Carbon utilisation to accelerate the transition to net zero

Captured carbon can be converted into valuable products, enabling circularity and decarbonisation of hard-to-abate industries

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Global decarbonisation targets are driving the demand for carbon capture, utilisation, and storage (CCUS) solutions that can be applied within power generation and manufacturing facilities to slash CO_2 emissions. As the CCUS offering continues to expand, it is important for companies to be able to recognise the technologies that are ready and feasible for commercial use and best suited to drive more sustainable practices while maximising profitability and efficiency.

Since the beginning of the first Industrial Revolution in 1750, more than 1.7 trillion tonnes of CO_2 have been emitted, most of which (87%) were due to the combustion of fossil fuels from the second half of the 20th century onwards (Friedlingstein, *et al.*, 2022). On average, global emissions increased by nearly 2.8% annually from 1950 to 2021, and are now more than 63% above the levels of 1990 (Friedlingstein, *et al.*, 2022), the reference year for the Kyoto Protocol and the Paris Agreement.

This continuous growth is in stark contrast to worldwide efforts to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels. In fact, meeting these targets would require a linear decrease in anthropogenic CO_2 emissions by about 1.4 billion tonnes of CO_2 each year (Friedlingstein, *et al.*, 2022).

To meet this challenge, energy and manufacturing players worldwide need to adopt suitable mitigation strategies and solutions. Industrial GHG emissions comprise 29% of global emissions. Eliminating the emissions from the use of energy in industry and direct industrial processes would curtail global emissions by 14.7 billion tonnes per annum (Ritchie, Roser, & Rosado, 2020).

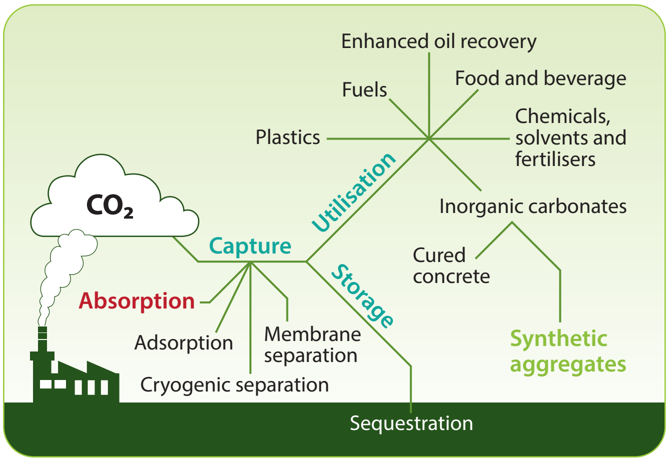

Figure 1 Overview of the main CCUS solutions currently available or under development, with the main solutions discussed in this article highlighted in colour

Fortunately, industrial players can employ a range of technologies to reduce their carbon emissions. One of the most popular and effective groups of technologies currently available is CCUS, which embraces carbon capture and storage (CCS) and carbon capture and utilisation (CCU, see **Figure 1**). CCUS techniques within the energy sector are generally classified based on how emissions are captured and then processed, as outlined below.

Carbon capture methodologies

When looking at capturing methodologies, these are generally discerned within the energy sector as pre-, post-, and oxy-fuel combustion solutions, depending on

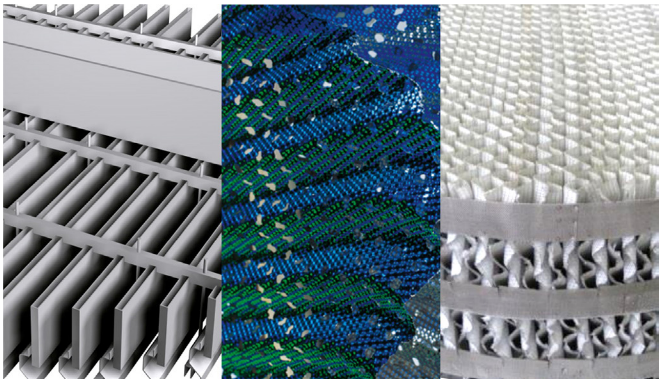

Figure 2 Close-up views of MellaTech liquid distributor, and Mellapak CC and AYPlusDC structured packings (from left to right)

whether CO_2 is captured during intermediate reactions, from waste streams, or in processes involving the burning of fuels with diluted or concentrated oxygen.

While all these carbon capture methods have been applied to different setups, post-combustion strategies offer the most mature and easy-to-implement technologies. They are the most common solution utilised in commercial-scale energy plants, and similar approaches are being applied to waste-to-energy and biomass-to-energy facilities as well as to reduce carbon emissions from waste gas effluents in chemicals, metals, and cement production plants.

By contrast, pre-combustion involves high capital expenditure (Capex) and operational expenses (Opex) due to the complexity of its processes and the number of operating units required. Oxy-fuel frameworks are generally economical; however, current applications have failed to offer feasible options for large-scale facilities, mainly because of various operational challenges (Kheirinik, Ahmed, & Rahmanian, 2021).

Post-combustion technologies

Currently, post-combustion technologies feature different technology readiness levels. The most commonly discussed methods leverage absorption or adsorption technologies to remove CO_2 from flue gases, whereas fewer approaches rely on permeation principles (membrane separation).

The mechanisms behind these three alternatives can differ greatly. Membranes for carbon capture are designed so that they are highly permeable for CO_2. In this case, the specific properties of the membrane determine the efficiency of the separation process. In adsorption methods, CO_2 binds to the surface of a solid sorbent, such as hydrotalcites, lithium zirconate, active carbon, molecular sieves, calcium oxides, or zeolites. Following this step, CO_2 is desorbed via pressure or temperature swings.

Absorption techniques, on the other hand, use liquid solvents, such as aqueous monoethanolamine, diethanolamine, piperazine, or potassium carbonate, rather than solids. These absorb the CO_2 gas through the formation of a chemical bond with the dissolved reactant. The CO_2-rich liquid solvent is then processed to release the CO_2 (stripping) and regenerated, returning as a CO_2-lean chemical for reuse in more cycles, in line with circular practices. To date, absorption is the most mature solution for post-combustion installations, as it has been extensively researched and commercialised.

Absorption for large-scale CO_2 capture

This method offers optimum separation efficiencies, which can reach 90% and above. To achieve peak performance, it is important to leverage the most effective column components for absorption and stripping, such as bed packings and other internals. Specifically, while the number of beds and their height play a key role in the separation process, their design also heavily influences the possible outcomes, with the geometrical structure of the packings defining the hydraulic and mass transfer properties.

For example, CO_2 absorption towers typically perform better when equipped with structured rather than random packing. In addition, the structured packing's microstructure, surface, and corrugation angle, as well as the number and size of holes within it, influence wetting capabilities, pressure drop, reaction regime, and, ultimately, separation efficiency.

To support energy and manufacturing companies in setting up CCUS facilities that can separate CO_2 from flue gases efficiently, Sulzer Chemtech has developed a range of application-specific column components. These include the MellapakCC and AYPlusDC structured packings and the MellaTech liquid distributors (see **Figure 2**) (Mellon & Duss, 2011).

The first technology, which is installed in nearly all pump-arounds, is designed to maximise separation while reducing pressure drop by up to 60% compared to top-end, previous-generation structured packings for general applications. These features ultimately lead to considerable reductions in Capex and Opex. Given the 2021 cost of electricity at approximately EUR 0.2 kWh in Europe, even a limited pressure drop reduction of 5 mbar can lead to considerable cost savings in energy bills. For example, for an 800 MW coal power station, nearly €1 million can be saved yearly. In practice, In practice, SaskPower's Boundary Dam Unit 3,115 MW coal-fired power unit in Saskatchewan, Canada, captures 800 kilo-tonnes of CO_2 annually, in part thanks to Sulzer Chemtech's solutions

AYPlus DC, which is installed above the absorption section, enhances separation performance by limiting solvent emissions to sub-ppm levels thanks to remarkable wetting properties. MellaTech systems ensure a homogeneous liquid distribution from high to low liquid loads and support special requirements such as space, turndown ratio, flashing, fouling, and foaming. Finally, to support future-oriented decarbonisation strategies, Sulzer Chemtech is expanding its solvent portfolio to further enhance CCUS processes.

CO_2 storage or utilisation?

After capturing activities, carbon is stored or utilised to prevent its release into the atmosphere. In effect, the widespread adoption of CCUS can only occur if the infrastructure for CO_2 use or storage is developed at the same speed or faster than capturing facilities.

Traditionally, CO_2 has been sequestered in geological formations, such as depleted oil and gas reservoirs, coal beds, deep saline aquifers, and ocean sites. The first subsurface injections started in the 1970s and dedicated CO_2 storage from the late 1990s, with the first large-scale CCS project commissioned at the Norwegian Sleipner offshore gas field in 1996. The project has now stored more than 20 million tonnes of CO_2 in a deep saline formation (IEA, 2021).

A risk associated with such practices is leakage of the gas, which can migrate to the surface. This can hinder decarbonisation efforts while also having a negative impact on shallow potable aquifers, fauna, flora, and humans.

An alternative to storage is the conversion and direct use of captured carbon. Moreover, utilisation is in line with the principles of the circular economy and can help meet the demand for greener chemicals, fuels, and materials. CO_2 is largely being used in commercial-scale enhanced oil recovery (EOR) and the food and beverage industry (see Figure 1). It also finds some use in chemical manufacturing, biotechnology, and pharmaceutical manufacturing, such as for the production of urea, cyclic carbonates, salicylic acid, and poly(propylene) carbonate. For reference, approximately 70-80 million tonnes are used as feedstock for EOR every year. In addition, the fertiliser production industry uses around 215 million tonnes of CO_2 annually (IEA, 2021), mostly to deliver blue urea and a growing volume of other, more circular, ammonium nitrate products.

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In addition to these commercial applications, new uses for CO_2 are being developed. For example, methanol, formic acid, and polycarbonate etherols processes are now at the pilot plant or demonstration scale. In addition, laboratory-scale systems are exploring the use of CO_2 to produce alcohols, aldehydes, dimethyl ether (DME), organic acids, and carbamates. (Draxler, Schenk, Burgler, & Sormann, 2020). Most of these applications require hydrogen as a co-reactant, as well as high pressure and temperature.

Mineralisation-based CCUS solutions

More recently, new routes that solely rely on acid-base equilibria in the aqueous phase have emerged. These leverage mineralisation processes, particularly mineral carbonation, to react CO_2 with metal oxides, hydroxides, silicates, or other inorganic materials to form

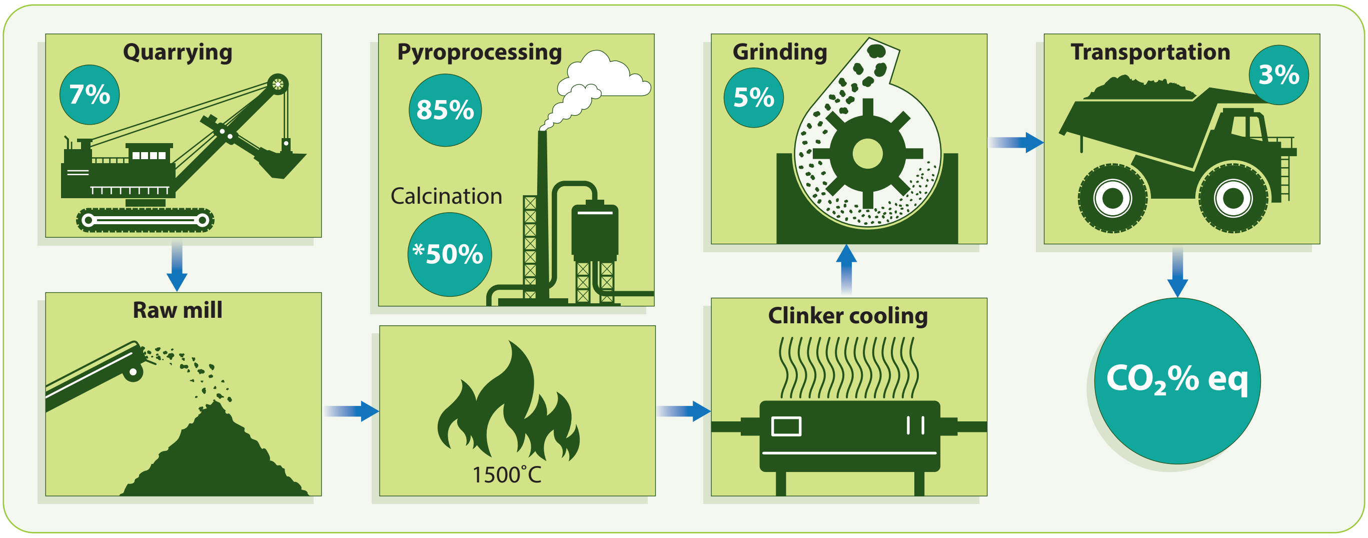

Figure 3 Geogenic emissions upon limestone calcination account for about 50% of the total process emissions, as indicated by *

carbonated products (see Figure 1). The reaction is typically exothermic; hence it is not particularly energy-consuming, and the heat generated can be easily recovered and reused.

Most importantly, these processes combine both storage and utilisation, with the resulting materials being fit for use by the large construction and building materials sector. These industries are currently characterised by a considerable carbon footprint, as the cement industry alone is responsible for at least 8% of global anthropogenic emissions (Ellis & et al., 2020). The production of cement involves heating calcium carbonate, commonly known as limestone, to approximately 1,450°C (2,700°F) to separate calcium and carbon and make clinker. As a result, CO_2 emissions are generated both by the fuel burned to heat up the limestone and by the decomposition of the latter (see **Figure 3**). Hence cement accounts for over 90% of the carbon intensity of concrete, even though it only represents 10-17% of the mass of concrete.

The adoption of mineralisation-based CCUS solutions for point source emitters can therefore act as a gateway to an immense market and unlock the sequestration of high volumes of CO_2. Moreover, as buildings and their components are characterised by long service lives, these can be considered carbon storage facilities.

When looking at the specific technologies and opportunities available, the mineralisation of captured CO_2 can support the concrete industry through two alternatives. Specifically, carbon emissions can be used as feedstock to cure cement, also known as carbonate hardening, or to produce synthetic aggregates.

Carbon storage via aggregate production

The first is initiated by the diffusion of gaseous CO_2 to the external surface of concrete materials, from where it enters the pores. The gas subsequently reacts with calcium sources, such as calcium silicate in Portland clinker, to form calcium carbonate and silica-rich components that reduce the material's porosity. Therefore, the technique acts as an enforced (or active) carbonation treatment to increase the hydration of cement. The superficial layer of calcium carbonate ($CaCO_3$) generated ultimately improves key properties, such as compressive strength.

To date, curing processes can only be performed in batch conditions and require an accurate tuning of temperature and pressure to facilitate the reaction, contributing to higher energy requirements. Also, carbon storage only occurs on the surface of cementitious materials, sequestering limited volumes of CO_2, especially when components are made of large particles and have compact surfaces. Usually, the natural carbonation of concrete is limited to a few millimetres from the exterior surface exposed to the atmosphere (Kaliyavaradhan & Ling, 2017).

Conversely, carbon storage through aggregate production can be 10-40 times higher and continuous processing is possible, limiting energy usage and increasing throughput. This method relies on a capture system that transforms CO_2 into aqueous carbonate. By adding calcium ions, derived from materials such as construction and demolition waste, to the capture solution, solid precipitates of $CaCO_3$ are formed.

These synthetic limestones can be used to produce aggregates with high mechanical strength, making them suitable for construction. At end of life, they can re-enter the mineralisation-based CCUS process as calcium-rich feedstock. Therefore, the process is completely circular and a valuable way to endlessly store carbon.

Case study: manufacture of carbon-negative synthetic limestone aggregate

A key example of the benefits of CCUS for aggregate production is offered by Blue Planet, whose patented geomimetic process can permanently sequester large volumes of CO_2 within construction materials (see **Figure 4**).

When looking for a technology partner to commercialise its novel mineralisation process, Blue Planet partnered with Sulzer Chemtech. The collaboration involves the use of Sulzer Chemtech's separation technologies to support the development of an efficient and effective carbon capture unit within San Francisco Bay Aggregates' first pilot-scale plant in Pittsburg, California, USA.

This can effectively treat flue gas streams of variable CO_2 content. The captured CO_2 from emissions generated by heavy industries does not need to be purified or liquified before being combined in solution with metal ions obtained from concrete or other industrial wastes. The process delivers carbonate minerals that are worked up into synthetic limestone aggregates. These can then be combined with cement to produce high-quality, sustainable concrete.

The process can store up to 440 kg (970 lb) of CO_2 per tonne of aggregate produced. As a result, it is possible to curb the environmental footprint of cement, producing carbon-negative concrete. In particular, by including Blue Planet's resulting coarse and fine aggregates within a typical concrete mix formulation, it is possible to store 508 kg (1,120 lb) of CO_2 in less than a cubic metre of concrete, shifting the embodied emissions from more than 272 kg (600 lb) of CO_2 to -224 kg (-494 lb).

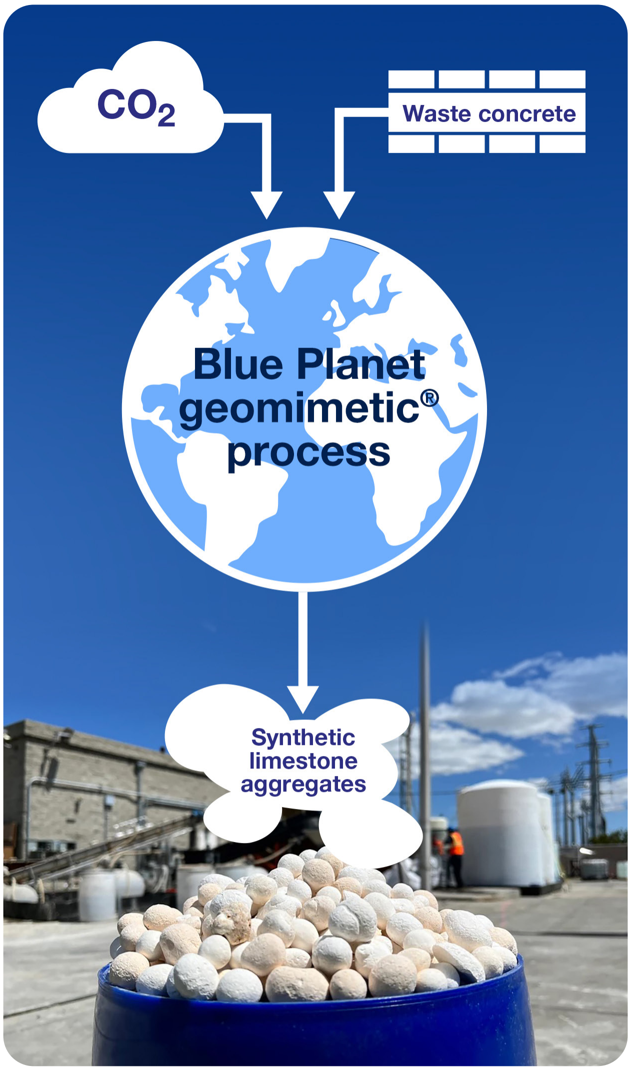

Figure 4 Blue Planet's patented geomimetic process can permanently sequester large volumes of CO_2 within construction materials

The energy load of Blue Planet's solution, less than 0.1 MWh per tonne of CO_2eq as projected by the company's lifecycle assessment, is well below conventional CCS estimations. Therefore, users can reduce the operational costs and environmental footprint of such activities, driving effective decarbonisation strategies forward.

MellapakCC, AYPlusDC and MellaTech are trademarks of Sulzer Chemtech. geomimetic is a trademark of Blue Planet.

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