



White Paper

# Carbon Capture, Utilisation & Storage:

*A Filtration Perspective*

# FOREWORD

Decarbonisation of industrial activities is key to mitigating climate change. From energy generation to transportation to food production, there is a clear imperative to reduce the amount of carbon dioxide (CO<sub>2</sub>) entering the atmosphere. Techniques for separating CO<sub>2</sub> from gas streams are well-established, but the sustainability imperative is driving innovation in carbon capture, utilisation and storage (CCUS) – particularly in utilisation.

CCUS encompasses a suite of technologies designed to capture CO<sub>2</sub> emissions from point sources such as power plants and industrial facilities, prevent its release into the atmosphere, and either store it underground or repurpose it for industrial use. These processes hold the potential to significantly reduce CO<sub>2</sub> emissions and mitigate the effects of climate change.

This white paper explains the technical aspects of filtration equipment within CCUS systems. It highlights the importance of filters in enabling the efficient removal of CO<sub>2</sub> from industrial exhaust streams, as well as exploring the capital and operational costs associated with different carbon capture methods. It also examines current primary methods of CO<sub>2</sub> capture (namely pre- and post-combustion cycles and oxygen-based combustion with adsorption), along with the rapid developments taking place in direct air capture (DAC) systems – and the essential role that filters play in each process.

# 1. THE CONTEXT FOR CARBON CAPTURE

## 1.1 Climate change and carbon dioxide

Rapid industrialisation and increasing reliance on fossil fuels over the past two centuries have caused an unprecedented rise in atmospheric carbon dioxide (CO<sub>2</sub>) levels. Fossil fuels, including coal, oil and natural gas, are combusted daily in power plants, factories, vehicles and other industrial activities, releasing CO<sub>2</sub> as a byproduct. Since the middle of the 20th century, annual emissions from burning fossil fuels have increased every decade, from almost 11 billion tons of carbon dioxide per year in the 1960s to an estimated 36.6 billion tons in 2023<sup>1</sup>. As levels of greenhouse gases like CO<sub>2</sub> increase, they prevent heat escaping from the earth's atmosphere. This warming trend is causing severe disruptions to the planet's climate system, resulting in extreme weather events, rising sea levels, and widespread ecological damage. These phenomena pose significant threats to global economic stability and human health<sup>2</sup>.

To combat the negative impacts of rising CO<sub>2</sub> levels, countries around the world signed the Paris Agreement in 2015, committing to limit global temperature rise to well below 2°C above pre-industrial levels<sup>3</sup>. Achieving this target requires aggressive decarbonisation efforts. Estimates suggest that between 350 and 1,200 gigatonnes (Gt) of CO<sub>2</sub> will need to be captured and stored this century. Currently, around 40 megatonnes (Mt) of CO<sub>2</sub> are captured and stored annually, so capacity must increase at least 100-fold by 2050 to meet the necessary targets<sup>4</sup>. Development and deployment of carbon capture, utilisation and storage (CCUS) technologies at scale is therefore a key imperative on the journey towards global decarbonisation.

## 1.2 Principles of carbon capture and storage

The need to capture carbon dioxide as part of an industrial process is not new. Various capture technologies already exist, including the use of solvents and membrane technology (see Section 2). These tried and trusted techniques are being adapted to improve efficiency and reduce costs in industrial carbon capture applications. They are complemented by innovative techniques that can remove CO<sub>2</sub> from the atmosphere, such as direct air capture and storage (DACs)<sup>5</sup>.

Once captured, the CO<sub>2</sub> must be transported to the storage site. This is generally achieved by placing the gas under pressure and transporting it via pipelines, which requires constant monitoring to maintain the desired levels of safety and integrity. Over longer distances, the use of liquefied CO<sub>2</sub> (LCO<sub>2</sub>) carriers is the preferred

option, in which LCO<sub>2</sub> is transported at high pressure and low temperatures.

Storing CO<sub>2</sub> in large quantities is not simple. The most common means is geological storage, which requires a thorough understanding of the geological formations suitable for CO<sub>2</sub> sequestration to ensure the gas will remain trapped. In some circumstances, depleted oil and gas wells are proving suitable repositories. One example is the Sleipner CCS facility in Norway, which is one of the world's longest-running large-scale CCS projects. The facility has been operational since 1996, capturing and storing approximately one million tonnes of CO<sub>2</sub> per year in geological storage deep under the North Sea<sup>6</sup>.

## 1.3 A new 'U'

The practical challenges of permanent CO<sub>2</sub> storage are considerable. Identifying and assessing potential storage sites can be time-consuming and expensive. Not all sites will be suitable, and even where appropriate geological sites are identified, they are likely to need adapting to guarantee safe storage and then monitored to ensure there is no leakage. Where the storage site is in a remote location, the captured CO<sub>2</sub> may need to be transported across large distances. Building, monitoring and maintaining the necessary infrastructure adds significant costs<sup>7</sup>.

All these factors mean that storage is not necessarily the best outcome. Indeed, CO<sub>2</sub> has many practical industrial and commercial applications, ranging from carbonating drinks and extending the shelf life of food to chemical production, refrigeration and fire suppression<sup>8</sup>. One emerging opportunity is in low-carbon synthetic fuels, or efuels, which are made by combining captured CO<sub>2</sub> with low-carbon hydrogen produced using renewable energy. This energy-intensive technology is just moving from pilot plants to small-scale industrial units and is seen as being pivotal for reaching the aviation sector's decarbonisation goals.

So, it makes practical, environmental and economic sense to re-use the captured CO<sub>2</sub> wherever possible. Applying circular economy principles means that less CO<sub>2</sub> needs to be stored because it can be reused in other industrial processes, creating a value stream rather than a financial burden and supporting wider sustainability objectives<sup>9</sup>. As a result, CCS becomes CCUS – with a preference for Utilisation rather than Storage.

**Whichever outcome is desired, the quality of the captured CO<sub>2</sub> is critical for success.**



# Let us now examine in more detail how filtration is applied in the different phases of carbon capture, as defined by the National Energy Technology Laboratory (NETL)<sup>10</sup>

## 2.1 Post-combustion capture

Post-combustion capture is the most widely used method for separating CO<sub>2</sub> from exhaust gases after the combustion of fossil fuels. This process is commonly employed in power plants, cement production, steel manufacturing, and other industries that burn hydrocarbons to produce energy.

The flue gases generated by combustion contain a mixture of CO<sub>2</sub>, nitrogen (N<sub>2</sub>), water vapour (H<sub>2</sub>O), and other compounds. In post-combustion capture, the CO<sub>2</sub> is separated or 'scrubbed' from this gas mixture.

Chemical absorption is the most mature technology for post-combustion capture, in which solvents such as amines are used to absorb CO<sub>2</sub> selectively from the flue gas. The CO<sub>2</sub>-laden solvent is then heated to release the captured CO<sub>2</sub>, which is subsequently compressed for transportation or storage. Filtration helps to protect the solvent from impurities in the flue gas, which can cause fouling, foaming, and degradation of the solvent.

Inefficient operation due to liquid/solid contamination and solvent foaming will result in a lower per unit CO<sub>2</sub> capture rate and will invariably lead to exhausted CO<sub>2</sub> escaping into the atmosphere. Residual organics and hydrocarbon removal via activated carbon filtration is equally important, for much the same reasons. Any contamination reaching the top of the absorber column will directly impact the quality of the CO<sub>2</sub> and may lead to inefficient CO<sub>2</sub> capture.

## 2.2 Pre-combustion capture

Pre-combustion capture is a method in which CO<sub>2</sub> is separated from the fuel before combustion occurs. This technique is commonly used in integrated gasification combined cycle (IGCC) plants, where fossil fuels such as coal or natural gas are converted into syngas — a mixture of carbon monoxide (CO), hydrogen (H<sub>2</sub>), and CO<sub>2</sub>. The CO undergoes a reaction with steam in a process known as the phase shift reaction, which increases the concentration of H<sub>2</sub> and CO<sub>2</sub> in the gas mixture. The CO<sub>2</sub> is then separated from the H<sub>2</sub>, allowing the hydrogen to be used as a clean fuel.

Pre-combustion capture requires filtration to remove impurities such as sulfur compounds, particulates, and moisture from the syngas before CO<sub>2</sub> separation. Membrane technologies, pressure swing adsorption (PSA), and solid sorbents are often used for CO<sub>2</sub> removal in pre-combustion systems.

## 2.3 Oxy-combustion capture

Oxy-combustion is a process that involves burning fossil fuels in an environment of pure oxygen (O<sub>2</sub>) instead of air. Since air contains 78% nitrogen, burning in pure oxygen reduces the presence of nitrogen in the flue gas, leaving primarily CO<sub>2</sub> and water vapour as combustion byproducts. This simplifies the CO<sub>2</sub> separation process, as the water vapour can be easily condensed, leaving a highly concentrated stream of CO<sub>2</sub>.

The key component of oxy-combustion systems is the air separation unit (ASU), which generates the pure oxygen required for combustion. Filters are essential for removing impurities from the incoming air to protect the ASU and ensure efficient oxygen production.

## 2.4 Direct air capture

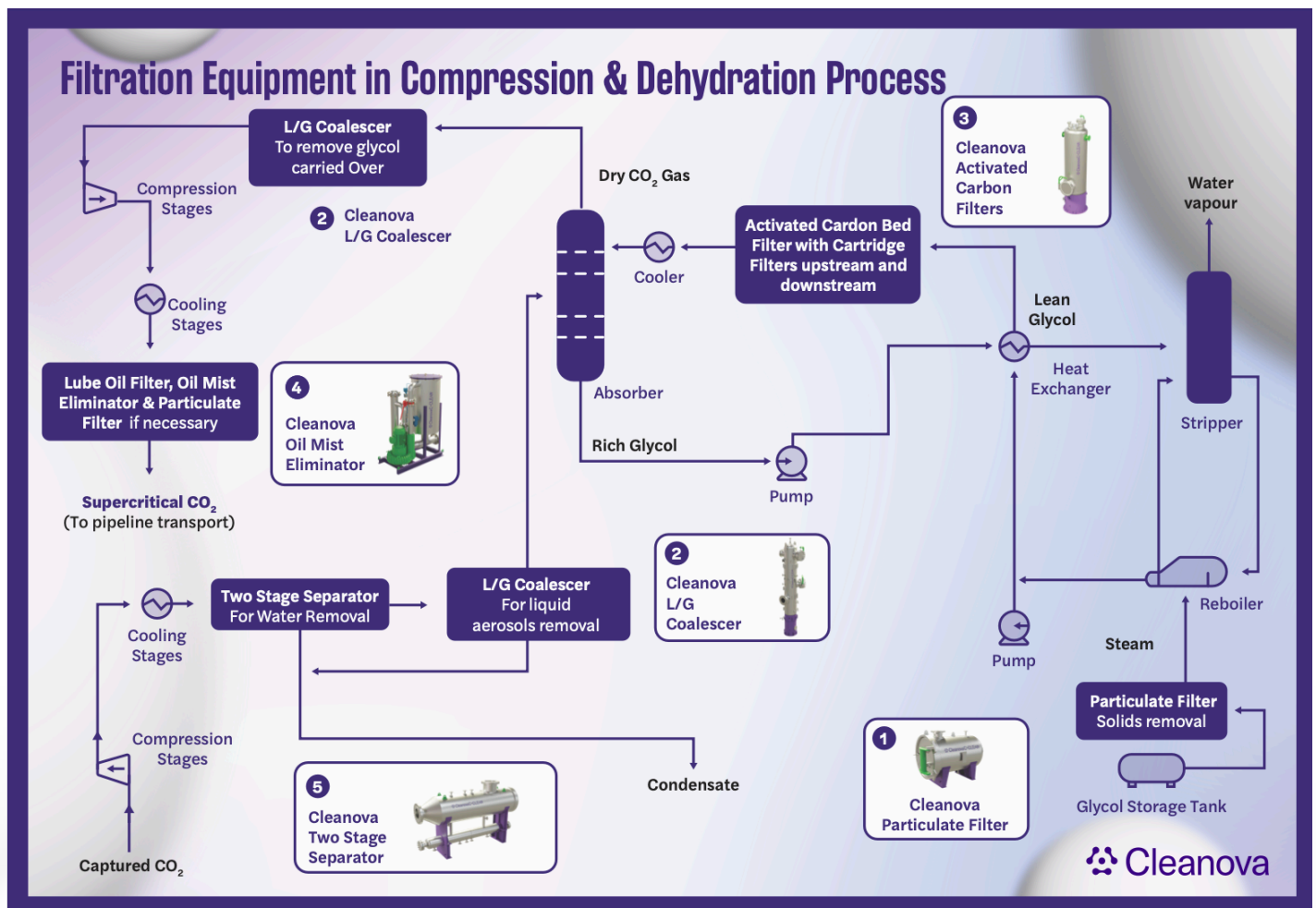
Direct air capture (DAC), as the name suggests, is a non-combustion form of carbon capture and enables CO<sub>2</sub> removal directly from atmospheric air. Ambient air is drawn through the DAC system and CO<sub>2</sub> is extracted directly from the atmosphere using solid or liquid DAC. Solid DAC relies on sorbent materials with an affinity towards CO<sub>2</sub> and uses a cycle system of adsorption and desorption. Liquid DAC utilises solvents in a process based on absorption and regeneration loops.

There are similarities between DAC and the conventional methods of carbon capture from industrial gases, creating significant potential for the transfer of existing filtration technologies into DAC processes. Indeed, filters play a key role throughout the DAC process: filtering the incoming air, maintaining solvent purity, and removing residual liquids from the CO<sub>2</sub>-free air released back into the atmosphere.

# 3. FILTRATION IN CO<sub>2</sub> COMPRESSION & SEQUESTRATION – THE ‘SUPERCRITICAL’ PHASE

After CO<sub>2</sub> has been captured, it is dehydrated and compressed to high pressure for transport and storage, also known as the ‘Supercritical’ or ‘Dense Phase’ state. Converting CO<sub>2</sub> to a dense phase requires energy input

through several compression stages but enables the use of smaller pipelines and increases the amount of CO<sub>2</sub> that can be stored in reservoirs.



1. Cleanova UNIQ-MAX high-capacity filters remove suspended particles from the glycol, helping to maintain downstream equipment throughputs.
2. Cleanova Coalescers remove liquid aerosols from the CO<sub>2</sub> stream, protecting downstream equipment, such as compressors and absorber.
3. Cleanova Activated Carbon Filters eliminate organic contaminants and hydrocarbons to prevent foaming.
4. Cleanova Oil Mist Eliminators guarantee clean and oil-free exhaust air from high-speed rotating equipment, ensuring compliance with air quality standards.
5. Cleanova Two-Stage Separators remove particles and condensate released during the compression and cooling stages.

Figure 2: Filtration equipment in the compression and dehydration process

After compression and dehydration, undesired contaminants such as water, lube oil, oxygen, and hydrogen sulphide (H<sub>2</sub>S) present in the CO<sub>2</sub> can pose a threat to the integrity of the pipelines. H<sub>2</sub>S and oxygen are corrosive: damaging the pipelines and, in the worst case, causing cracks. Trace water can react with CO<sub>2</sub> to form corrosive byproducts and can also form hydrates, both of which produce pipeline blockages.

As pipelines deteriorate, solid corrosion products and pipe scale formed through these reactions can be carried downstream, plugging critical equipment needed for carbon capture and storage, such as control valves, metering stations, and high-pressure

injection pumps. This increases maintenance costs and can require equipment replacement or unscheduled downtime. Solid contaminants can also plug permeable storage reservoir pore structures, requiring increased energy for CO<sub>2</sub> injection and even limiting the amount of available and accessible reservoir storage capacity.

In selecting filters and separators for dense phase CO<sub>2</sub> applications, substantial care must be taken about which materials are used, how filter sizing is performed, and what the filtration rating is. To fully protect reservoirs, the filter rating must be selected based on the reservoir permeability and approximate pore diameter.

## 4. FILTRATION TECHNOLOGIES

The main types of filters used in CCUS include physical filters for the removal of solid particulates, separation of liquid from the process gases, and removal of residual hydrocarbon/organic compounds, and membrane filters for gas separation.

### 4.1 Physical filtration

Physical filters are used to remove particulates and liquid droplets including dust, ash, and aerosols from gas streams. These filters protect downstream equipment such as compressors and CO<sub>2</sub> separation units from damage caused by contaminants.

- **Bag filters** are used in industrial applications to capture fine particulates from flue gases in post-combustion capture systems. They consist of fabric bags that trap particles while allowing clean gas to pass through.
- **Cyclone separators** use centrifugal forces to remove large particulates from gas streams. They are often used as pre-filters before more sensitive filtration systems in combustion and oxy-combustion processes.
- **Coalescing filters** are designed to separate liquid droplets from gas streams, preventing liquids from entering the CO<sub>2</sub> capture system. Coalescing filters are particularly important in pre-combustion capture processes, where syngas can contain water vapour and other liquid contaminants. They are also applied in the CO<sub>2</sub> gas compression cycles to condition the CO<sub>2</sub> prior to post-dehydration and processing, ready for sequestration or supply to utilisation processes.
- **Activated carbon** filters primarily function as a means of maximising absorber column efficiency and operation. They are mainly deployed to remove organic contaminants and residual hydrocarbons from the lean solvent streams, thus preventing contactor foaming.

### 4.2 Membrane filters

Membrane filters are widely used in CCUS systems for separating gases based on molecular size or chemical properties.

- Polymeric membranes are effective at separating CO<sub>2</sub> from other gases, such as nitrogen, in post-combustion capture systems. Polymeric membranes offer a cost-effective solution for CO<sub>2</sub> capture in industries with high gas flow rates.
- Carbon molecular sieve membranes (CMSM) are highly selective for CO<sub>2</sub> and hydrogen separation, making them ideal for pre-combustion capture processes. These membranes are used to produce high-purity hydrogen for use in power generation or industrial applications.

# 5. INNOVATIONS IN CCUS FILTRATION

While on a rapid development track, the carbon capture, utilisation and storage sector is far from mature, and focused primarily on finding new CCUS technologies and materials. The challenge for filtration specialists is to leverage the proven benefits of technologies that have been used successfully for many years in conventional natural gas applications and redesign these to meet the requirements of CCUS applications.

As no 'standard' design for CCUS exists, and each application will have its own process challenges, this is not easy: but significant progress is being made<sup>11</sup>.

## 5.1 Early collaboration pays dividends

Cleanova.C-CLEAN provides an innovative approach which recognises that each process has unique parameters and each customer has specific needs and desired outcomes. It provides tailored filtration solutions designed for each carbon capture process, based on the chosen method, load quantities, type of contaminants, CO<sub>2</sub> concentration, pressure and temperature.

The aim is to collaborate with CCUS operators from the earliest concept stages, because considering filtration

requirements early, within the context of the entire system design and business model, will yield the best results.

## 5.2 Tailored and configurable filtration

Absorption-based CCUS systems are prone to high levels of particulate contaminants that can impede the effectiveness of the amine in capturing CO<sub>2</sub> and lead to clogging of downstream process equipment including heat exchangers, strippers and dehydration systems. UNIQ-MAX filter technology is designed to provide a market-leading solid removal capacity per unit area, in addition to being configurable across a wide range of filtration efficiencies (1 – 100µ) that can be specified to maximise the operational efficiency of any customer installation.

UNIQ-MAX filter technology is absolute rated and tailored to protect a range of physical solvent processes, including monoethanolamine and diethanolamine (MEA/DEA), Selexol™ and Purisol, which are currently gaining traction for pre-combustion carbon capture. In parallel, UNIQ-MAX filtration is highly effective in high pressure supercritical CO<sub>2</sub> injection applications where low particle concentrations are critical to the efficient sequestration of the gas into depleted rock formations.

# 6. WHERE NEXT FOR CCUS FILTRATION?

Driving down costs, optimising uptime, and delivering high quality products are common aims in any industrial application. The successful adaptation of existing technologies such as filtration to meet the specific requirements of CCUS operations is an ongoing process.

Cleanova are actively developing partnerships with new process developers and licensors to ensure that our new product development and product introduction strategy meets CCUS developments now and in the future.

We have been working closely with our CCUS technology partners and conducting in-house research into the opportunities in new technologies like direct air capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS).

We anticipate exciting developments in solvent-based methods, particularly with the use of hydroxide solutions that can offer a simpler and less energy demanding regeneration loops when compared to amines while maintaining the CO<sub>2</sub> absorption capacity. On the other hand, advancements in adsorbent materials and the use of highly porous structures (similar to activated carbons or zeolites) will provide a viable and possibly more efficient CO<sub>2</sub> capture alternative to solvents, and Cleanova are working on the filtration equipment specifications to support these developments.

# CASE STUDY

## Cartridge Filters for Dense Phase CO<sub>2</sub>

Cleanova supplied 10-micron cartridge filters specifically designed for dense phase CO<sub>2</sub> used for a sequestration application in the Middle East. The dense CO<sub>2</sub>, which was originally captured from a nearby refinery & industrial plant and later subjected to compression stages, required filtration to remove particulate that could affect both downstream equipment and injection efficiency. Operating at pressures greater than 200bar, the Cleanova solution enabled maximum process performance and contributed to the sustainable sequestration of captured CO<sub>2</sub>.



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