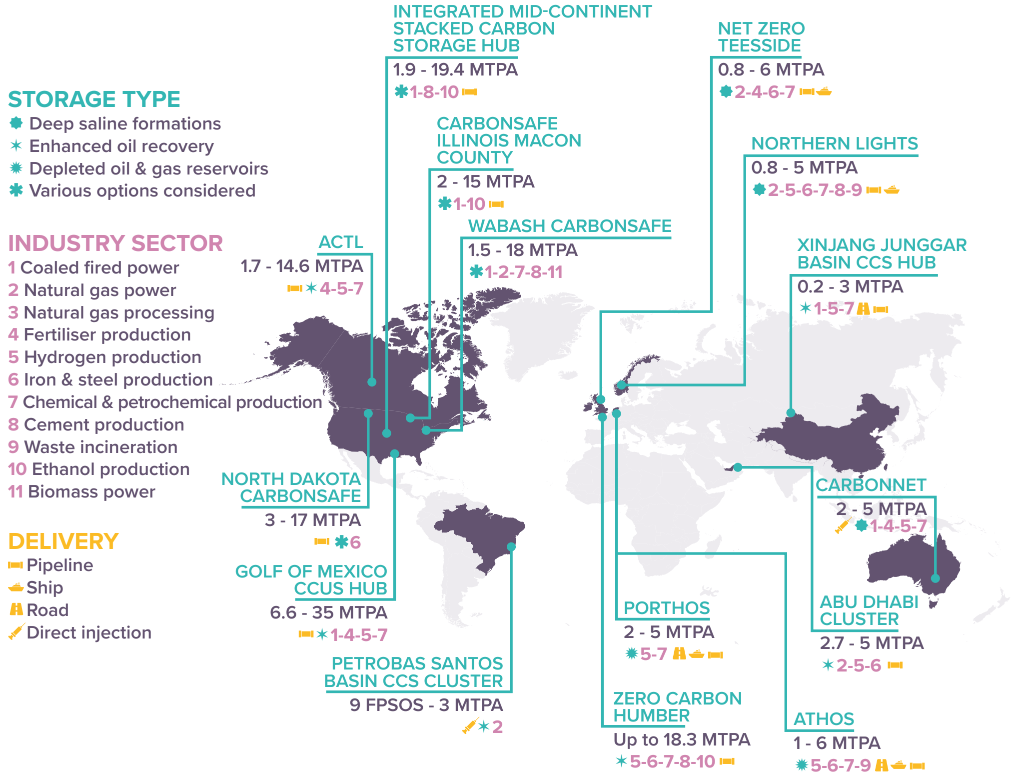
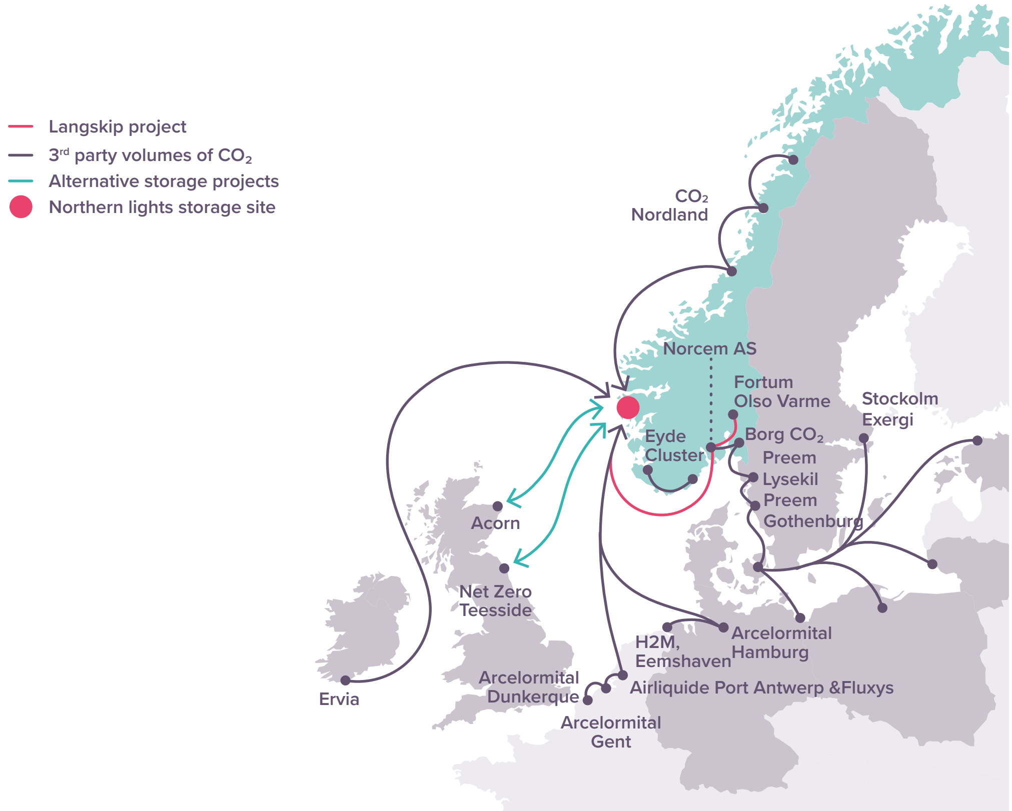


Figure 18: CCUS Hubs and Clusters globally, with significant developments in 2019 (Source: Global Status of CCS, 2020)

For all these reasons, most CCS projects worldwide are now planned as hubs and clusters. This is the case of the Northern Lights project in Europe, which is itself part of the imminent Longship project ('Langskip' in Norwegian). The Northern Lights Project

(Figure 19) is one of the most advanced hubs, connecting many CO_2 streams from different locations, in development in the North Sea. Its commissioning date is expected in 2024.



↑ Figure 19: Northern Lights Project – Potential Sources of CO_2 (Source: Global Status of CCS, 2020)

The Norwegian full-scale CCS project aims to expand CO_2 capture from industrial sites in Norway to other European countries and ship liquid CO_2 from these capture sites to an onshore terminal on the Norwegian west coast. From this terminal, the liquefied CO_2 will be transported by pipeline to an offshore location in the North Sea for permanent storage. Suitable places to store CO_2 in the North Sea have been identified as part of the Northern Lights project. This project will be the first large-scale CCS facility for the waste-to-energy and cement production sectors.

3.2. The European 3D project: development of a CO_2 Hub in the North of France

Apart from demonstrating DMX™ capture technology, the **3D project** also aims to develop the future European cluster in Dunkirk, a coastal city in Northern France, close to the North Sea potential storage zone, for capture and storage in the North Sea (Figure 20). Indeed, Dunkirk is one of the largest CO_2 emission zones in France due to its harbour activities, steel industry and various other industrial activities.

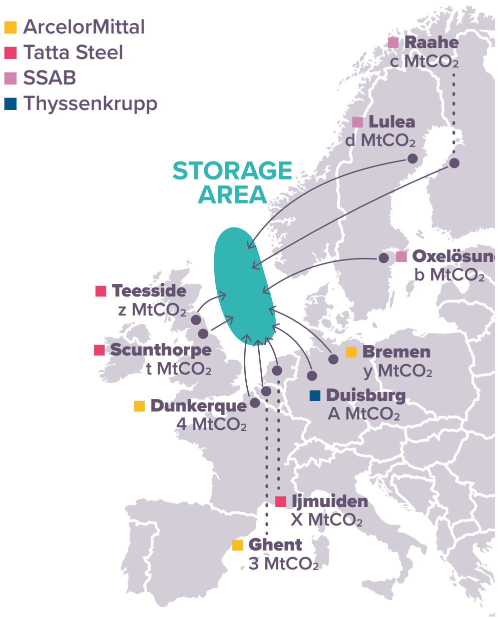
The 3D project therefore aims to participate in the worldwide rollout of carbon capture and storage.

LEARN MORE ABOUT

- **3D CCUS**

Go to the top of the document

Coordinated by IFPEN, the “3D” project brings together Axens and nine other partners from research and industry from six European countries: ArcelorMittal, Total Energies, Air Products, Brevik Engineering, CMI, DTU, Gassco, RWTH and Uetikon. This large group of partners ensures that all steps in the CO_2 capture chain (capture, conditioning of the CO_2, liquefaction, transport and storage) will be properly addressed.



The purposes of 3D include:

- Separate the energy molecules from our blast fumace gas to avoid further combustion
- Carbon Monoxide and Hydrogen to be used in ethanol fermentation
- Pure CO_2 that can also be re-used (like methanol, polyols, formic acid...) provided that there is enough renewable energy
- Industrial waste heat and excess renewable energy can be use.
- Develop a technology that is able to provide large quantities of storable CO_2
- Develop a technology that can be used in other industries.

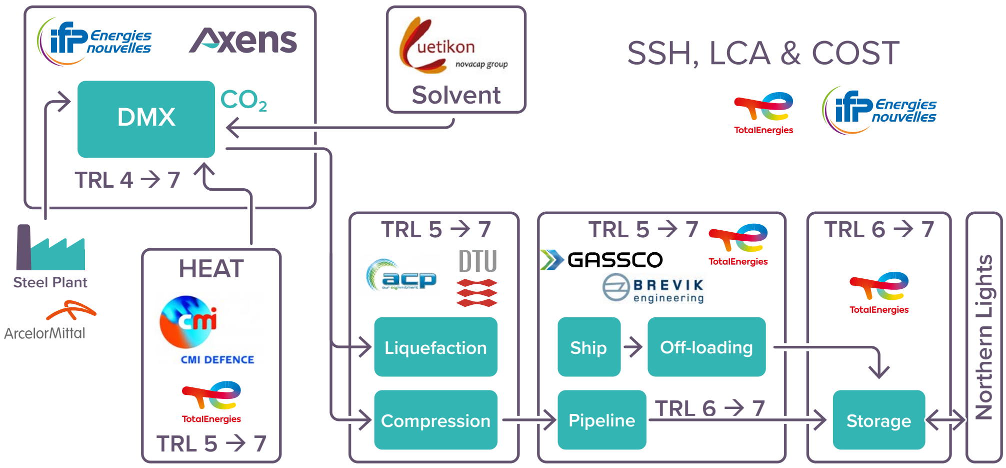
↑ Figure 20: 3D project purposes (Source: https://3d-ccus.com)

Of course, the first objective of the 3D Project is to demonstrate DMX™ technology through the construction and operation of the demonstration unit at the ArcelorMittal steel mill.

The second objective is to design a full-scale plant to capture 1 $MtCO_2$ per year for geological storage in the North Sea. This plant should be operational by 2025 and will implement the first industrial unit at the ArcelorMittal site in Dunkirk.

The third objective of this future European North Sea cluster in Dunkirk (Figure 21) is to capture, condition, transport and store 10 million tonnes of CO_2 per year and should be operational by 2035.

This cluster will have access to CO_2 transport and storage infrastructures in the North Sea developed by other projects such as Northern Lights.



↑ Figure 21: CCS Cluster in Dunkirk, 2035 (Source: https://3d-ccus.com)

The 3D project intends firstly to demonstrate the whole CCS chain from CO_2 conditioning and transport to storage at the CO_2 hub in Dunkirk.

Depending on the distance between the temporary storage facility and the reservoir, the CO_2 is transported by pipeline (for short distances) or by ship and then by pipeline (for long distances). For easier shipment, the CO_2 could be liquefied. The CO_2 captured from industrial plants will be stored permanently in gas (or supercritical) form in reservoirs under the seabed, in depleted gas fields and in geological cavities under the North Sea.

Go to the top of the document

CONCLUSION

Carbon Capture and Storage (CCS) is expected to play a vital role to the power and industry sectors that should be at the front line of efforts to tackle the global climate change. In fact, the CCS contribution is key for achieving the net-zero emission scenarios of the International Energy Agency (IEA). In response, CCS hubs and clusters are arising throughout the world, consisting of new-wave CCS ecosystems sharing facilities allowing operational synergies and economies of scale, but are yet today far too few as regards the decarbonisation targets.

The Carbon Capture technologies are classified from emerging to mature ones, the primary goals being to deploy commercially the mature technologies and go on with further innovations to reach the challenging climate targets.

The two main types of carbon capture application are the pre-combustion for the CO_2 capture on synthetic gas before its combustion or for blue hydrogen production and the post-combustion designed for exhaust gases. For both, a wide range of technical solutions are available, among which chemical and physical absorptions, to name some of the most significant.

Moreover, the combination of carbon capture and storage with bioenergy is part of the few technologies that may offset hard-to-abate emissions to achieve the net-zero climate goal.

The **3D (for DMX™ Demonstration in Dunkirk) project**, consists in the demonstration of the new breaktrough CO_2 capture technology DMX™ together with the development of a future European cluster in Dunkirk (France) that is one of the largest CO_2 emission zone in France due to its harbour activities and its steel and other industries. This project is definitely an important step for the deployment of carbon capture and storage worldwide.

OIL REFINING

PETROCHEMICALS

GASES

ALTERNATIVES
& RENEWABLES

WATER

Axens is a Group providing a complete range of solutions for the conversion of oil and biomass to cleaner fuels, the production and purification of major petrochemical intermediates as well as all of natural gas treatment and conversion options. The integrated offer includes technologies, equipment, furnaces, modular units, catalysts, adsorbents and related services, commercialized under "Axens Solutions", "Heurtey Petrochem Solutions" and "Axens Horizon" brands.

Axens
Powering integrated solutions

axens.net