# Technologies at the service of CCUS

**Enrico Zuin, Nazmi Adams and Herbert Abbott of voestalpine Böhler Welding present their company's welding solutions in support of carbon capture, utilisation and storage (CCUS).**

Carbon dioxide ($CO_2$) emissions resulting from human activities, particularly from the combustion of fossil fuels, have led to atmospheric $CO_2$ concentrations in the earth's atmosphere rising from pre-industrial levels of around 280 ppm to a current average of 420 ppm. While this may not sound like much, anthropogenic emissions have increased by 67 %, 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 (37 Gt).

To reach carbon neutrality, the point at which $CO_2$ concentration in the atmosphere stop rising, carbon capture, utilisation and storage technology (CCUS) has emerged as a promising solution to mitigate $CO_2$ emissions and combat climate change. CCUS prevents $CO_2$ from industrial processes and power generation facilities being released into the atmosphere. This helps mitigate climate change while enabling continued use of fossil fuels during the transition to renewable energy sources.

## Principles of carbon capture

CCUS is an acronym that groups together all the carbon capture related technologies – available or under development – that can prevent $CO_2$ from entering the atmosphere.

Captured $CO_2$ can be transported via pipeline or transported in its liquid state by ship; it can be utilised in some industrial applications as a raw material to create other products, and excess captured $CO_2$ can be injected and permanently stored in deep geological formations or depleted oil and gas reservoirs, which may be on land or offshore.

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

Fifty new capture facilities are set to be operating by 2030, increasing the total capture capacity to 383 Mt/$CO_2$/y. To be on track with the net zero emissions (NZE) scenario by 2050, however, the total capacity by 2030 should be at least 1 100 Mt/$CO_2$/yr.

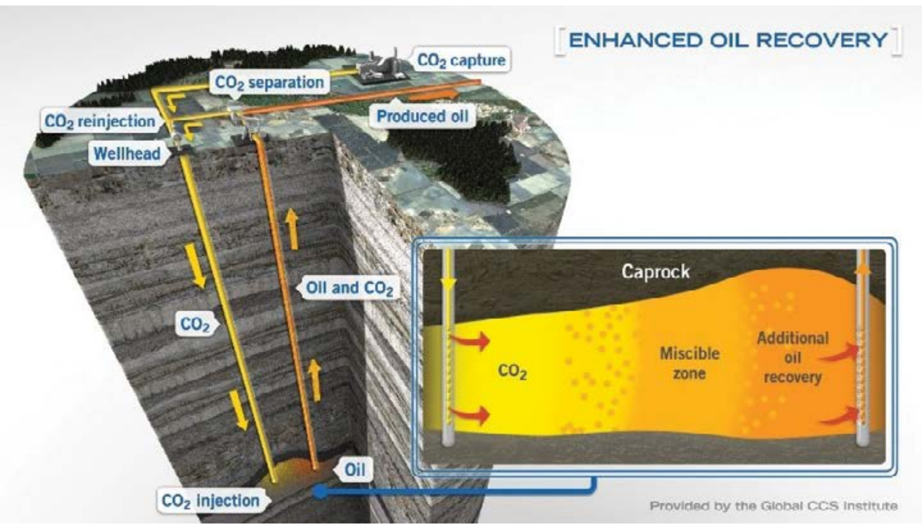
## Carbon capture technologies

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).

### *Pre-combustion carbon capture*

Pre-combustion carbon capture allows for the removal of $CO_2$ from a gas mixture before it is used, 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.

Proprietary physical solvents used to capture the $CO_2$ include Selexol and Rectisol, which work well at high concentrations of $CO_2$ and can tolerate the presence of residual oxygen. The $CO_2$ is then desorbed and released from the solvent by decreasing the pressure in a stripper vessel.




*Most of the captured $CO_2$ is used in enhanced oil recovery (EOR) processes to improve oil and gas extraction.*

*Principle author: Enrico Zuin, Head of Global Welding Technology for voestalpine Böhler Welding.*

In an integrated gasification combined cycle (IGCC) power plant, coal, petroleum coke and other feedstocks can be used to produce electricity via a gasification process. The feedstock is first converted to syngas in a gasifier. After cooling and desulphurisation, the syngas is subjected to the shift reaction to convert the CO to $CO_2$, which produces a gas mixture composed of $H_2$ and $CCO_2$, which is used as a syngas with a high $H_2$ content in a gas turbine for power generation.

In the steam turbine phase of the combined cycle, a heat recovery steam generator (HRSG) then uses the waste heat from the hot exhaust gas to generate steam, while the $CO_2$ from the combustion phase is captured, compressed and sent to its destination.

To produce blue hydrogen the steam methane reforming (SMR) process is used, where natural gas is used to produce hydrogen with $CO_2$ as a by-product. This $CO_2$ can be captured and separated from the hydrogen.

Most of the world's sources of natural gas (CH4) also contain $CO_2$ and H2S that must both 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*

To separate and capture $CO_2$ from the flue gas of a combustion system, oxygenate compounds, NOx, SOx, metal dust, and other contaminants must be removed from the exhausted flue gas. After cooling, the $CO_2$ is separated from the flue gas by passing the gas through a continuous scrubbing system consisting of an absorber and a stripper.

Amine-based solvents are typically used. The release of $CO_2$ is obtained by using heat to break the chemical bond between the $CO_2$ and the solvent. 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 (monoetha- nolamine) and more tolerant of the impurities associated with this process.

### *Carbon capture from industrial processes*

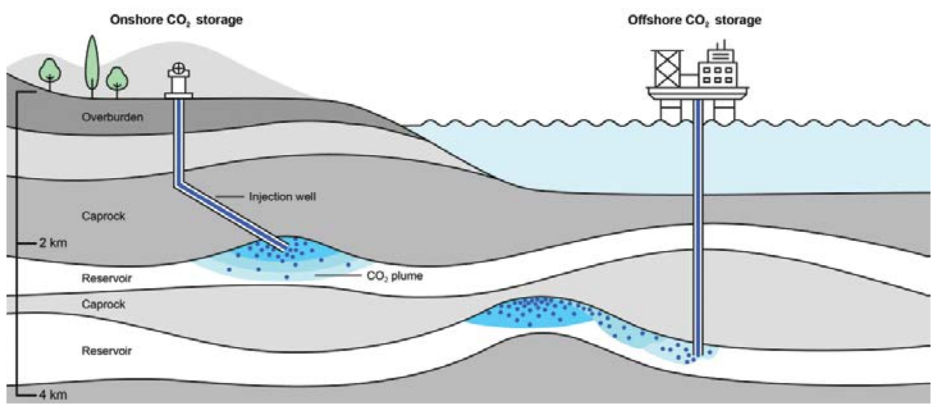
At gas- or coal-fired power plants, a carbon capture facility is coupled with a fossil fuel power plant to separate the $CO_2$ from the flue gas. The cleaned flue gas released into the atmosphere is composed of nitrogen and water vapor. The separated $CO_2$ is compressed and dehydrated for transport to storage or utilisation sites.

In the oxy-fuel combustion process, also known as the Allam cycle, coal or natural gas fuel is burned in 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 from the air, the $CO_2$ concentration increases to more than 90%.

Since flue gas is now composed of only $CO_2$ and $H_2O$, which can be easily removed by condensation, high purity $CO_2$ is easy to capture from this process, making it ideal for use as a working fluid in a supercritical $CO_2$ power cycle – and the low-cost of the electricity produced compensates for air separation unit needed to extract the $N_2$.

The first utility scale power plants based on this Allam cycle are under construction in Permian region of Texas and will begin operation in 2027/2028 [Source: https://netpower.com/first-utility-scale-project].

If using coal with an air separation unit operating in front of a coal-fired power plant to separate $O_2$ from the air, the flue gases need to be further treated to separate SOx, NOx and other impurities, before the $CO_2$ processing unit removes the water by dehydration and the $CO_2$ is compressed for storage or transportation purposes.




*Permanent onshore and offshore solutions for storing $CO_2$. [Source: IEA]*

### *Direct air capture (DAC)*

Direct air capture (DAC) of $CO_2$ 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 present. two start-ups possess the most promising technologies for DAC.

- Carbon Engineering is a Canadian company that uses a capture technology on an aqueous hydroxide liquid-solvent solution. The most common alkalis used are potassium hydroxide (KOH) and sodium hydroxide (NaOH). 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 then heated in a calciner to around 900 °C to release the captured $CO_2$ and the solvent is regenerated in a closed chemical loop. [Source: CarbonEngineering.com]
- Climeworks is a Swiss company that bases its capture technology on a solid sorbent filter. 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 fully loaded with $CO_2$, 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; and metal organic frameworks (MOF).

A very promising solution to provide carbon-free energy to a DAC system consists of integrating three different systems together: BIGCC (biomass integrated gasification combined cycle); CCS (carbon capture and storage); and DAC. This combination that can be 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 has been previously absorbed from the atmosphere by the biomass thanks to the photosynthesis during the growing process. The $CO_2$ absorbed from the atmosphere during photosynthesis is simply released back. Together, therefore, these integrated systems can achieve compound negative emissions.

Biomass, such as wine lees, crop waste, livestock manure, municipal garden waste or kitchen waste, is converted into syngas by the gasification process. This syngas is moved to a combined cycle power plant to be combusted highly efficiently by gas turbines to produce electricity. The excess heat from the turbines and the gasification reaction is then captured, converted

| Base material | SMAW | FCAW | SAW |
|---|---|---|---|
| P355NL2 or P355ML2 | Bohler FOX EV 50 | Diamondspark 53 RC | Union S3Si UV 418TT |
| P460NL2 or 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[1] | Union S3NiMo1 UV 418TT |

*Table 1: Examples of vaBW filler materials typically used in the construction of cryogenic storage tanks for $CO_2$ storage. 1: only for as welded condition. Note: If PWHT has been requested, consult the vaBW Global Welding Technology team.*


*pipeRunner® is designed for pipeline and process piping girth welds for carbon steel to corrosion resistant alloy (CRA) materials.*

into steam and sent to a steam turbine to produce additional electricity.

The carbon capture unit sequesters the carbon dioxide 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 can be used to drive a DAC unit that captures additional $CO_2$ from the atmosphere and transfers it to $CO_2$ storage.

This new concept power plant technology can produce energy and at the same time contribute to removing $CO_2$ from the air. In addition, it offers an important contribution to waste management.

## Permanent storage and utilisation of $CO_2$

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 about 5.9 Gt of $CO_2$ will be captured and stored by 2050. This will require a considerable expansion of $CO_2$ storage capacities.

A typical option for permanent storage is to inject the captured $CO_2$ into a suitable geological reservoir where remains trapped. Suitable examples of geological reservoirs include depleted oil and gas fields, and saline formations.

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 utilisations are:

- Methanol production, for direct used as a liquid fuel for internal combustion engines and direct methanol fuel cells (DMFC).
- Methane production: Synthetic methane is a readily exportable fuel that is supported by existing infrastructure for storage, transport and use.
- Methanol synthesis via $CO_2$ hydrogenation: $CO + 3H_2 \rightarrow CH_3OH + H_2O$.
- Methanol synthesis via $CO_2$ hydrogenation using a specific catalyst: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$.
- Urea production via the reaction of carbon dioxide and ammonia. $2NH_3 + CO_2 \rightarrow NH_4{+}NH_2COOH \rightarrow CO(NH_2)_2 + H_2O$
- Building materials production: $CO_2$ can be used in the production of building materials such as concrete for permanent sequestration.

## Solutions from voestalpine Böhler Welding $CO_2$ storage and transportation

Captured carbon dioxide must be transported from the point of capture to the point of permanent storage or use. Intermediate storage vessels will sometimes be necessary, especially in the case of intermittent production/shipping. The two most relevant means of transportation are pipeline and maritime transport using large $CO_2$ carriers.

vaBW welding experience gained from the maritime transport of LNG is significant for developing $CO_2$ transport solutions.

## Intermediate storage solutions

Immediately after liquefaction, the $CO_2$ must be stored in cylindrical tanks, spherical tanks or bullet type tanks. Operating temperatures vary according to the tank pressure design, with typical storage conditions being 6-7 bar at temperatures of -50 to -52 °C.

Base materials used for the welded construction of these tanks include boiler and pressure vessel steels such as 355NL2 or P355ML2; P460ML2 or P460NL2; SA537 Cl.2 and SA738 Gr.B.

voestalpine Grobblech and voestalpine Bohler Welding can offer different package solutions for plates and welding consumables for these vessels. Table 1 gives an example of filler materials typically used in the construction of storage tanks. This selection was made assuming a PWHT of 580 - 600°C for 3 hours.

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, however, pipeline transportation of $CO_2$ captured from industrial emitters – pre-combustion, post-combustion or oxy-fuel methods – must take into account the presence of contaminants such as: $N_2$, $O_2$, $H_2$, $CH_4$, SOx, $H_2S$, NOx, CO, chlorides and $H_2O$.

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 considered, which is why a high priority 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 such as 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 fulfil the welding requirements in various positions.

Most notably, pipeRunner® – the orbital welding system for FCAW – is designed for pipeline and process piping girth welds for carbon steel to corrosion resistant alloy (CRA) materials. Advantages of using this system include:

- pipeRunner® is designed for girth welding in the vertical up position with flux cored wires.
- Being one of the lightest systems on the market makes it easy to handle.
- All the components are premium products designed in Germany.
- No need for site bevelling machines and internal clamps.
- Very easy to operate as the remote control has puts all the functions in the palm of the welder's hand.
- It is suitable for welding high strength pipeline steels, but also ideal for clad piping and high-alloy pipes.

## Liquid $CO_2$-cargo vessel

Depending on the pressure and temperature conditions required for these vessels, suitable material can range from carbon steel with improved toughness properties to high-strength steels.

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 for these vessels, while low-alloy solutions are under development.

## Corrosion and material selection for CCUS

Typically, the $CO_2$ used for enhanced oil recovery (EOR) comes from a clean source, such as natural reservoirs, with well-controlled water content. For CCS, the $CO_2$ can originate from a variety of industrial sources and/or CCS-hubs, so it can therefore contain a mixed variety of impurities.

Complete removal of these impurities may not be cost-effective or technically feasible. Therefore, it is advisable to select materials that can withstand potentially unfavourable conditions at the extreme limits of the expected impurity and temperature levels.

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

Considering that many planned projects are based on the CCS hub concept, the material selection must mitigate the corrosion risk posed by all the potential impurities and mechanisms. Water must be present


*voestalpine Böhler Welding has solutions for $CO_2$ liquid cargo vessels applications. Photo: HB Hunte Engineering*

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 ($HNO_3$) and sulfuric acid ($H_2SO_4$), and possibly, elemental sulphur.

The low pH of the condensed water can also lead to the depassivation of corrosion-resistant alloys, resulting in localised corrosion and 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 learned 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 include all the necessary treatment processes to remove most of the impurities and water before $CO_2$ capture takes place. These are associated with corrosion risks from impurities such as: $N_2$, $O_2$, $H_2$, $CH_4$, SOx, $H_2S$, NOx, CO, chlorides in the presence of $H_2O$. The possible material selection includes carbon steel or low-alloy materials clad with CRA such as 22Cr, 25r, Ni-base alloy or solid-wall parts made of stainless steel.

Absorber Vessel & $CO_2$ stripper/desorbers present corrosion risks from amine/oxygen interaction, glycol and residual impurities. The possible material selection includes carbon steel or low-alloy materials clad with a CRA such as 316L, 904L, 6Mo grades and Ni-based alloys.

Materials for high corrosion risk process piping includes 316L, 22Cr, 25Cr and Ni-based alloys, while for low corrosion, carbon steels with an adequate corrosion allowance be acceptable.

Compressors may also need to use carbon steel/low-alloy steel with corrosion resistant cladding to cover 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 several impurities in the $CO_2$ stream. voestalpine Böhler Welding can offer a complete range of filler materials for welding and cladding, including stainless and Ni-based material.

In addition, voestalpine Grobblech offers a wide range of roll-bonded clad plates with excellent corrosion resistance, which offer 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 food grade facilities. These clad plates are particularly suitable for the construction of absorbers and strippers for amine scrubbers.

## Conclusion

The goal of decarbonisation can only be achieved through a mix of current and future technological possibilities. Without the successful 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 alongside our customers to help them build the infrastructure necessary for this energy transition.

***www.voestalpine.com/welding***

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