CCUS – A POWERFUL SET OF TECHNOLOGIES AT THE SERVICE OF DECARBONIZATION

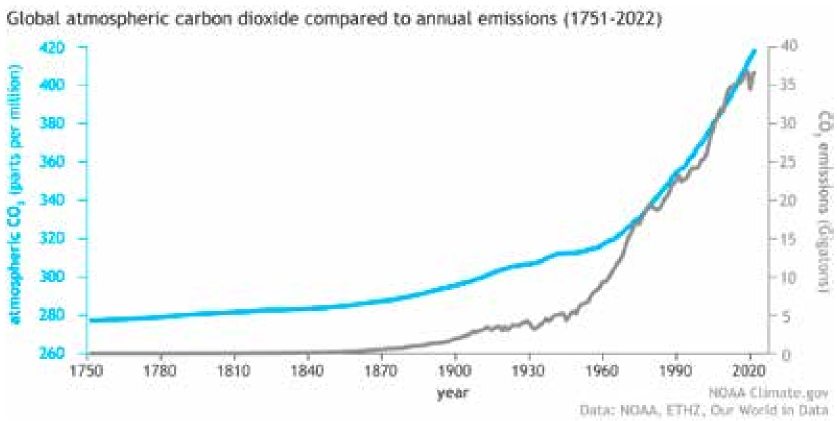
BY ENRICO ZUIN, HEAD OF GLOBAL WELDING TECHNOLOGY

Carbon dioxide (CO_2) emissions resulting from human activities, particularly from the combustion of fossil fuels, have led to unprecedented levels of atmospheric CO_2 concentration, contributing significantly to global warming and climate change. Due to the increasing amounts emitted by human activities, the concentration of CO_2 in the earth's atmosphere averages 420 ppm.

This may not sound like much but consider that in pre-industrial times when anthropogenic emissions were practically absent, the concentration level was around 280 ppm. There has been a 67 % increase with a sharp acceleration since the 1970s.

The development of renewable energy sources in recent years has failed to compensate humanity's growing demand for energy. As a result, total CO_2 emissions have grown over time to approximately 37 billion tons (37Gt).

Carbon Capture and Storage technology is considered one of the most important solutions to reach carbon neutrality.



Source: http://www.climate.gov/media/14596

PRINCIPLES OF CARBON CAPTURE

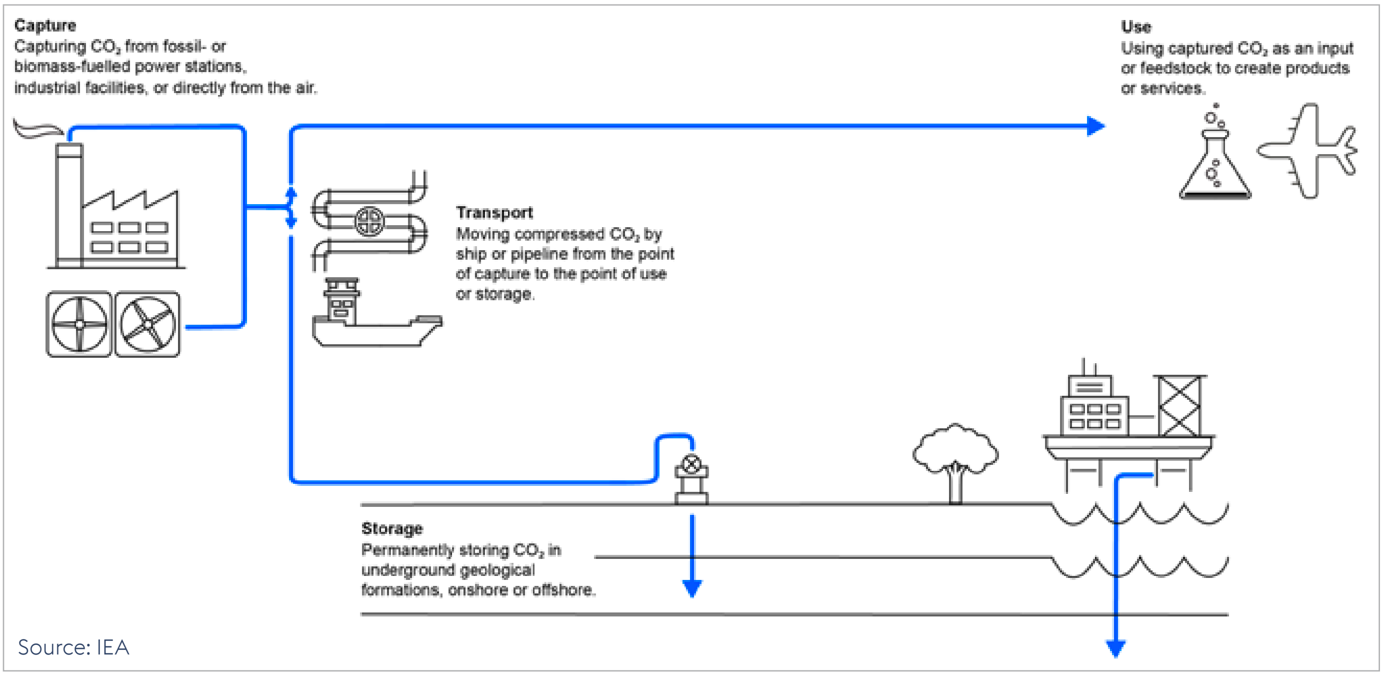
In response to these challenges, carbon capture technology has emerged as a promising solution to mitigate CO_2 emissions and combat climate change.

Carbon capture technology plays a crucial role in reducing CO_2 emissions by capturing CO_2 from industrial processes and power generation facilities before it is released into the atmosphere. By preventing the release of CO_2, carbon capture technology helps mitigate climate change while enabling continued use of fossil fuels during the transition to renewable energy sources.

CCUS is an acronym that groups together all technologies, available or under development, suitable for capturing the CO_2 emitted by industrial facilities or directly from the air:

CC = carbon capture, it refers to the capture of the CO_2
U = utilization of the CO_2 captured
S = permanent storage of the CO_2 captured

The CO_2 Value Chain



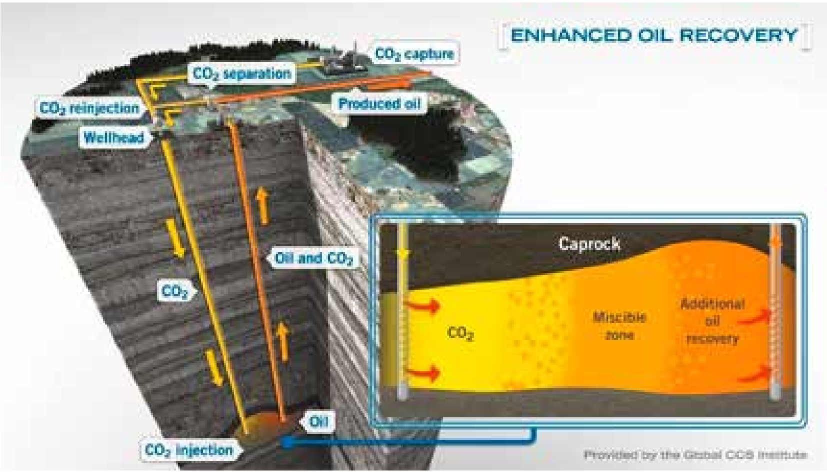
Source: IEA

The captured CO_2 can be transported via pipeline or transported in its liquid state by ship. Then it can be used in other industrial applications as a raw material to create other products. Finally, the captured CO_2 can be injected and permanently stored into deep geological formations or depleted oil and gas reservoirs which may be on land or at offshore sites.

CO_2 CAPTURE – THE CURRENT SITUATION

Today, only 45 Mt of CO_2 are captured every year in about 40 operational plants. Most of the captured CO_2 is used in EOR (enhanced oil recovery) processes to improve oil and gas extraction.

50 new capture facilities are set to be operating by 2030, increasing the total capture capacity to 383 Mt/CO_2/yr.
To be on track with the NZE Scenario, the total capacity in 2030 should be at least 1.100 Mt/CO_2/yr.



Source: Global CCS Institute
www.globalccsinstitute.com/resources/ccs-image-library

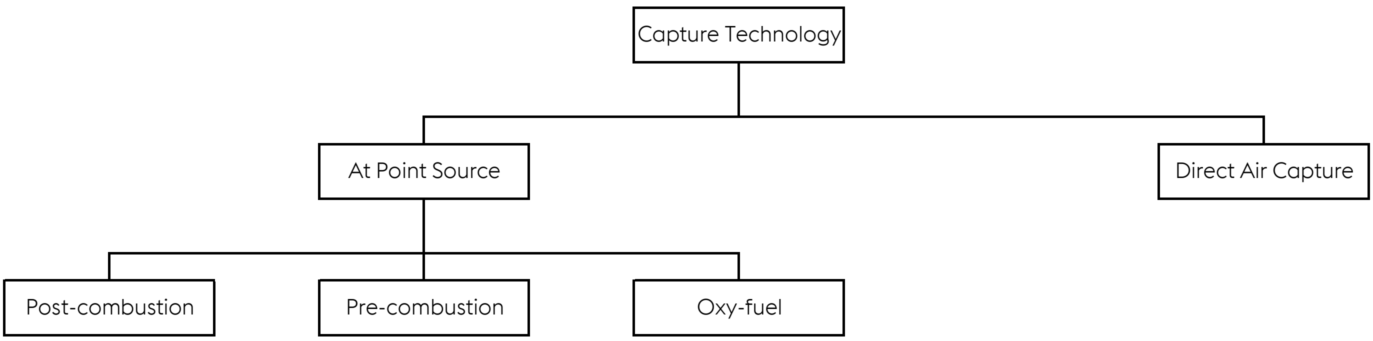
Enhanced Oil Recovery (EOR)

If the differential pressure between the surface and the underground well is not enough to drive the extraction, CO_2 is then injected to decrease the oil viscosity, enabling additional extraction.

While initial EOR developments used naturally occurring carbon dioxide deposits, technologies have been developed to inject CO_2 captured from industrial point sources.

TYPES OF CARBON CAPTURE TECHNOLOGIES

Carbon capture technologies can be classified into four main categories: pre-combustion capture, post-combustion capture, oxy-fuel combustion capture and direct air capture (DAC). Each type of technology utilizes different capture mechanisms and processes to capture CO_2 from different sources.



Pre-combustion and post combustion are mature technologies that can be useful in eliminating emissions from existing industrial plants after retrofitting operations. Here are some examples:

Industrial Process	CO_2 Content (%)	Applicable Technology
Aluminum production	1 - 2	Post-combustion
Natural gas-fired power plant	3 - 4	
Coal-fired power plant	13 - 15	
Cement production	14 - 33	
Hydrogen production	15 - 20	Pre-combustion
Natural gas processing	2 - 65	

Source: Axens

Oxy-fuel is a viable alternative to removing CO_2 from the flue gas of a conventional air-fired fossil fuel plant. The idea is to burn the fuel with almost pure oxygen to produce a flue gas composed essentially of H_2O and CO_2. The high concentration of CO_2 in the flue gas will make the capture and separation easy, decreasing the overall efficiency penalty.

Some industrial processes involving the production of syngas will be described in the following chapters. It is worth remembering what syngas is and how it is produced. Syngas is a mixture of primarily hydrogen and carbon monoxide that can contain some small amount of carbon dioxide, methane and water. It is mainly produced by Steam Methane Reforming (SMR) and the gasification of coal or biomass.

The following reactions take place in SMR in the presence of a specific catalyst:

$CH_4 + H_2O \rightarrow 3H_2 + CO$ (syngas)
$CO + H_2O \rightarrow CO_2 + H_2$ (water gas shift reaction)

The first reaction is the reforming reaction and the second reaction is the water gas shift reaction which increases the amount of hydrogen produced.

Coal gasification involves the following reactions:

$3C + O_2 + H_2O \rightarrow H_2 + 3CO$ (syngas)
$CO + H_2O \rightarrow CO_2 + H_2$ (water gas shift reaction)

Syngas is used in the refinery process, for power generation and as a raw material to produce other chemical compounds.

PRE-COMBUSTION CAPTURE

Pre-combustion carbon capture allows the removal of CO_2 from a gas mixture before its utilization, typically from syngas. Purified syngas can subsequently be burned to produce electricity using suitable gas turbines. This process can also be used to produce Blue Hydrogen or for natural gas sweetening after extraction. The proprietary physical solvents used to capture the CO_2 are Selexol (UOP) and Rectisol (Linde/Air Liquide), which works well at a high concentration of CO_2 and can tolerate the presence of residual oxygen. CO_2 is then desorbed and released from the solvent by decreasing the pressure in the stripper vessel.

Industrial Process

Integrated Gasification Combined Cycle (IGCC)

Coal, petroleum coke and other feedstocks can be used to produce electricity via a gasification process.

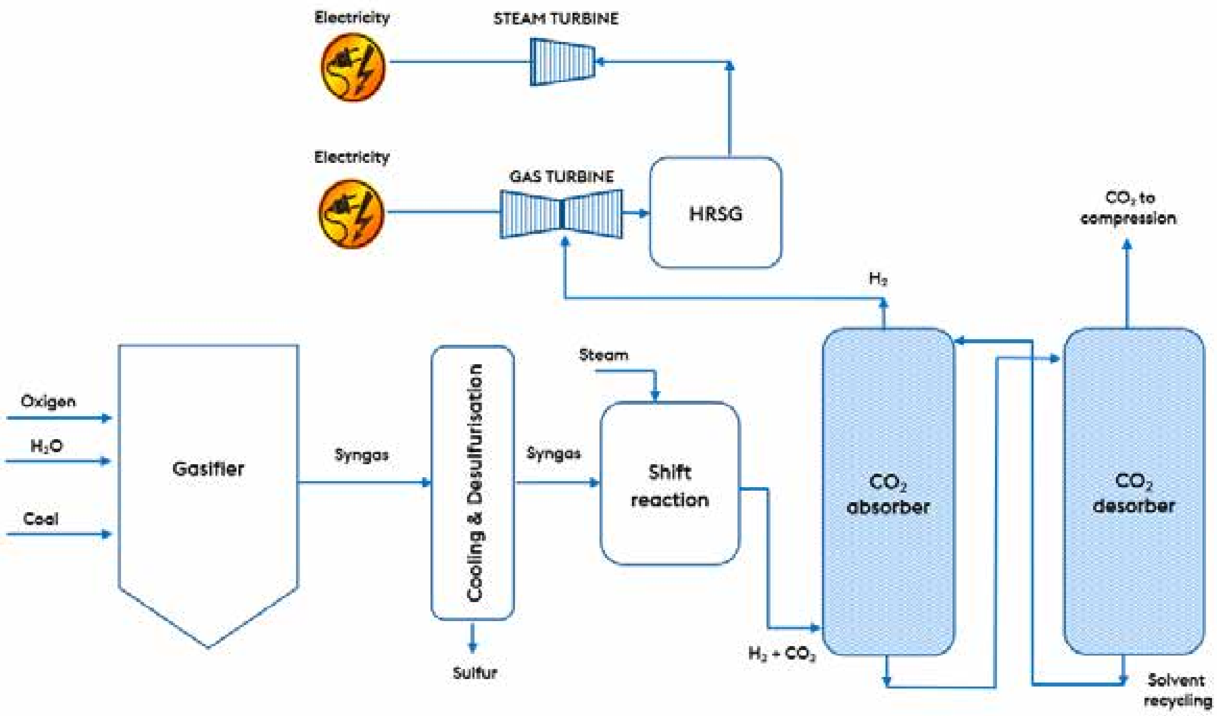
1. The feedstock is gasified in the Gasifier and converted to syngas.

2. After cooling and desulfurization, the syngas is subjected to the shift reaction to convert the CO to CO_2 and obtaining a gas mixture composed primarily by H_2 and CO_2.

3. The latter are removed to feed syngas with a high H_2 content into a gas turbine for power generation (a gas turbine that can be operated with 100% H_2 is under development, currently H_2 can only be used in mixed form).

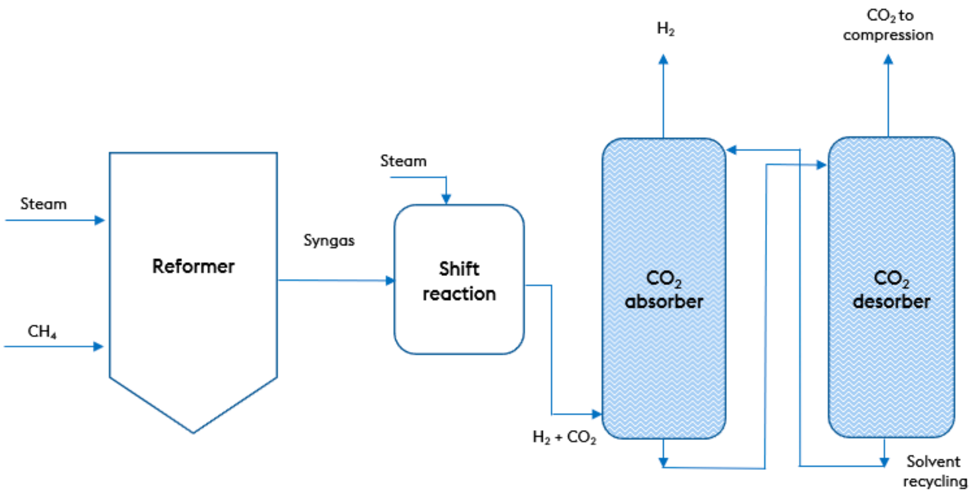
4. The heat recovery steam generator (HRSG) utilizes the waste heat from the hot exhaust from the gas turbines to generate steam. This is used to produce additional power in the steam turbine phase of the combined cycle.

5. The captured CO_2 is compressed and sent to its final destination.



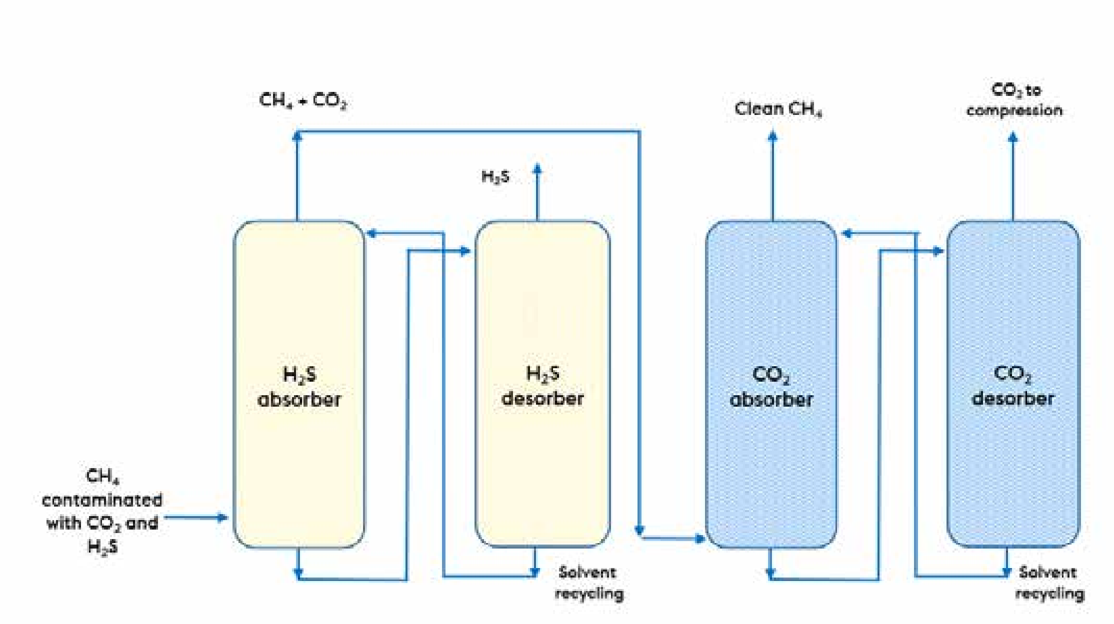
Production of Blue Hydrogen

In the Steam Methane Reforming process, natural gas is used to produce hydrogen having CO_2 as a by-product. This CO_2 can be captured and separated from the hydrogen.



Natural Gas processing plant

Most of the world's sources of natural gas (CH_4) also contain CO_2 and H_2S that must be removed before shipping natural gas via pipelines or liquefying it to produce LNG. This process, known as NG sweetening, is very well established in the oil and gas sector.



POST-COMBUSTION CAPTURE

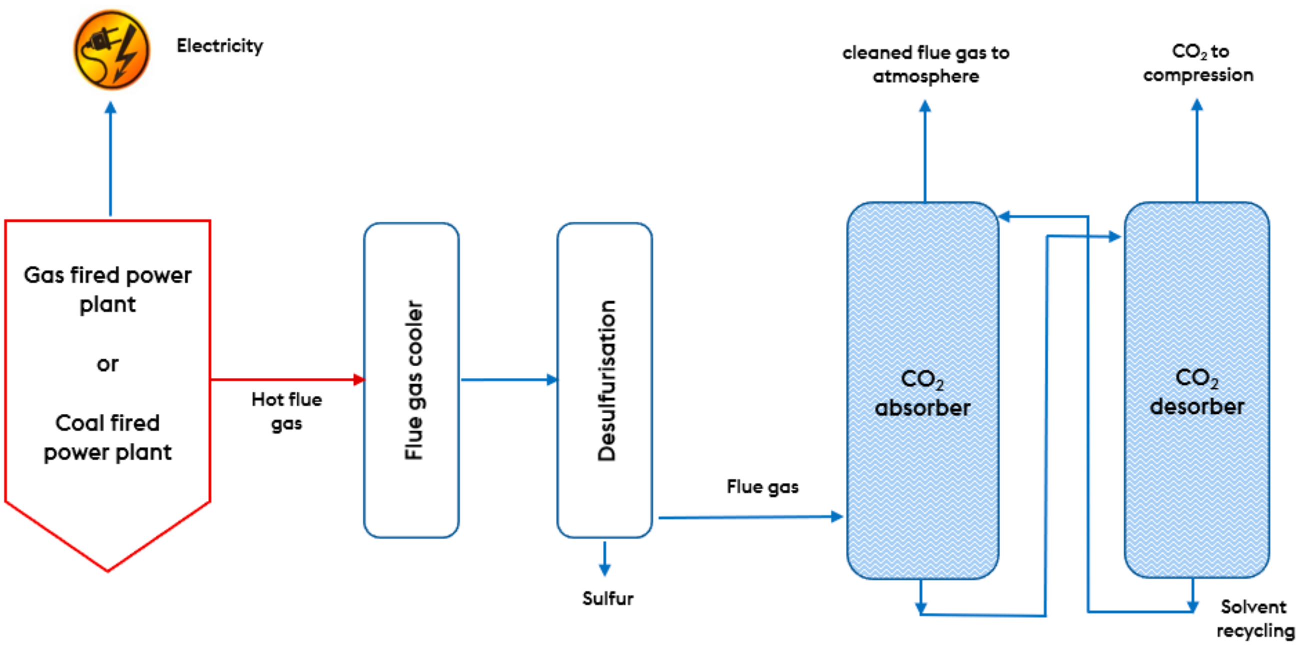
The Capture and separation of CO_2 from the flue gas of a combustion system. First, exhausted flue gas must be purified (removal of oxygenate compounds, NOx, SOx, metal dust, etc.) and cooled, then the CO_2 is separated from the flue gas by passing the flue gas through a continuous scrubbing system. The system consists of an absorber and a stripper. Typically, amine-based solvents are used.

The release of CO_2 is obtained by breaking the chemical bond between CO_2 and the solvent by providing heat. The greater the energy required to release CO_2 from the solvent, the lower the overall efficiency of the process. This is why research is focusing on developing capture mechanisms that are more efficient than first-generation MEA (monoethanolamine) and more tolerant of the impurities associated with this process.

Industrial Process

Gas-fired or coal-fired power plant

A carbon capture facility is coupled with a fossil guel power plant in order to separate the CO_2 from the flue gas. Cleaned gas that is released into the atmosphere is composed of nitrogen and water vapor. Any CO_2 resulting after separation is compressed and dehydrated for transport and storage or utilization purposes.



OXY-FUEL COMBUSTION CAPTURE

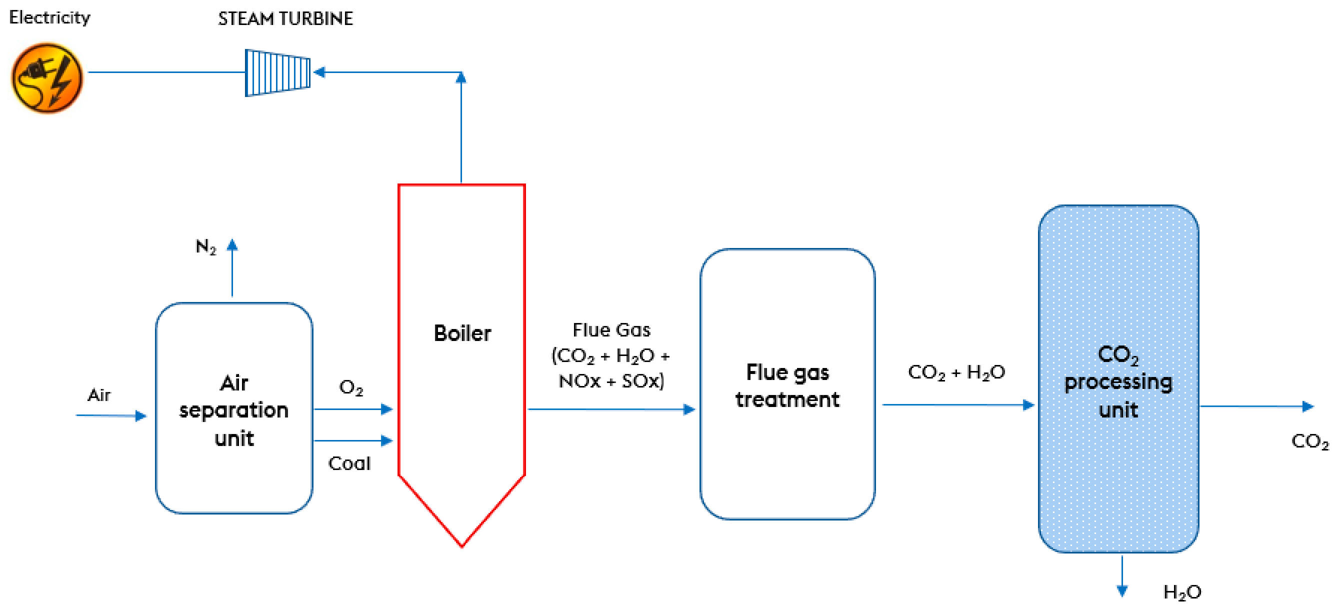
In the oxy-fuel combustion process the fuel (Coal or natural gas) is burned with almost pure oxygen instead of air. When using air to burn coal, the CO_2 concentration in the flue gas is about 15%. If N_2 is removed and only O_2 is used, then the concentration increases to more than 90%.

As flue gas is composed of CO_2 and H_2O, the latter can be easily removed by dehydration to obtain high purity CO_2. The large amount of CO_2 produced makes its use ideal as a working fluid in a supercritical CO_2 power cycle, which produces low-cost electricity and in addition compensates the cost of the air separation unit. The first utility scale power plants based on the Allam cycle are under construction in Perman Region (Texas) and will begin operation in 2027/2028 (https://netpower.com/first-utility-scale-project).

Industrial Process

Coal-fired power plant

An air separation unit operates in front of a coal-fired power plant in order to separate O_2 from the air. Flue gasses are treated to separate SOx, NOx and other impurities. Finally, the CO_2 processing unit removes the water by dehydration and the CO_2 is compressed for storage or transportation purposes.



DIRECT AIR CAPTURE (DAC)

As we have seen the three main technologies: pre-combustion capture, post-combustion capture, and oxy-fuel combustion capture can help to reduce, or eliminate, the non-avoidable emissions when working in conjunction with an emitting industrial sites. But how can we remove the historic accumulated CO_2 from the air?

The answer is the Direct Air Capture (DAC) that consist in a chemical process able to remove CO_2 from the atmosphere. Capturing CO_2 from the air is more energy intensive – and therefore more expensive – than capturing it from a point source. This is because CO_2 in the atmosphere is much more dilute than, for example, in the flue gas of a power station. One way to provide the DAC system with the energy it needs could be to combine it with a clean power generation system, such as solar or wind, but the intrinsic discontinuity of these power generation technologies could be a limiting factor.

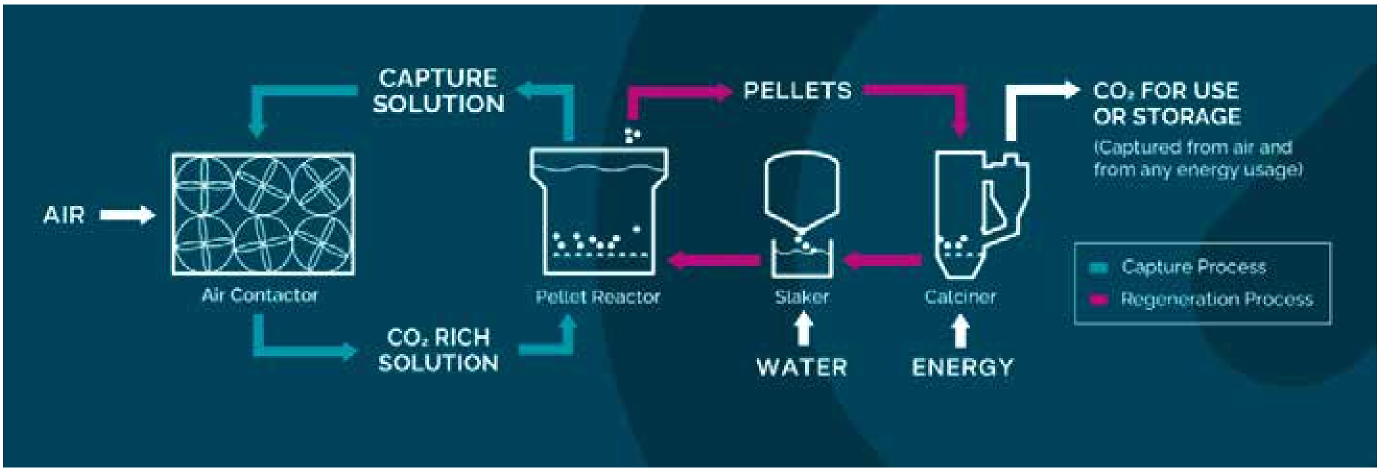
At the present time two start-ups possess the most promising technologies for DAC.

CARBON ENGINEERING

Carbon Engineering is a Canadian company that uses a capture technology on an aqueous hydroxide's solution used as liquid solvent. The most common alkali used are potassium hydroxide (KOH) and sodium hydroxide (NaOH).

Process Description

The KOH solution reacts with the CO_2 in the air contactor to form K_2CO_3 that is subsequently converted to solid $CaCO_3$. The calcium carbonate is heated In the calciner to around 900 °C to release the captured CO_2 and the solvent is regenerated in the closed chemical loop.



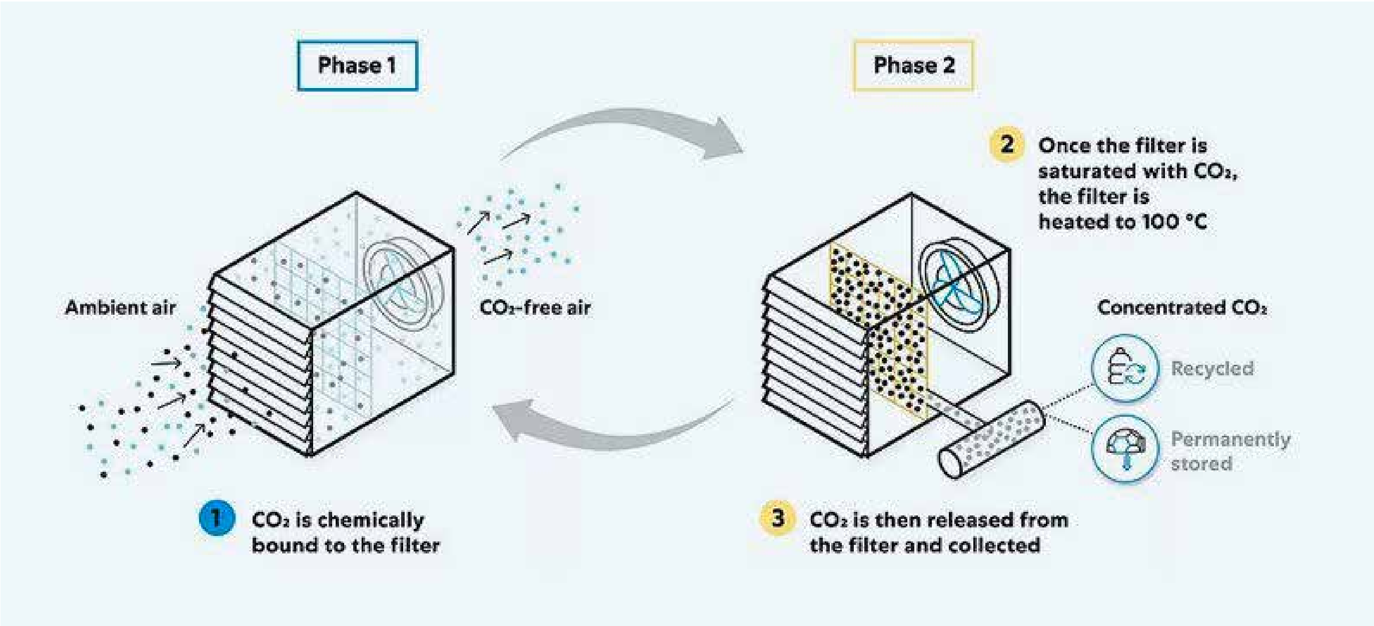
Source: CarbonEngineering.com

CLIMEWORKS

CLIMEWORKS is a Swiss company that bases its capture technology on a solid sorbent filter.

Process Description

Air is drawn into the collector with a fan. Carbon dioxide is captured on the surface of a highly selective filter. Once the filter material is full of carbon dioxide, the collector is closed. The filter material is then heated to approximately 100 °C to release the carbon dioxide.



Source: Climeworks.com

Dozens of other companies are involved in researching DAC methods that can reduce the amount of energy required to support the process.

Some of the most promising capture technologies include:

- Electro swing adsorption
- Zeolites
- Highly selective ion membranes
- Metal organic framework (MOF)

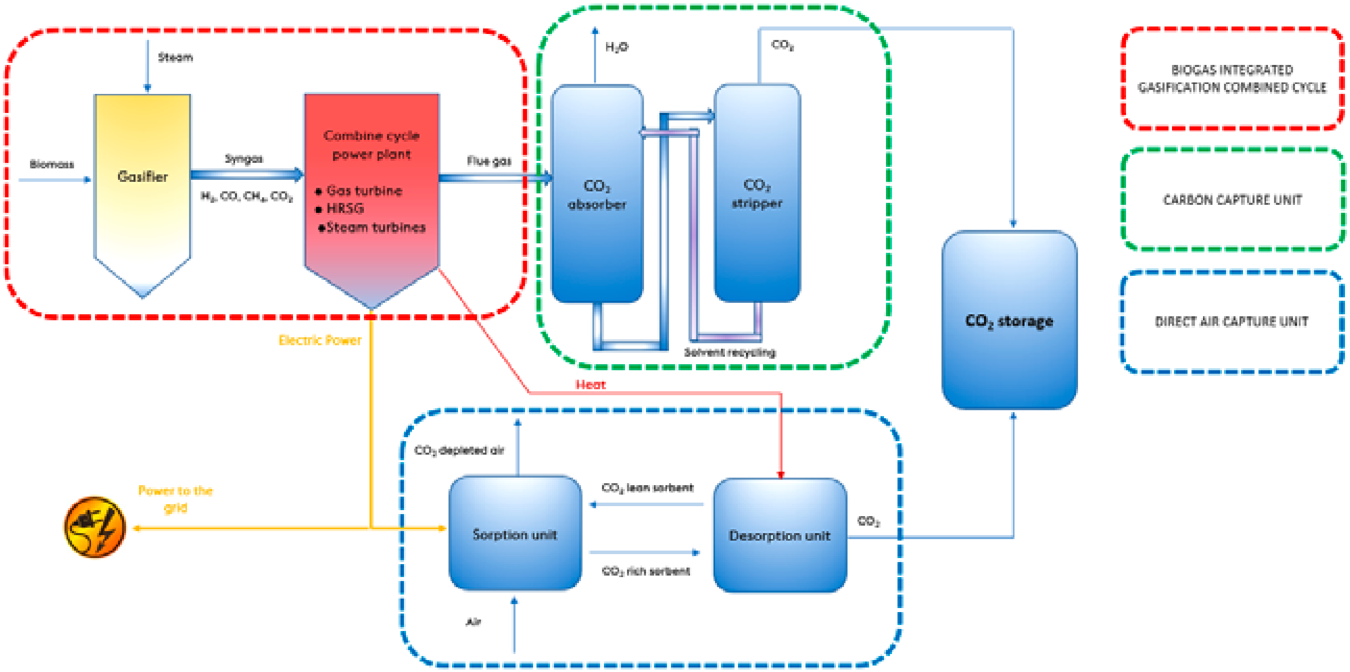
THE NEGATIVE EMISSION CONCEPT

A very promising solution to provide carbon-free energy to a DAC system consists of integrating three different systems together:

1) BIGCC (biomass integrated gasification combined cycle)
2) CCS (carbon capture and storage)
3) DAC (direct air capture)

The combination of BIGCC + CCS is defined as BECCS (bio energy with carbon capture and storage).

The conversion of biomass into energy is considered carbon neutral because the CO_2 released during energy conversion is considered to have been previously absorbed by biomass during the growing process thanks to the photosynthesis. The CO_2 absorbed from the atmosphere during photosynthesis is simply released back. Together, the integrated systems can achieve compound negative emission.



The biomass (e.g wine lees, crop waste, livestock manure, municipal garden waste, kitchen waste) are converted into syngas by the gasification process, then the syngas is moved to the "combined cycle" power block (consisting of one or more gas turbines and steam turbines). Syngas is combusted in highly efficient gas turbines to produce electricity. The excess heat from the gas turbines and from the gasification reaction is then captured, converted into steam, and sent to a steam turbine to produce additional electricity.

The carbon capture unit sequesters the carbon dioxide resulting from the combustion of the syngas (post-combustion technology) and stores it for future transportation, use or permanent storage. Part of the electricity and heat produced by the BECCS unit is utilized to drive the DAC unit that captures CO_2 from the atmosphere and transfers it to the CO_2 storage.

This new concept of power plants can produce energy and at the same time contribute to eliminating CO_2 from the air and, ultimately, it offers an important contribution to waste management.

CARBON DIOXIDE: INTERMEDIATE STORAGE AND TRANSPORTATION

The captured carbon dioxide must be transported from the point of capture to the point of permanent storage or use. Intermediate storage will sometimes be necessary, especially in the case of intermittent production/shipping. The two most relevant means are **pipeline transport** and **maritime transport** using large CO_2 carriers. The experience gained from the maritime transport of LNG will be important for developing CO_2 transport.

Intermediate storage

After liquefaction, the CO_2 is intermediately stored in cylindrical tanks, spherical tanks or bullet type tanks. Operating temperatures vary according to the tank pressure design. Typical storage conditions include a pressure of 6-7 bar and a temperature of -50/-52°C.

Base materials used for the construction of this tanks are:

- P355ML2
- P355NL2
- P460ML2
- P460NL2
- SA537 Cl.2
- SA738 Gr.B

voestalpine Grobblech and voestalpine Bohler Welding can offer different package solutions for plates and welding consumables for this application.

The following table gives an example of filler materials typically used in the construction of storage tanks:

Base material	SMAW	FCAW	SAW
P355NL2 P355ML2	Bohler FOX EV 50	Diamondspark 53 RC	Union S3Si UV 418TT
P460NL2 P460ML2	Bohler FOX EV 65	Diamondspark Ni1 RC-SR	Union S2NiMo1 UV 420TTR-C
SA537 Cl.2	Bohler FOX EV 65	Diamondspark Ni1 RC-SR	Union S2NiMo1 UV 420TTR-C
SA738 Gr.B	Bohler FOX EV 65	Diamondspark Ni2 RC*	Union S3NiMo1 UV 418TT

*only for as welded condition.
If PWHT has been requested, consult the Global Welding Technology team.

The selection was made assuming a PWHT of 580 - 600°C for 3 hours.

Pipeline

For large volume pipelines, transporting CO_2 in dense and/or gaseous phases may be the preferred solution. The transportation of pure CO_2 (>99%) in dry or wet form and free of impurities is not a major problem.

On the contrary, pipeline transportation of CO_2 captured from industrial emitters (by pre-combustion, post-combustion or oxy-fuel methods) must take into account the presence of contaminants such as: N_2, O_2, H_2, CH4, SOx, H_2S, NOx, CO, chlorides and H_2O.

However. no matter how low the concentration of these contaminants may be, even a few hundred ppm can lead to problems of phase stability and corrosion. The possible formation of dry ice must also be taken into account which is why high demands must be placed on low temperature toughness.

International standards such as ISO 27913 and DNV-RP-F104 can support the design of new pipelines. Depending on the corrosion risk assessment, the material selection may include carbon steel pipes (e.g., API 5L X65 – X70) with internal CRA cladding or with a corrosion allowance.

Voestalpine Grobblech and voestalpine Bohler Welding offer various solutions for pipeline plates and welding consumables, either for manual or mechanised welding processes. The wide range of electrodes (basic and cellulosic), solid and flux cored wires fulfill the welding requirements in different positions.

pipeRunner® – The orbital welding system for FCAW system is designed for pipeline and process piping girth welds (from carbon steel to CRA materials).

» pipeRunner® is designed for girth welds vertical up with flux cored wires.
» Being one of the lightest systems on the market makes it easy to handle.
» All of the components are first-class products designed in Germany.
» No need for site beveling machines and internal clamps
» Very easy to operate as the remote control has all the functions in the palm of your hand
» For high strength pipeline steels but also perfectly suitable for piping and high-alloyed clad pipes

Liquid CO_2-cargo Vessel

Depending on the pressure and temperature conditions, the material can range from carbon steel with improved toughness properties to high-strength steel.

voestalpine Grobblech has launched two new steel grades for LCO_2 transportation that have been approved by all renowned classification societies.

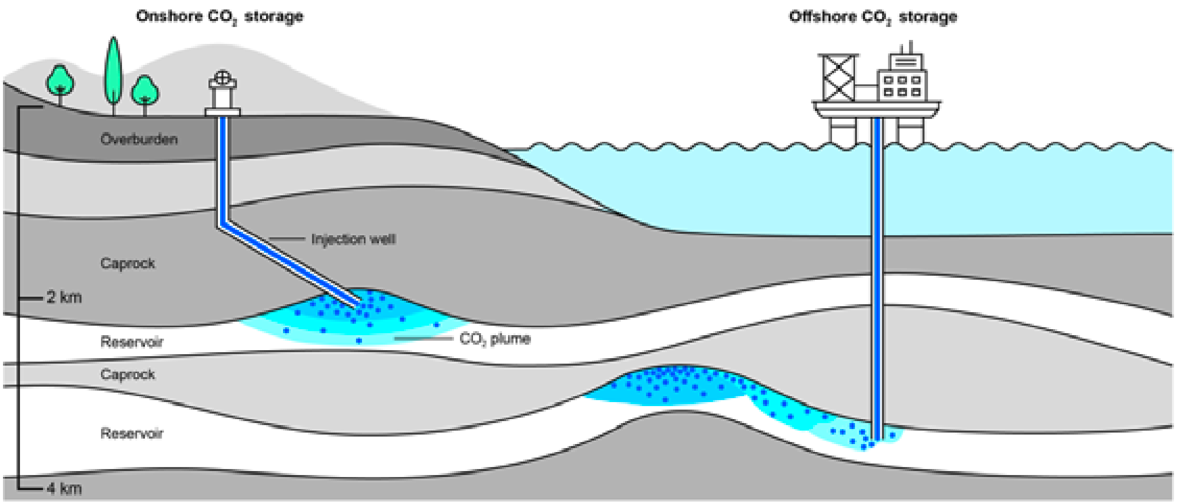
» F550 TMCP Toughcore for medium pressure storage design
» F460 TMCP Toughcore for low pressure storage design.

Nickel-based welding consumables meet the high toughness requirements, low-alloy solutions are under development.

Source: HB Hunte Engineering
Heavy plates for CO_2 applications (voestalpine.com)

CARBON DIOXIDE: PERMANENT STORAGE OR UTILIZATION

Once the CO_2 has been captured using one or more of the techniques described above, it can be stored permanently or used as raw material to produce other valuable products. In the IEA Net Zero Emissions by 2050 Scenario (Net Zero Scenario), about 5.9 Gt of CO_2 will be captured and stored in 2050. This will require a considerable expansion of CO_2 storage capacities.



Source: IEA

A typical option for permanent storage is to inject the captured CO_2 into a suitable geological reservoir where remains trapped.

» Examples of suitable geological reservoirs are: Depleted oil and gas field
» Saline formation

The alternative to permanent storage is to use the captured CO_2 as a raw material for the manufacture of valuable products. The creation of a CO_2 value chain will help to expand the opportunities for the use of CO_2 and will make this new market financially viable and attractive.

Some potential utilizations are:

Methanol production	Methanol can be used directly as a liquid fuel for internal combustion engines and direct methanol fuel cells (DMFC) Methanol synthesis can be synthesized via CO_2 hydrogenation: $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$
Methane production	Synthetic methane is a readily exportable fuel that is supported by existing infrastructure for storage, transport and use. Methanol synthesis can be synthesized via CO_2 hydrogenation using a specific catalyst: $CO_2+4H_2 \rightarrow CH4+2H_2O$
Urea production	Urea is produced by the reaction of carbon dioxide and ammonia. $2NH_3 + CO_2 \rightarrow [NH_4]+[NH_2COOH]-$ (ammonium carbamate) $[NH_4]+[NH_2COOH]- \rightarrow CO(NH_2)2 +H_2O$
Building materials production	CO_2 can be used in the production of building materials such as concrete. This option achieves two goals: 1) CO_2 utilization 2) Permanent sequestration into the product

CORROSION AND MATERIAL SELECTION FOR THE CAPTURE PROCESS

Typically, the CO_2 used for EOR process come from a clean source, like natural reservoirs, with well-controlled water content. For CCS, the CO_2 can originate from a variety of industrial sources (most are relevant for CCS hub-projects) and therefore contain a variety of impurities. Complete removal of these impurities may not be cost-effective or technically feasible. Therefore, it would be advisable to select materials that can withstand potentially unfavorable conditions at the extreme limits of the expected impurities and temperature.

Depending on the capture process and the origin on the CO_2, the environment may be more reducing or oxidizing. For example, the CO_2 stream coming from a pre-combustion capture plant is likely to contain more H_2S (reducing agent), while the CO_2 stream coming from post-combustion and oxy-combustion is expected to be more oxidizing in nature (presence of O_2, NO_2, SO_2).

Considering that many planned projects are based on the CCS hub concept, the material selection must mitigate the corrosion risk posed by all all the potential impurities and mechanisms. Water must be present for corrosion to occur. The CO_2 dissolves in the water and forms carbonic acid. SOx, NOx, H_2S, and other contaminants can also react with each other to form strong acids, including nitric acid (HNO3) and sulfuric acid (H_2SO_4), and possibly elemental sulfur.

The low pH of the condensed water can also lead to the depassivation of corrosion-resistant alloys, resulting in localized corrosion and possibly stress corrosion cracking. Oxygen, H_2S and chlorides are also triggers for SCC. When selecting materials, it is important not to forget what has been learnt in the processes of the oil and gas industry and the performance of materials in flue gas desulphurisation plants and in amine treatment units.

We can analyse the following components for the CO_2 capture process:

» **Scrubbers and dehydration**

All the necessary treatments to remove the most part of impurities and water before the capture process takes place.
Corrosion risk from impurities such as: N_2, O_2, H_2, CH4, SOx, H_2S, NOx, CO, chlorides in the presence of H_2O.
The possible material selection includes carbon steel or low-alloy cladded materials with CRA such as 22Cr, 25Cr, and Ni-base alloy or solid wall parts made ofstainless steel

» **Absorber Vessel & CO_2 stripper/desorber**

Corrosion risk from amine/oxygen interaction, glycol and residual impurities. The possible material selection includes carbon steel or low-alloy cladded materials with CRA such as 316L, 904L, 6Mo grades and Ni-based alloys.

» **Process Piping (High corrosion risk)**

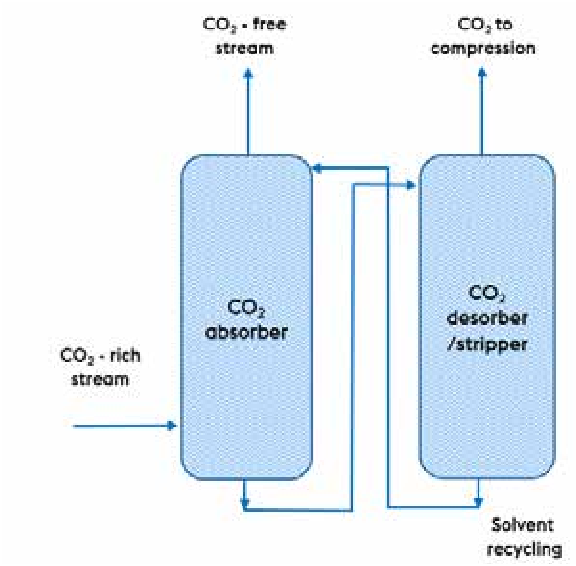
General corrosion risk as described above.
The possible material selection includes materials like 316L, 22Cr, 25Cr and Ni-based alloys.

» **Process Piping (Low corrosion risk)**

Carbon steel + corrosion allowance

» **Compressors**

Carbon steel/low-alloy steel + CRA cladding to cover downtime condition when condensation may occur.



The AMPP Guide 21532 ed. 2023 “Guideline for Materials Selection and Corrosion Control for CO_2 Transport and Injection” proposes upper concentration limits for a number of impurities in the CO_2 stream. voestalpine Bohler Welding can offer a complete range of filler materials for welding and cladding stainless and Ni-based material.

https://www.voestalpine.com/welding/global-en/products/consumables/welding-consumables/

In addition, voestalpine Grobblech offers a wide range of roll-bonded clad plates with the best corrosion resistance and represents an intelligent and cost-effective alternative to solid stainless steel. This very efficient solution has been successfully used for decades in oil and gas plants as well as in FGDs . The clad plates are particularly suitable for the construction of absorbers and strippers for amine scrubbers.

CONCLUSION

The goal of decarbonization can only be achieved through a mix of current and future technological possibilities. Without an adequate implementation of CCUS, achieving this goal is difficult to imagine.

What is special about this group of technologies is that they are applicable to both existing industrial plants and future constructions.

As a provider of Welding Solutions, voestalpine Bohler Welding will once again be at the side of our customers to help them build the infrastructure necessary for this energy transition.

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