

BEYOND EMISSIONS

Jens Kristian Jørsboe, Jimmy Andersen, Christian Riber, and Burcin Temel McKenna, Ramboll, discuss various carbon capture technologies and their advantages and disadvantages.

ement production is the foundation of global construction, indispensable for infrastructure projects ranging from towering skyscrapers to intricate road networks. However, the production of cement is emission-intensive and has a large environmental footprint. Despite significant progress, challenges remain in the widespread decarbonisation of cement production, where technical feasibility, cost considerations, and policy support are among the key factors. This article sheds light on the challenges and opportunities in achieving a more sustainable cement industry.

Ramboll is a global engineering consultancy with 18 000 experts based around the world. The carbon capture team has conducted over 125 studies ranging from feasibility to FEED, Balance-of-plant, and EPCM studies including projects being built in various geographies. Ramboll provides services for the whole

value chain of CCUS: carbon capture, liquefaction, transport via rail or pipelines, utilisation into methanol or aviation fuel, storage and regulatory advisory.

Options for the mitigation of greenhouse gas emissions

The deployment of carbon capture in the cement industry is a significant area of interest when it comes to reducing greenhouse gas (GHG) emissions. According to the Global Cement and Concrete Association, cement production is responsible for approximately 7% of the global carbon dioxide (CO₂) emissions. This is due to the calcination process, which releases CO₂ from limestone (calcium carbonate) during clinker production. The production of clinker also requires high temperatures and combustion of fuels to provide energy for the process. Therefore, the



emissions from cement production come primarily from the process and fuel consumption for the calcination process.

There are various options available to cement producers to reduce their environmental impact:

- ▶ **Energy efficiency improvements:** Implementing energy-efficient technologies and practices can reduce the energy consumption of clinker production, thereby lowering CO₂ emissions. This includes optimising kiln operations, improving heat recovery systems, and minimising energy waste.
- ▶ **Alternative fuels (AF):** Substituting traditional fossil fuels with AF such as biomass, waste-derived fuels, and non-recyclable plastics can reduce the CO₂ emissions from clinker production. These AF often have some biogenic carbon content and can help lower the overall fossil carbon footprint of the cement manufacturing process.
- ▶ **Lower carbon products:** Blending clinker with supplementary cementitious materials such as fly ash or slag can reduce the amount of clinker needed in cement production.
- ▶ **Oxyfuel combustion:** The cement kiln and/or calciner can be designed to use pure oxygen instead of air. This results in a flue gas stream with higher CO₂ concentration, making it easier to capture.

- ▶ **Carbon capture and storage (CCS):** This method captures CO₂ from the flue gases emitted during cement production. Carbon capture technologies are more widely applicable and can be retrofitted to existing cement plants.

While there are diverse options available, there are limitations to these approaches. For example, the energy efficiency of the cement plant has typically been optimised, and further optimisation or improvements may require considerable investments. AF vary in terms of their availability and quality, and the infrastructure for supplying them must be established.

Substituting clinker with supplementary materials can affect the performance and quality of the final cement product, potentially impacting properties such as strength, durability, and setting time. The availability and cost of supplementary materials, such as fly ash and slag, can vary regionally, limiting their widespread adoption as clinker substitutes.

These general improvement approaches reduce emissions but there will always be inherent release of CO₂ during the calcination process.

Oxyfuel combustion aims to produce a highly concentrated CO₂ stream by using pure oxygen for the combustion process. However, the false air ingress in the cement plant will pollute the highly concentrated CO₂ product and an added carbon

capture unit might be needed.

CCS technologies are still relatively new as an application for cement plants and may require further development and optimisation to achieve widespread deployment. CCS implementation can be expensive, and the scale of deployment needed to achieve significant emission reductions in the cement industry may pose logistical and economic challenges. Finding suitable storage sites for captured CO₂ and ensuring their long-term integrity and security can be challenging. However, carbon capture technologies offer a significant reduction in CO₂ emissions, as it is possible to capture most of the CO₂ from the flue gas released from cement production.

Overview of carbon capture technologies

Carbon capture technologies can be used to capture CO₂ emissions from various industries like cement, power

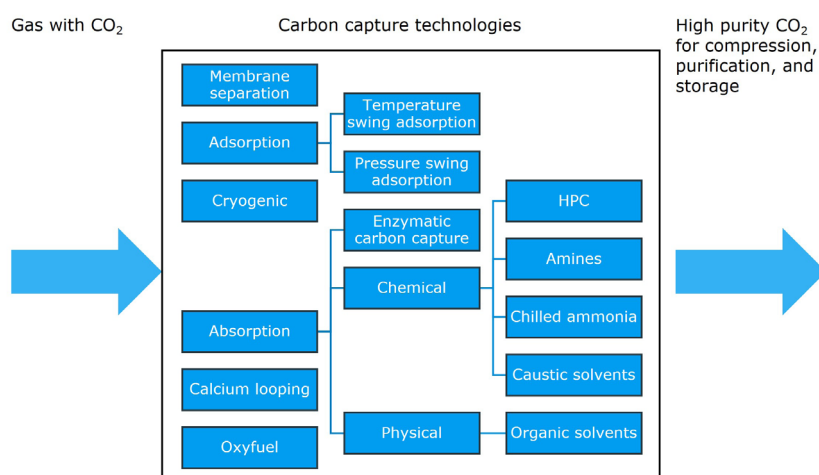


Figure 1. Overview of carbon capture technologies.

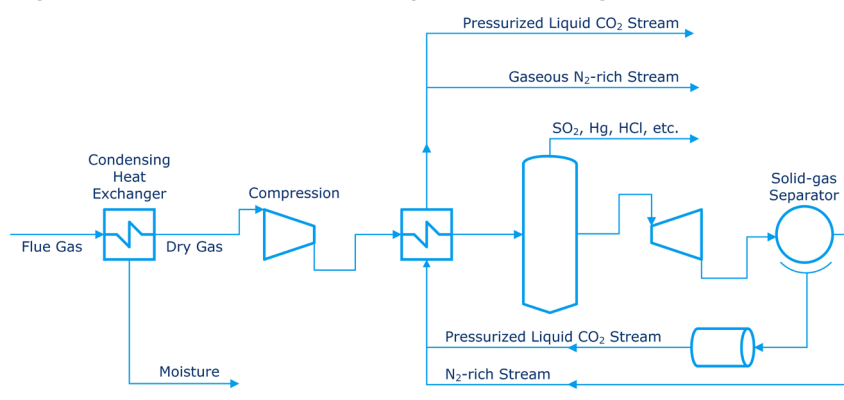


Figure 2. Flow diagram of the cryogenic carbon capture process.

generation, steel, biogas plants, and refineries. Currently, there is a wide array of carbon capture technologies available. The high CO_2 concentration in the flue gas from cement production is an advantage as the carbon capture technologies benefit from higher CO_2 concentrations. Another advantage is that cement plants are large CO_2 point sources, which allows for economies of scale, thereby reducing the capital investment per ton of CO_2 . Moreover, the cement plants are operated at a steady base load thereby incurring low variation of CO_2 emissions. The location of cement plants can, however, be challenging for CO_2 infrastructure.

An overview of the carbon capture technologies is given in Figure 1.

Each carbon capture technology has advantages and challenges, including energy consumption, cost, scalability, and environmental impact. The carbon capture technologies apply either a chemical or physical separation principle.

The physical separation processes include adsorption, membrane separation, and cryogenic separation. Adsorption processes involve passing flue gases through a solid material, known as an adsorbent, which can selectively capture CO_2 . Common adsorbents are either activated carbon or zeolites. Once the adsorbent is saturated with CO_2 , it is regenerated by changing temperature or pressure, releasing the captured CO_2 for storage or utilisation. Membrane separation uses semi-permeable membranes to selectively separate CO_2 from flue gases based on differences in molecular size and solubility. Cryogenic separation involves cooling the flue gas to extremely low temperatures to condense and separate CO_2 from other gases.

Physical separation processes are widely applied for removal of CO_2 from biogas (biogas upgrading), which has a slightly higher concentration of CO_2 compared to flue gas from cement production. The physical separation processes can also be combined in hybrid systems to take

advantage of their complementary strengths and to obtain higher CO_2 purity. However, there are limited references for these processes for large-scale application.

Currently, the amine-based absorption process is the most mature carbon capture technology with references for large-scale application. In this process, the flue gas, containing CO_2 , is directed through an absorber column, and contacted with an alkaline solution denoted as solvent. The CO_2 reacts and is absorbed into the solvent. The solvent with the absorbed CO_2 is regenerated in a stripping column, typically conducted at elevated temperatures. Once the CO_2 is released, the regenerated solvent is returned to the absorber column to capture more CO_2 from the flue gas. The released CO_2 can then be compressed and transported for storage or utilisation.

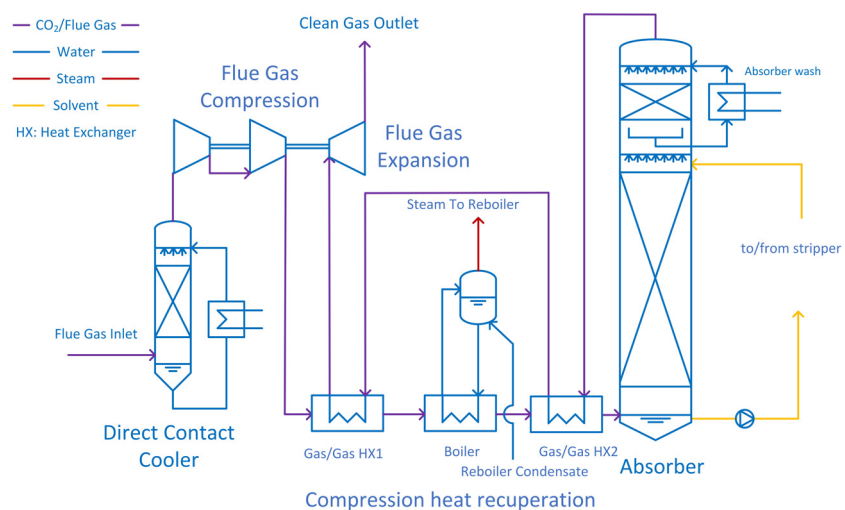


Figure 3. Flow diagram of the absorber column for the hot potassium carbonate process.

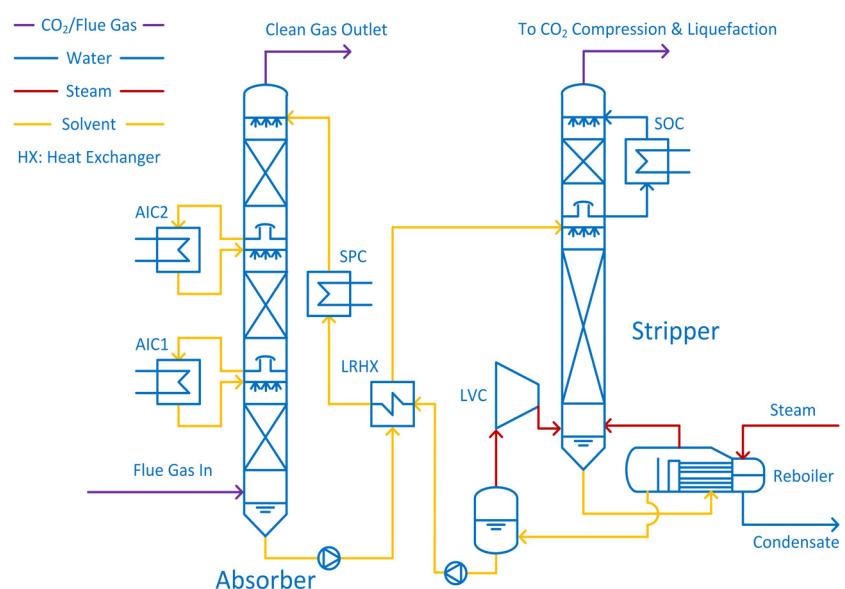


Figure 4. Amine-based carbon capture with absorber intercooling (AIC) and lean vapour compression (LVC).

Cryogenic carbon capture

Cryogenic carbon capture is a physical separation process that separates CO₂ by cooling the gas stream to very low temperatures, typically between -100 and -135°C. The process diagram of the cryogenic separation is illustrated in Figure 2. In the flow diagram, the water content of the gas stream is removed by condensation. The gas stream then undergoes compression and subsequent cooling to achieve conditions where CO₂ desublimates, becoming solid from its gas phase, and the CO₂ can then be removed.

Due to costs associated with compression of the flue gas, the cryogenic carbon capture process greatly benefits from high CO₂ concentrations in the treated flue gas such as in the case for cement production. The cryogenic separation process may also be coupled with pressure swing adsorption, membrane separation or oxyfuel to increase the CO₂ concentration prior to the cryogenic separation.

Cryogenic carbon capture has several advantages including high capture rate of above 95%, high CO₂ purity, and, relatively, energy requirements are potentially low compared to other carbon capture technologies. Cryogenic carbon capture is a tail-end technology that only requires access to sufficient power and cooling, and a low energy penalty can be ensured with heat integration. However, it also has challenges, such as high capital costs associated with the cryogenic equipment and has limited references in large-scale application.

Hot potassium carbonate (HPC) carbon capture

The HPC solution reacts with CO₂ in the flue gas, forming potassium bicarbonate (KHCO₃) when water is present. The HPC process is an example of a chemical absorption process for carbon capture. The chemical absorption process includes an absorption column and a regeneration column. The flow diagram, excluding the regeneration vessel, is illustrated in Figure 3.

HPC offers high CO₂ capture efficiency (removal rates typically exceeding 90%), low thermal energy requirements, and can handle fluctuating CO₂ concentrations and flow rates in industrial flue gases.

The potassium carbonate solution has lower affinity towards CO₂ compared to other solvents and therefore requires an elevated partial pressure of CO₂ in the absorber column. The elevated partial pressure of CO₂ is obtained by compression of the flue gas to obtain a CO₂ partial pressure of approximately 1 bar. The compression of the flue gas requires electrical energy, however a lot of the thermal energy needed in the desorption process can be recuperated from the compression step as shown in Figure 3.

The HPC process benefits from the high CO₂ concentrations in the flue gas from cement production. Considering a typical CO₂ concentration of 20%, the flue gas must undergo compression to only 5 bar compared to 7 – 8 bar for solid fuel combustion plants such as biomass or waste-to-energy facilities. Further, HPC does not need much steam, which cement plants do not have. The HPC is therefore a good fit for carbon capture from cement plants.

However, challenges associated with hot potassium carbonate carbon capture include the corrosive nature of potassium carbonate solutions, reduced reaction speed over time, and the need for efficient heat integration and solvent regeneration to minimise energy consumption and operating costs. Ongoing research and development efforts focus on addressing these challenges and improving the overall performance and cost-effectiveness of the technology. The maturity of the technology is the main drawback, as the flue gas compression has not been displayed or confirmed/verified for post-combustion applications.

Optimisation of the amine-based carbon capture process

Amine-based carbon capture is widely used and offers several advantages such as high CO₂ capture, scalability making it suitable for large-scale applications, and compatibility with existing industrial infrastructure, easing retrofitting to existing plants. However, challenges associated with amine-based carbon capture include a high energy consumption for solvent regeneration, solvent degradation, and potential corrosion issues. Efforts continue to focus on reducing the energy requirements of the process,

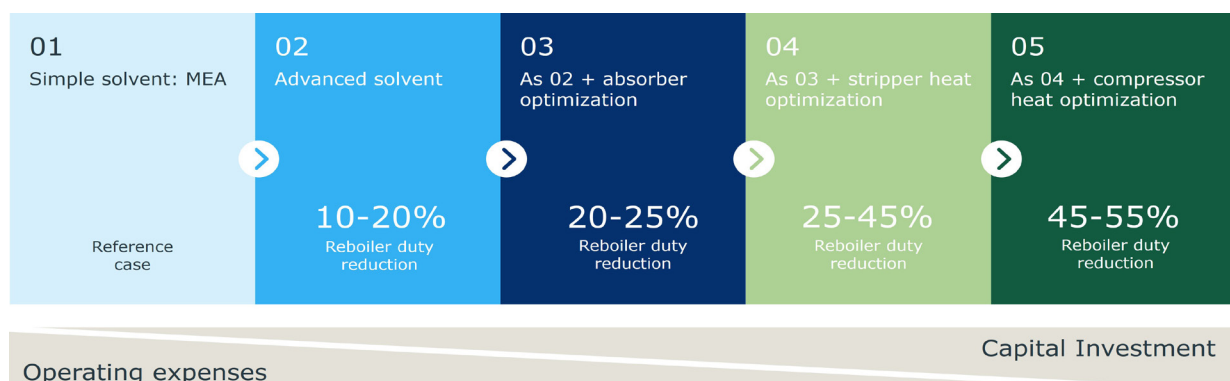


Figure 5. Optimisation of amine-based carbon capture.

especially reboiler duty, and improving the solvent resistance towards degradation.

One approach to improve amine-based carbon capture is to use alternative amines or blends of amines. The traditional amines include monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA). In recent times, amine blends have been developed such as AMP-PZ (CESAR1) and AMP-DMSO. Furthermore, there are advanced supplier designed amines commercially available: MHI (KS-1™, KS-21™), OASE®blue, ACC™ S21 & S26, APBS-CDRMax®, CANSOLV DC-103, or Econamine FG PlusSM. The development of these new amine solvents has resulted in 10 – 20% lower energy consumption, more stable solvents, and less make-up/reclaiming needed. However, these new solvents are more expensive and careful emission control may be required depending on flue gas NOx levels, and the temperature and pressure in the absorber column.

Another approach to reduce the energy requirement of the carbon capture process is internal carbon capture improvements. There are various approaches for optimising the flow diagram of carbon capture. Some improvements include absorber intercooling (AIC), lean vapour compression (LVC), or mechanical recompression systems (MVR). A flow diagram of the amine-based carbon capture with AIC and LVC is illustrated in Figure 4. By using AIC, the solvent can absorb more CO₂, consequently reducing the reboiler duty. The LVC configuration flashes the hot regenerated solvent from the reboiler to provide additional stripping steam. This reduces the amount of necessary reboiler duty, but it comes at the expense of compressor power costs.

Amine-based carbon capture at cement plants faces different challenges such as the availability of steam, and the cleaning and cooling of the flue gas to make it suitable for carbon capture. The need for steam can be reduced by optimisation of the heat integration and by implementation of heat pumps and steam fans. The amine-based carbon capture can thereby be considered with varying complexity. Different cases of the amine-based carbon capture process are shown in Figure 5, where the expected reduction in the reboiler duty is included.

To supply the carbon capture plant with heat, waste heat can be recovered from both calciner flue gas and clinker cooler gas through large waste heat recovery (WHR) units, also called boiler units. WHR allows for some steam production to be used directly in the carbon capture reboiler. It can also be used to upgrade hot water with heat pumps and steam fans to provide a significant amount of steam for the reboiler. The potential energy available in a standard cement kiln process allows for approximately 30 – 40% of the energy needed to be delivered as steam, and 40 – 100% of the energy needed to be delivered as hot water. By optimisation of the amine-based carbon capture process and using WHR, it is thereby

almost possible to cover the heat demand for the amine-based carbon capture facility without investing in a dedicated steam producing system.

Carbon capture in the cement industry

According to IEA, the cement sector is the third-largest industrial energy consumer and the second-largest industrial CO₂ emitter globally. To get on track with the Net Zero Scenario, emissions from cement production must fall by an average of 3% annually by 2030. Carbon capture is crucial for the cement industry as it offers a pathway to mitigate the significant GHG emissions associated with its production. Currently, there are many projects working on improving ways to capture carbon emissions from the cement industry. Some methods, like cryogenic and membrane technologies, are being developed, but they have not been tested on the scale needed for cement production yet. Oxyfuel technology is also receiving a lot of attention, although it requires a larger interaction with the main process than post-combustion technologies. Finally, there are also other carbon capture technologies only focusing on the calcination part of cement production, which may become feasible.

There are various technologies available for carbon capture and some may see implementation on a large-scale in the future, but the carbon capture technology with the most large-scale references is currently the amine-based capture technology. This technology is commercially available, can be retrofitted to an existing cement plant, and there are various options for heat integration to reduce the operating costs of the technology. By adopting carbon capture and through the continued innovation of emissions reduction technologies, the cement industry can make significant strides towards decarbonisation and sustainable production of cement. ■

About the authors

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Jimmy Andersen, Lead Carbon Capture Consultant, has more than 10 years of experience in the power plant industry and has comprehensive knowledge of operation and optimisation of the carbon capture process.

Jens Kristian Jørsboe, Consultant, has more than five years of experience within carbon capture technologies and a strong background in process modelling and optimisation.