

## Adding Value in the Journey Towards Net-Zero Carbon Emissions with Filtration and Separation

### Summary

Carbon capture is at the core of enabling the energy transition in the near-term and meeting global net zero emissions in the long run. While carbon capture technology has been around for decades, there will need to be a massive ramp up in the number of projects to meet climate targets between now and 2050. Filters and separators are pivotal elements of carbon capture systems: they maintain high process efficiency and reliable equipment operation to keep capture costs low and help achieve on-spec liquid and gas streams to help meet regulations, safety requirements, and other specifications.

As the leader in separation and purification technology, Pall Corporation has a breadth of experience in filtration and separation applications and is excited to partner with you to achieve a low-carbon future.

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### Introduction

Due to the widespread use of fossil fuels for energy, heating, and transportation, the amount of CO<sub>2</sub> in the atmosphere has increased by almost 50% compared to pre-industrial levels. Overall, anthropogenic-caused greenhouse gases such as CO<sub>2</sub> have led to an approximate 1°C increase in global temperatures, which has notable implications for the climate (1). In 2015, countries worldwide signed on to the Paris Agreement, which sets an upper limit at 2°C (2). To meet this 2°C climate target, aggressive decarbonization technologies are required. Carbon capture and utilization or storage, or CCUS, projects are already underway to meet this need. However, project capacity will need to accelerate rapidly to meet the 2-degree warming target, from approximately 40Mtpa in 2021 to over 5,600 Mtpa by 2050 (3).

So, what is CCUS? It is a collection of technologies that separate CO<sub>2</sub> from gas streams, concentrate it, transport it via ship or pipeline, and ultimately either store it or utilize it to prevent it from being emitted to the atmosphere. The full value chain is shown in **Figure 1**.

Most CCUS projects focus on removing CO<sub>2</sub> at point sources, where CO<sub>2</sub> is produced. This is because it is easier and cheaper to capture CO<sub>2</sub> from gases with high concentrations of CO<sub>2</sub>. While capture costs vary widely depending on the industry and technology employed, point-source capture costs can go below \$30/ton for high-purity streams. In contrast, direct air capture (DAC) processes capture CO<sub>2</sub> directly from the air, enabling 'negative' emissions. However, DAC technologies are still emerging, with high capture costs exceeding \$100/ton (4).

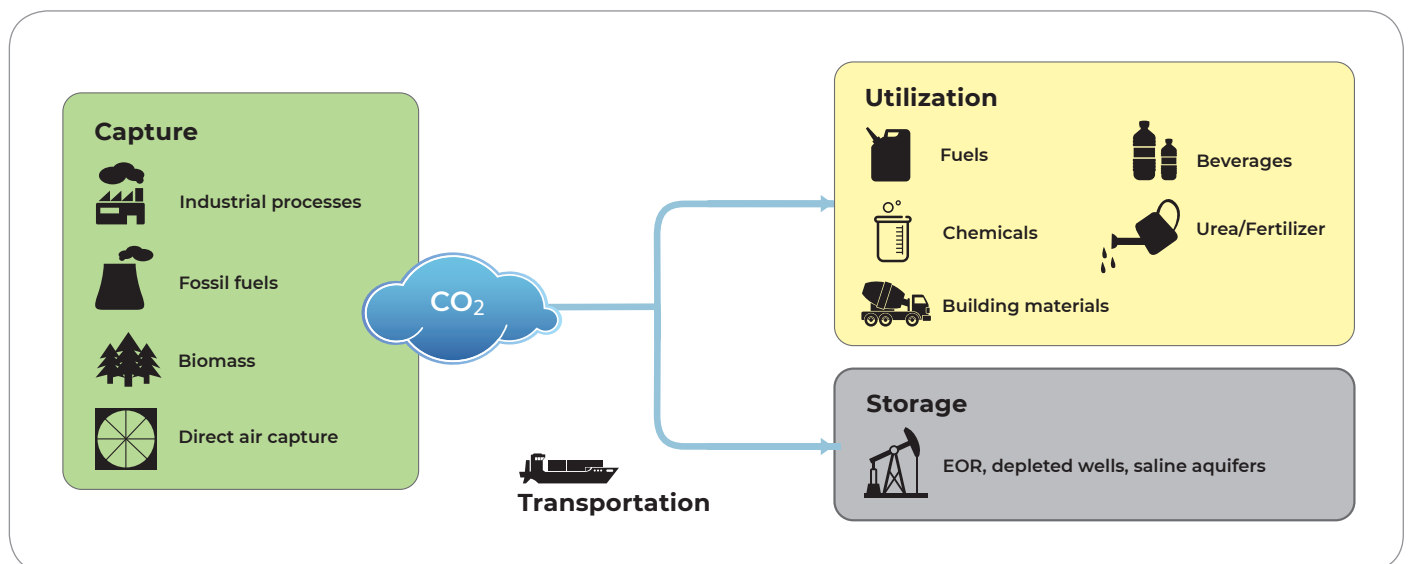


Figure 1. Carbon capture, utilization, and storage (CCUS) value chain

Point-source carbon capture can be segmented into 3 processes: post-combustion, pre-combustion and oxy-combustion (5):

- **Post-combustion** is the process of separating CO<sub>2</sub> directly from flue gases produced during combustion of hydrocarbons. Flue gases often contain a mix of CO<sub>2</sub>, N<sub>2</sub>, and other compounds. Post-combustion capture can easily be retrofitted into existing industrial plants.
- **Pre-combustion** refers to separating CO<sub>2</sub> from gas streams before combustion. This is common in coal power generation, where the feedstock is gasified to form syngas. Syngas, which contains CO, CO<sub>2</sub>, and H<sub>2</sub>, can undergo a water-gas shift reaction to increase the fraction of H<sub>2</sub> and CO<sub>2</sub>. CO<sub>2</sub> is then separated from H<sub>2</sub> to yield a hydrogen-rich stream, called 'blue hydrogen' due to the method of production.
- Finally, **oxy-combustion** uses a stream of pure O<sub>2</sub> rather than air for combustion. Because far less nitrogen is present in the process, the process yields a gas stream with a very high concentration of CO<sub>2</sub>, simplifying downstream CO<sub>2</sub> separation.

Current CO<sub>2</sub> separation technologies include **absorption**,

which uses solvents, **membranes**, **adsorbent** materials such as zeolites or MOFs, **cryogenics**, and **chemical looping**. At present, capture technologies have diverse levels of commercial readiness and performance.

Once separated, CO<sub>2</sub> is compressed, transported via ship or pipeline, then either stored or utilized. Storage reservoirs include depleted wells and saline aquifers. CO<sub>2</sub> can also be pumped into reservoirs to increase unrecovered stores of oil in a process known as EOR (enhanced oil recovery). CO<sub>2</sub> can alternately be utilized to produce fuels and chemicals, carbonated beverages, urea or fertilizer, or construction materials such as cement.

Which projects move forward depend on economics: how much it costs to remove CO<sub>2</sub> from gas streams compared to regional investment, policy incentives, and regulatory frameworks.

As decarbonization projects continue to accelerate, filtration and separation products will play a critical role across the value chain of carbon capture, storage, and utilization. Both liquid gas separators and solid removal products will be key to both increasing process efficiency and protecting process equipment.

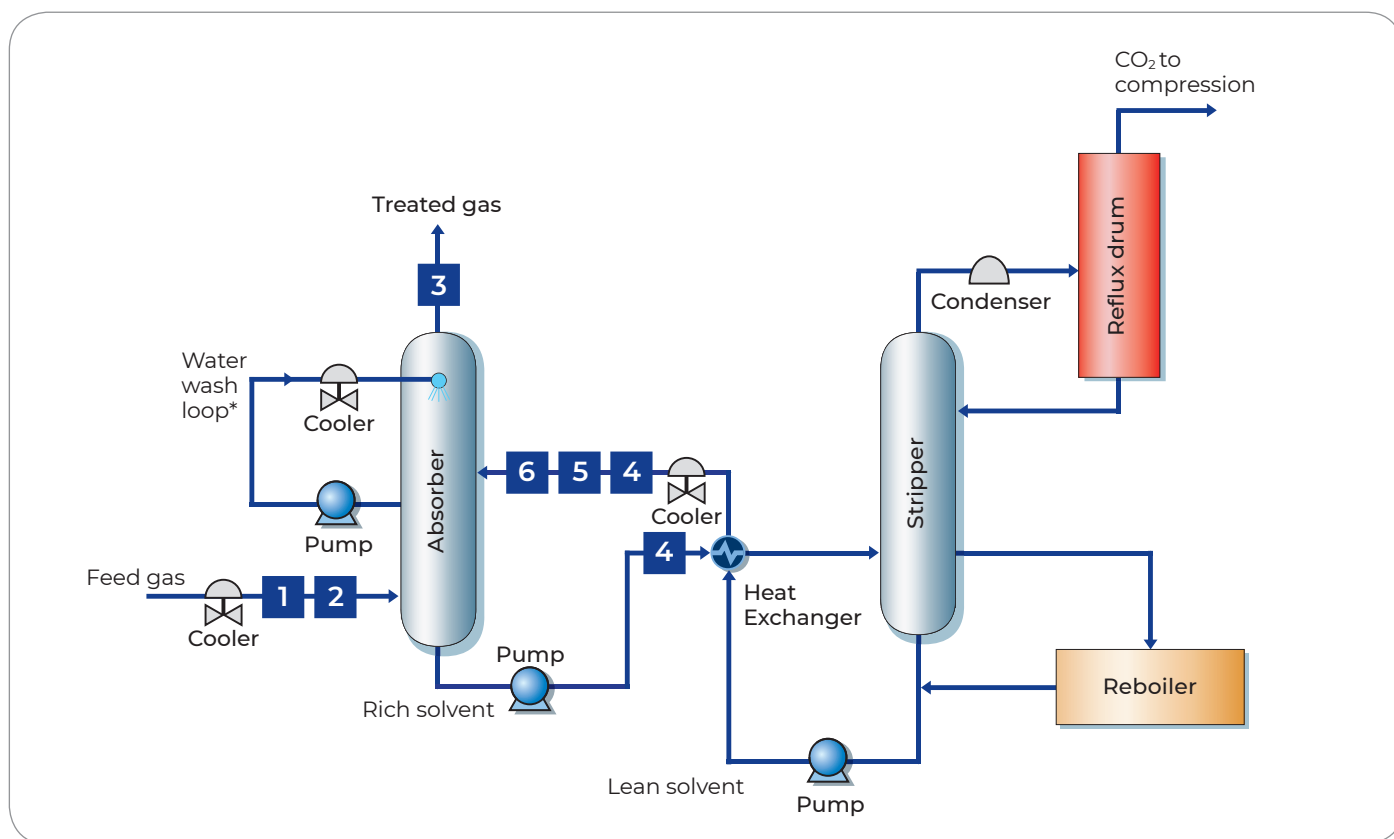


Figure 2. Process Flow for Solvent-Based Absorptive Carbon Capture.

| # | Application  | Product                 |
|---|--|-------------------------|
| 1 | Bulk particulate removal from dry gas feeds*             | Regenerable gas filter* |
| 2 | Remove contaminants on inlet gas**                       | L/G coalescer**         |
| 3 | Prevent amine carry over on absorber outlet              | L/G coalescer           |
| 4 | Remove solid contaminants from solvent loop              | 1-10 micron filter      |
| 5 | Remove organics, degradation products to reduce foaming  | Activated carbon filter |
| 6 | Prevent activated carbon fine carry-over in solvent loop | 1-5 micron filter       |

\* denotes an application for power gen and FCC units, with flue gas feeds.

\*\* denotes applications for oil and gas or LNG, with sour gas feeds.

At present, due to process economics and maturity, the most common carbon capture technology for both pre- and post-combustion processes is solvent-based absorption. Thus, the remainder of the article will focus on best practice filtration and separation solutions in solvent-based capture processes and in downstream compression and storage. In this growing market, filtration and separation are key to ensuring that your process equipment is protected, and that process efficiency remains high. As a filtration and separation provider, Pall Corporation is looking towards a low-carbon, sustainable future, and is committed to developing and advancing quality solutions to enable CCUS.

## Absorptive (Solvent-Based) Carbon Capture

As discussed earlier, solvent-based absorption is currently the most mature and widely-used method for carbon capture. A schematic of a solvent-based absorption carbon capture process is shown in **Figure 2**. In these applications, feed gas flow rates for CO<sub>2</sub> capture units are high, and can exceed 1,000,000 Nm<sup>3</sup>/h (over 620,000 SCFM) (6). Available pressures are also low, often below 60mbar (0.87 psi).

Common problems caused by solvent contaminants in carbon capture systems include solvent foaming, corrosion, and fouling of critical equipment such as heat exchangers, contactor and absorber plugging, and hotspots on reboiler tubes which can cause solvent degradation. All told, these problems can lead to reduced carbon capture efficiency, solvent regeneration issues, unscheduled downtime, equipment damage, and increased maintenance costs. Proactive contaminant removal can thus provide a good return on investment (7).

Best-practice filtration and separation recommendations differ slightly depending on the application. For power gen and fluid catalytic cracker (FCC) applications, unique recommendations and process steps are denoted by an asterisk (\*).

For carbon capture in power gen and FCC applications, the carbon capture process feed is flue gas. It contains N<sub>2</sub>, CO<sub>2</sub> (3-16%), and unreacted O<sub>2</sub>, with highly variable compositions. It can also contain water vapor, unreacted hydrocarbons, and trace amounts of NO<sub>x</sub>, SO<sub>x</sub>, and H<sub>2</sub>S. At **location (1)**, contaminants such as fly ash must be removed to protect CO<sub>2</sub> capture equipment to reduce foaming, reduce solvent losses and unwanted emissions from the absorber vent gas due to nucleation of solvent on fine contaminants, and ultimately to keep capture efficiency high. CO<sub>2</sub> capture processes often have high gas flow rates with fine contaminants and operate near atmospheric pressure, so removing contaminants economically is quite challenging. If the feed has high levels of fine contaminants and the gas is dry, regenerable blowback filters with high surface area can be used.

On the other hand, for oil and gas applications or LNG, the feed is called 'sour gas', and treated gas is called 'sweet gas'. Sour gas can contain acid gases (CO<sub>2</sub> and H<sub>2</sub>S), sulfur-containing compounds, heavy organics, water, N<sub>2</sub>, O<sub>2</sub>, NH<sub>3</sub>, CO, and HCN. To remove both solids and aerosols on the feed to prevent solvent foaming and heat stable salts (HSS) formation, high-efficiency L/G coalescers are recommended at the absorber inlet at **location (2)**.

For all applications, the gas passes through the absorber, where CO<sub>2</sub> is selectively absorbed by the solvent.

Standard solvents include amines such as MEA, DEA, and MDEA, and physical solvents such as methanol. Non-solvents such as potassium chloride can also be used for Benfield processes.

For power gen or downstream from FCC units, if filtration is not implemented upstream of the absorber and there are fine contaminants present in the amine or if there are high levels of SO<sub>3</sub> in the feed, the solvent can form fine sub-micron aerosols and be emitted along with the vent gas. High-efficiency L/G coalescers installed on the vent gas stream at **location (3)** can prevent aerosol carry-over emissions to both protect the environment and to minimize solvent losses. L/G coalescers at **location (3)** are also used in oil and gas and LNG to prevent amine carry-over and ensure on-spec sweet gas.

Going back to the solvent loop, CO<sub>2</sub> is removed from the solvent in the stripper for downstream processing. The solvent is then cycled back to the absorber.

One critical element of the solvent capture process is that the solvent needs to be clean to reduce foaming, to limit equipment corrosion and heat exchanger fouling, and to maintain process efficiency, so high-efficiency filtration and separation steps are vital. Pall recommends 5-10µm absolute rated filters on the solvent loop on the lean or rich solvent at **location (4)**. These filters have two purposes: first, to achieve best practice <5mg/L total suspended solids (TSS) for a clear and bright solvent, and second, to protect activated carbon beds from being plugged and needing to be replaced (7). Activated carbon products at **location (5)** are used to remove organics and heavy-molecular weight amine degradation products, and has been found to reduce foaming (8). Filters are also recommended downstream from the carbon bed at **location (6)** to prevent carbon fines carry-over.

To keep process efficiency high, absolute filters are recommended over nominal filters due to the variation in nominal filter performance. Absolute filters, as defined by the National Fluid Power Association (NFPA), are filters where "The diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. It is an indication of the largest opening in the filter element". In contrast, the NFPA defines nominal filter ratings as "An arbitrary micron value assigned by the filter manufacturer, based upon removal of some percentage of all particles of a given size or larger". This definition can lead to a wide range of variability in removal efficiency (9). Therefore, absolute filters are recommended to maintain solvent cleanliness and protect process equipment.

### Case Study – Flue Gas Feed to CO<sub>2</sub> Capture System

Due to high gas flowrates, low available pressure drop, and fine contaminants present in flue gas feeds to CO<sub>2</sub> capture systems, standard disposable filters on the inlet for the carbon capture absorption unit are not economical. Pall developed a novel regenerable gas filter that targets CO<sub>2</sub> capture process parameters and installed a demo unit at a pilot in 2016. The demo unit performed well in operation and provided cost savings compared to alternative gas-solid separation systems.

## Compression and Storage

After CO<sub>2</sub> is separated, it is compressed, dehydrated, and can either be used or stored. **Figure 3** depicts an example CO<sub>2</sub> process flow after the CO<sub>2</sub> has been separated.

The purpose of CO<sub>2</sub> compression is to reduce the volume for efficient transportation and processing. CO<sub>2</sub> is compressed to a supercritical, or 'dense phase'. Dense phase CO<sub>2</sub> occurs above the critical point temperature and pressure for CO<sub>2</sub>, 31°C and 74 bar (1073 psi), respectively. Several stages of compressors are required to produce dense phase CO<sub>2</sub>.

At each stage in the process, compressor protection with L/G coalescers at **location (1)** is pivotal. Reciprocating compressors are highly sensitive to contaminants, and the presence of contaminants can cause corrosion and impact compressor yields. To boost compressor operation and reliability, L/G coalescers remove carry over liquids, free water, and particulate matter. For example, Pall SepraSol™ coalescers provide excellent solid and liquid removal ratings down to 0.003 ppmw free liquid, and 99.99% removal efficiency at 0.3µm per sodium chloride testing (10). Other products such as vent filters, vacuum purifiers, and particulate filters to remove contaminants from lube oil are recommended at **locations (2) and (3)**, depending on the type of compressor.

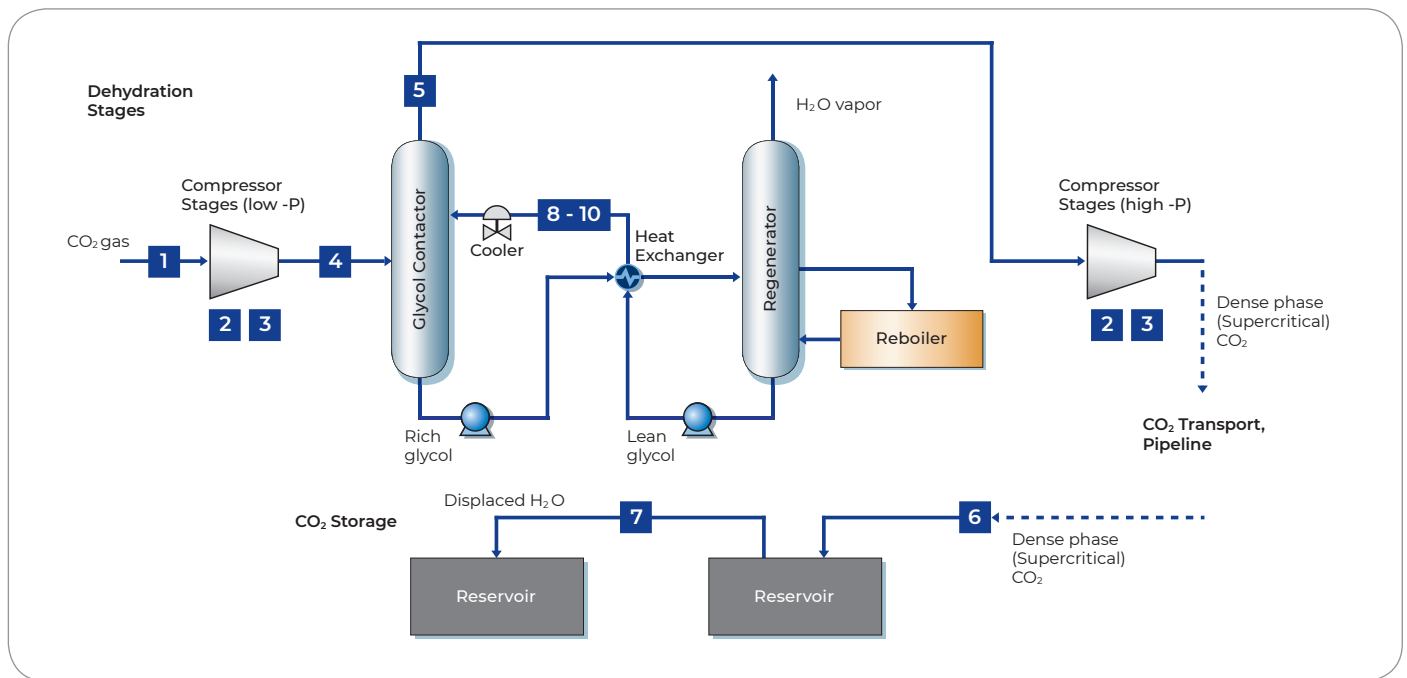
CO<sub>2</sub> is dehydrated with adsorbents or solvent-based glycol systems to meet pipeline safety specifications.

The presence of water and other contaminants in the pipeline can cause corrosion and stress cracking. Water can also cause hydrate formation, which can cause pipeline blockages. While specifications are continually evolving, water requirements can be << 50ppmv, and glycol specifications << 50 ppbv (11).

L/G coalescers at **location (4)** upstream the dehydration stages can limit lube oil carryover from compressors, which can cause foaming. If adsorbent beds are used for dehydration, L/G coalescers are also recommended upstream to remove residual liquids that can cause channeling, reduce adsorbent lifetime, or require more energy for an increased number of regeneration cycles. L/G coalescers are also recommended downstream from glycol dehydration units at **location (5)** to limit solvent carry over.

If the CO<sub>2</sub> is intended for storage and re-injection, particulate filters on compressed dense-phase CO<sub>2</sub> at **location (6)** are recommended to remove solid contaminants such as scale and corrosion products and to limit reservoir plugging. Finally, particulate filters at **location (7)** are recommended to clean up connate water for reservoir pressure management to ensure continued CO<sub>2</sub> injection.

Other recommendations for filtering the solvent within the solvent process loop, at **locations (8-10)** in the diagram, are similar to those in the previous section.



**Figure 2.** Process flow for CO<sub>2</sub> compression, dehydration, and injection

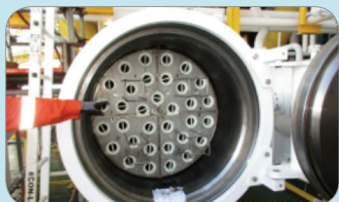
| #    | Application   | Product                               |
|------|---|---------------------------------------|
| 1    | Compressor protection                                     | L/G coalescer                         |
| 2    | Remove solid contaminants from lube oil                   | Particulate filter or vacuum purifier |
| 3    | Prevent compressor cavitation (depends on compressor)     | Vent filter, also called a "breather" |
| 4    | Prevent lube oil carry-over to TEG dehydration loop       | High efficiency L/G coalescer         |
| 5    | Remove solvent carry-over, protect compressor             | L/G coalescer                         |
| 6    | Prevent reservoir fouling - supercritical CO <sub>2</sub> | Particulate filter                    |
| 7    | Prevent reservoir fouling - displaced H <sub>2</sub> O    | Particulate filter                    |
| 8-10 | See applications 4-6 on solvent absorption diagram        |                                       |

## Case Study – CO<sub>2</sub> Injection Filters

CO<sub>2</sub> is often stored in underground reservoirs or used for EOR. Long pipelines that bring dense-phase CO<sub>2</sub> from upstream separation and compression often contain solid contaminants which can foul the reservoir.

Pall recommends high-efficiency particulate filters with 99.98%+ particle removal efficiency located at the reservoir

inlet. Pall filters sized specifically for dense-phase CO<sub>2</sub> filtration based on Pall filtration and separation expertise are shown in **Figure 4**.



**Figure 4.** Particulate filters for dense-phase CO<sub>2</sub>

## Bio

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