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Techno-economic analysis of an energy-optimised cryogenic carbon capture process for decarbonisation of cement production

Leonardo Varnier[a], Federico d'Amore[a], Bart de Groot[b], Fabrizio Bezzo[a,*]

[a] *CAPE-Lab – Computer-Aided Process Engineering Laboratory, Department of Industrial Engineering, University of Padova, via Marzolo 9, 35131 Padova, Italy*

[b] *Siemens Industry Software Limited, Hammersmith Grove 26-28, W6 7HA London, United Kingdom*

Abstract

The accumulation of greenhouse gases in the atmosphere, particularly carbon dioxide (CO_2), is a major driver of climate change. Cement production accounts for approximately 7% of worldwide emissions, making it the second largest industrial emitter after steel (Marmier, 2023). Notably, around 60% of these emissions arise from the calcination step in clinker production, the main component of cement. As a consequence, decarbonisation strategies other than carbon capture are insufficient to address the process-related emissions of cement plants (GCCA, 2021).

While research and industrial efforts have traditionally focused on well-established methods, such as solvent-based CO_2 capture, cryogenic CO_2 capture has gained popularity in recent years due to several advantages. These include the ability to achieve high capture efficiencies (potentially above 95%) and CO_2 purities exceeding 99.5%, while maintaining relatively low energy consumption (Font Palma et al., 2021). Additionally, cryogenic CO_2 capture relies entirely on electricity, ideally supplied by renewable sources, and has lower water consumption compared to other capture methods (Asgharian et al., 2025). This technology is classified at TRL 5–6, with a pilot plant successfully tested in the field capturing 1 t_{CO2}/d, while a 30 t_{CO2}/d demonstration plant is currently under development (Baxter et al., 2021).

Cryogenic capture separates CO_2 from flue gases through its deposition into a solid, driven by direct contact with a low-vapor-pressure hydrocarbon, typically isopentane, at extremely low temperatures (between -115°C and -110°C). Sensible heating and cooling are recovered through heat integration, leaving only the energy for phase change and separation to be supplied via refrigeration cycles (Baxter et al., 2021). Previous studies have demonstrated that cryogenic capture can achieve CO_2 removal in coal-fired power plants with an energy penalty as low as 0.9 MJ_{el}/kg_{CO2}, significantly lower than many alternative technologies (Hoeger et al., 2021).

Despite its potential benefits, cryogenic CO_2 capture remains in the early stages of development, with limited publicly available information on process design and techno-economic feasibility. This lack of data may hinder broader interest and commercial adoption. To address these gaps and build confidence in the technology, this work provides valuable insights into the techno-economic potential of cryogenic capture for the decarbonisation of cement production and enhances its understanding and viability as an alternative to conventional carbon capture methods.

This study simulates a cryogenic carbon capture process designed to separate the CO_2 from a cement plant flue gas using the gPROMS Process software (Siemens, 2025). The flue gas inlet composition aligns with Varnier et al. (2025) for a coal-fired cement plant producing 1 Mt clinker annually with a molar CO_2 concentration of 22%. A simplified process scheme is shown in Figure 1.

* Corresponding author. Tel.: +39 0498275468

E-mail address: fabrizio.bezzo@unipd.it (Fabrizio Bezzo)

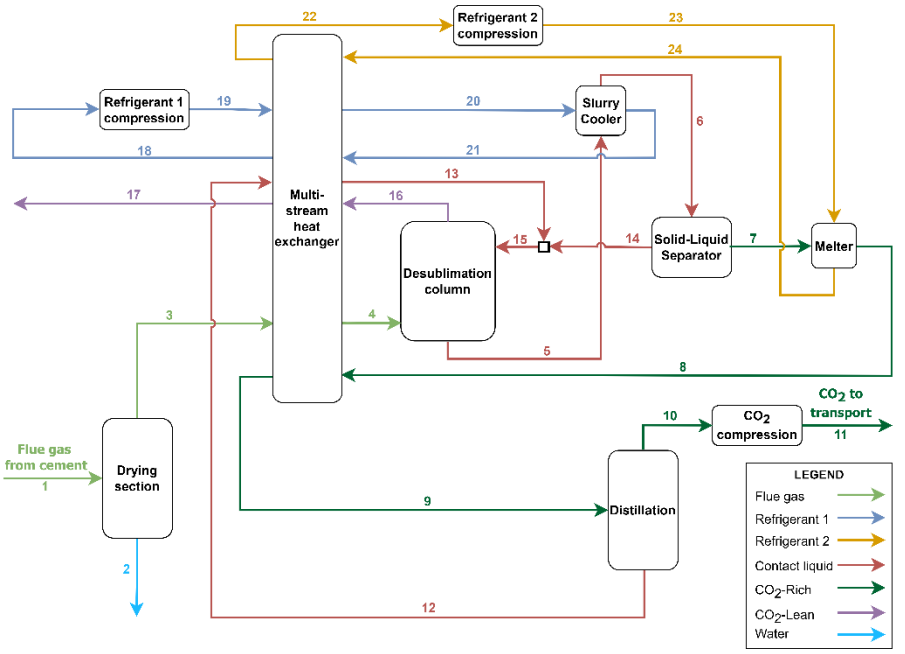

Figure 1. Simplified schematic of the cryogenic CO_2 capture process.

The flue gas (stream #1) is first dried to prevent ice formation in downstream equipment and to avoid water accumulation within the process. The dehydrated gas is then cooled to a temperature near its freezing point (approximately -93°C) in a multi-stream heat exchanger, utilising heat integration with colder process streams, before entering the desublimation column (stream #4). In this unit, the CO_2 is separated from the gas mixture into liquid and solid phases through direct heat transfer with cold isopentane. The resulting CO_2/isopentane slurry (stream #5) is further cooled by the mixed refrigerant 1 (stream #20) before the solid CO_2 (stream #7) is separated from the liquid isopentane, which is recycled back to the desublimation column (stream #14). The energy released during CO_2 melting is recovered by mixed refrigerant 2. Subsequently, the CO_2-rich stream (stream #8) undergoes heat integration before entering a distillation column, where any residual isopentane is separated and recycled via cooling.

The system is designed to achieve a 90% CO_2 capture rate, facilitating direct comparison with other capture technologies, while delivering compressed CO_2 with a purity of 99.9%.

Since the design variables of such an integrated separation process are highly interconnected, rigorous process optimisation is paramount to achieving an energy-efficient system, minimising operational costs, and enhancing the overall feasibility of cryogenic CO_2 capture in industrial applications. In this work, we performed such an optimisation on the composition and the condensation/evaporation pressures of the refrigeration cycles, aiming to minimise the system energy penalty.

As shown in Table 1, optimising the operating conditions of the refrigeration cycles has led to a reduction in compressor power requirements for both refrigerant 1 and refrigerant 2 compared to the preliminary base case. This, in turn, has resulted in a nearly 7% decrease in the overall process energy penalty.

Table 1. Comparison of power requirements for refrigerant compressors and energy penalty between the base case and the optimised case.

Variable		Base Case	Optimised Case	Variation
Power compressor Refrigerant 1	MW_{el}	23.43	21.59	-7.8%
Power compressor Refrigerant 2	MW_{el}	0.59	0.48	-19.3%
Energy penalty	**MJ_{el}/kg_{CO2}**	**1.15**	**1.07**	**-6.7%**

The process is further analysed from an economic standpoint, by evaluating the capital and operational costs, and calculating the cost of avoided CO_2 (CAC). With an energy penalty as low as 1.07 MJ_{el}/kg_{CO2} and a CAC lower than 120 €/t_{CO2} (including transportation and storage), the results indicates that cryogenic carbon capture is less energy intensive and potentially more cost-effective compared to traditional solvent-based methods.

Keywords: cement industry; decarbonisation; cryogenic carbon capture; techno-economic analysis;

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References

Asgharian H., Iov F., Nielsen M. P., Liso V., Burt S., Baxter L. (2025) Cryogenic Carbon Capture Process Combined with Absorption Refrigeration Cycle for Cement Plants - A Danish Case Study, *Separation and Purification Technology*, 353, 128419.

Baxter L., Hoeger C., Stitt K., Burt S., Baxter A. (2021) Cryogenic Carbon Capture™ (CCC) Status Report, *Proceedings of the 15th Greenhouse Gas Control Technologies Conference*. Available: ssrn.com/abstract=3820158 (accessed 14 March 2025).

Font-Palma, C., Cann, D., Udemu, C. (2021) Review of Cryogenic Carbon Capture Innovations and Their Potential Applications, *C*, 7(3), 58.

GCCA. (2021) Concrete Future - The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete. Available: gccassociation.org/concretefuture/wp-content/uploads/2022/10/GCCA-Concrete- Future-Roadmap-Document-AW-2022.pdf (accessed 11 December 2025).

Hoeger C., Burt S., Baxter L. (2021) Cryogenic Carbon Capture™ Technoeconomic Analysis, *Proceedings of the 15th Greenhouse Gas Control Technologies Conference*. Available: ssrn.com/abstract=3820158 (accessed 14 March 2025).

Marmier, A. (2023) Decarbonisation options for the cement industry, Publications Office of the European Union. Available: https://doi.org/10.2760/174037 (accessed 21 February 2025).

Siemens. (2025). gPROMS Process v2024.1.0. Available: https://www.siemens.com/global/en/products/automation/industry-software/gproms-digital-process-design-and-operations/gproms-modelling-environments/gproms-process.html (accessed 1 February 2025)

Varnier, L., d’Amore, F., Clausen, K., Melitos, G., de Groot, B., Bezzo, F. (2025) Combined electrification and carbon capture for low-carbon cement: techno-economic assessment of different designs, *Journal of Cleaner Production*, 498, 145029.