



## Techno-Economic Analysis of Cryogenic Carbon Capture for Cement Decarbonisation

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The increasing concern over climate change due to global warming has intensified efforts to reduce CO<sub>2</sub> emissions into the atmosphere, with a particular emphasis on carbon removal technologies, including carbon capture. While much of the current research and applications focus on well-established methods, such as solvent-based capture, cryogenic CO<sub>2</sub> separation techniques present several advantages. These include the ability to operate solely on electricity, ideally supplied by renewables, along with high capture rates and CO<sub>2</sub> purity. This study assesses a cryogenic carbon capture process for separating the CO<sub>2</sub> from the flue gases of a coal-fired cement plant. The process is investigated from a techno-economic standpoint by evaluating the capital and operative costs, and by calculating its key performance indicators. Simulation results estimate an energy penalty of 1.14 MJ<sub>el</sub>/kgCO<sub>2</sub> and a CO<sub>2</sub> avoidance cost of 118.2 €/tCO<sub>2</sub>, which would make cryogenic capture less energy-intensive and potentially more cost-effective than conventional solvent-based methods.

### 1. Introduction

The accumulation of greenhouse gases in the atmosphere, particularly carbon dioxide (CO<sub>2</sub>), has a detrimental effect on climate change. Cement production is responsible for 7 % of global CO<sub>2</sub> emissions, making this sector the second largest industrial emitter after steel (Marmier, 2023). The carbon footprint of cement averages 0.59 tons of CO<sub>2</sub> per ton of cement, varying by production technologies, fuel mixes, efficiency measures and cement types (Ferrario et al., 2023). As most of the CO<sub>2</sub> emissions derive from the calcination process for producing clinker, i.e., the main constituent of cement, the implementation of decarbonisation strategies other than carbon capture is insufficient to mitigate the environmental impact of these plants. Therefore, carbon capture technologies are key for addressing the process-related emissions of cement plants (Varnier et al., 2024). Among the various options to abate such CO<sub>2</sub> (e.g., chemical absorption, membranes, calcium-looping), cryogenic capture is gaining scientific interest due to the following potential advantages (Asgharian et al., 2025): (i) low energy consumption; (ii) high capture rate (potentially larger than 95 %) and purity (greater than 99.5 %), indicating that this process can meet stringent CO<sub>2</sub> requirements without additional downstream equipment; and (iii) high flexibility and retrofittability to (small-to-large) existing plants.

Cryogenic separation is based on capturing CO<sub>2</sub> from flue gases in the solid phase through direct contact with a low-vapour-pressure hydrocarbon. This process exhibits a good performance in terms of energy requirements due to its high potential for heat integration. Jensen et al. (2015) evaluated the performance of cryogenic CO<sub>2</sub> capture from a 550 MW coal-fired power plant, reporting an energy penalty between 0.71 and 0.92 MJ<sub>el</sub>/kgCO<sub>2</sub>. This result was confirmed by Hoeger et al. (2021), who demonstrated that cryogenic capture could abate the CO<sub>2</sub> from coal-fired power plants with an energy penalty of 0.89 MJ<sub>el</sub>/kgCO<sub>2</sub>, significantly lower than other technologies investigated in their study. In the cement sector, Asgharian et al. (2025) investigated the integration of cryogenic capture with a water-ammonia absorption refrigeration cycle, achieving an energy penalty below 0.70 MJ<sub>el</sub>/kgCO<sub>2</sub>. Despite the potential benefits, cryogenic CO<sub>2</sub> capture is still in the early stages of development and faces several technical challenges. Furthermore, limited data are available on its techno-economic feasibility for cement plant decarbonisation. To address these aspects, this work proposes a techno-economic

analysis of cryogenic carbon capture applied to cement plant flue gas, benchmarking its performance (i.e., energy demands and costs) against conventional carbon capture options.

## 2. Materials and methods

The cryogenic CO<sub>2</sub> capture plant, illustrated in Figure 1, was simulated in Aspen Plus V14.0 (AspenTech, 2025) according to the following assumptions: (i) pollutants such as SO<sub>x</sub>, NO<sub>x</sub>, HCl, CO and H<sub>2</sub>S are excluded; (ii) the inlet flue gas composition aligns with Varnier et al. (2025) for a coal-fired cement plant producing 1 Mt clinker annually (Table 1); (iii) a baseline 90 % CO<sub>2</sub> capture rate is set, to facilitate the comparison with other capture technologies; (iv) compressors and blowers operate at 90% and 85% polytropic efficiency, respectively, while pumps have an isentropic efficiency in the range of 70-85%; (v) electrical-to-mechanical efficiency is 95%; (vi) minimum pinch temperatures are 5 °C (intercoolers, liquid-liquid exchangers), 10 °C (gas-liquid exchangers), and 2 °C (multi-stream heat exchanger); and (vii) cooling water is available at 25 °C and returns at 35 °C. Accurate prediction of solid CO<sub>2</sub> formation requires robust solid-vapour equilibrium calculations. For this purpose, the Peng-Robinson cubic equation of state was selected due to its proven accuracy and effectiveness in solid-vapour equilibrium predictions for CO<sub>2</sub> (Jensen et al., 2015).

Table 1: Inlet flue gas properties and composition.

Properties	Unit	Value	Composition	Unit	Value
Flow rate	kg/s	91.79	CO <sub>2</sub>	%mol	22.2
	kmol/h	10759	N <sub>2</sub>	%mol	58.1
Temperature	°C	110	O <sub>2</sub>	%mol	6.9
Pressure	bar	1	H <sub>2</sub> O	%mol	12.1
			Ar	%mol	0.7

The flue gas leaving the cement plant at 110 °C (stream #1, Figure 1) is used in the distillation column reboiler before being pressurised by a blower to offset pressure losses throughout the process. After cooling to ambient temperature, the gas (stream #4) enters a dehydration section, where water is removed via chilled water absorption (DRY1) and a molecular sieve. Before entering the desublimation column (DES), the dehydrated gas (stream #6) is further cooled near the freezing point (-93 °C) within the multi-stream heat exchanger (MSHX) via heat integration with cold streams, including the CO<sub>2</sub>-lean stream (stream #23). Additionally, the CO<sub>2</sub>-lean stream is utilised to produce the chilled water required for flue gas dehydration. In the desublimation column, the CO<sub>2</sub> is separated from the gas mixture into liquid and solid phases via direct heat transfer with cold isopentane. The resulting CO<sub>2</sub>/isopentane slurry (stream #27) is pressurised above the CO<sub>2</sub> triple point and further cooled to increase the solid CO<sub>2</sub> content before entering the solid-liquid separator. Here, liquid isopentane is removed with an efficiency of 95 % (Asgharian et al., 2025) and recycled to the desublimation column, resulting in a CO<sub>2</sub> mass fraction of 0.66 (stream #30).

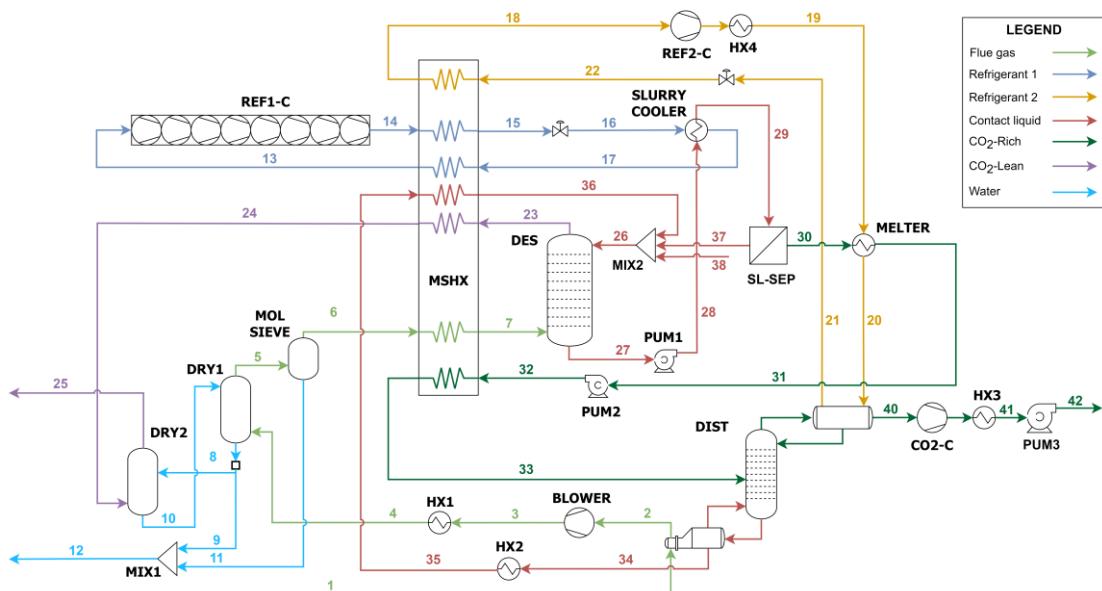


Figure 1: Cryogenic CO<sub>2</sub> capture process flow diagram.

The concentrated slurry is melted by condensing the second refrigerant, pumped to 30 bar (stream #32) and reheated to 25 °C in MSHX, yielding a liquid-vapour stream (stream #33), which is fed to the final distillation stage. In the distillation column, CO<sub>2</sub> is recovered as a vapour from the column top with a purity of 99.9 % by mass (stream #40). It is compressed to 80 bar, condensed, and further pressurised to 110 bar through a pump (stream #42) to meet transportation requirements. Isopentane is collected as the distillation residue (stream #34), cooled in HX2, further chilled to -80 °C in the MSHX, and recycled to the desublimation column.

Cooling is provided by two refrigeration loops. The first refrigerant (stream #13) consists of a hydrocarbon mixture comprising 45.2 % methane, 18.0 % ethane, 19.3 % propane, and 17.5 % butane by mass. This mixture is compressed to 37 bar in an 8-stage compressor with intercooling (stream #14), condensed, and expanded to 4.6 bar at -130 °C (stream #16) to cool the CO<sub>2</sub>/isopentane slurry. The second refrigeration loop (stream #18) uses a different hydrocarbon mixture, consisting of 25.2 % methane, 71.1 % ethane, 1.9 % butane, and 1.8 % isopentane by mass. The refrigerant is compressed to 13.1 bar, condensed by melting the CO<sub>2</sub> slurry, and used to operate the distillation condenser. It is then expanded to 10 bar to provide additional duty in the MSHX.

The economic analysis of the cryogenic capture plant includes the calculation of capital and operative expenses, expressed in €<sup>2024</sup> currency. The bare module cost ( $C_{BM}$ ) of the plant, which includes equipment purchase and installation costs, is determined using the methodology described in Turton et al. (2018). Total capital costs are evaluated according to the procedure of Rubin et al. (2013) and summarised in Table 2, alongside the main assumptions regarding the calculation of operative expenditures. The number of operators is based on values reported for CO<sub>2</sub> capture projects of comparable scale in the cement sector (Gardarsdottir et al., 2019).

Table 2: Cost structure for capital and operative costs calculation.

<b>Capital costs (CAPEX) calculation</b>	
Bare module cost ( $C_{BM}$ )	Turton et al. (2018)
Process contingencies ( $PC_1$ )	40 % $C_{BM}$
Total direct cost ( $TDC$ )	$C_{BM} + PC_1$
Engineering service ( $EPC$ )	14 % $TDC$
Project contingencies ( $PC_2$ )	20 % $TDC$
Total plant cost ( $TPC$ )	$TDC + EPC + PC_2$
Owner's and Start-up costs (OS)	10 % $TPC$
Total overnight cost (TOC)	$TPC + OS$
<b>Operative costs (OPEX) calculation</b>	
Personnel ( $PER$ )	20 operators (Gardarsdottir et al., 2019)
Operating labour ( $OL$ )	60000 €/y · $PER$ (Gardarsdottir et al., 2019)
Total maintenance ( $TM$ )	2.5 % $TPC$
Administrative and support labour ( $ASL$ )	30 % ( $OL + 40\% TM$ )
Insurance ( $INS$ )	2 % $TPC$
Fixed OPEX ( $FO$ )	$OL + TM + ASL + INS$
Utilities - Electricity	100 €/MWh <sub>el</sub> (Eurostat, 2025)
Utilities - Cooling water	0.02 €/ton of H <sub>2</sub> O
Utilities - CO <sub>2</sub> transport and storage	35 €/ton of CO <sub>2</sub> (d'Amore et al., 2024)
Variable OPEX (VO)	Sum of utilities

The technical and economic performance of the cryogenic carbon capture process was assessed using the key performance indicators (KPIs) outlined in the following. The energy penalty  $\gamma$  is the primary metric to quantify the process energy efficiency, given its fully electrified nature:

$$\gamma \left( \frac{\text{MJ}_{\text{el}}}{\text{kg}_{\text{CO}_2}} \right) = \frac{\dot{W}}{\dot{m}_{\text{CO}_2, \text{capt}}} \quad (1)$$

where  $\dot{W}$  (MW<sub>el</sub>) represents the total power consumed in the cryogenic capture process by compressors, pumps and the blower, while  $\dot{m}_{\text{CO}_2, \text{capt}}$  (kg/s) is the mass flowrate of captured CO<sub>2</sub>.

The equivalent CO<sub>2</sub> avoidance rate ( $AC_{eq}$  [%]) evaluates CO<sub>2</sub> reduction based on the equivalent CO<sub>2</sub> emissions ( $e_{eq}$  [kg<sub>CO<sub>2</sub>,eq</sub>/t<sub>clinker</sub>]), accounting for both direct and indirect emissions.  $AC_{eq}$  is defined as follows:

$$AC_{eq}(\%) = \left( 1 - \frac{e_{eq}^{\text{decarb}}}{e_{eq}^{\text{ref}}} \right) \cdot 100 \quad (2)$$

In Eq(2), the superscripts “decarb” and “ref” denote the decarbonised and reference plants, respectively. The reference plant equivalent emissions are set at 860.8 kg<sub>CO<sub>2</sub>,eq</sub>/t<sub>clinker</sub> (Varnier et al., 2025), based on the EU-27 energy mix scenario with an electricity carbon intensity of 210 kg<sub>CO<sub>2</sub>,eq</sub>/MWh<sub>el</sub> (EEA, 2025). The cost of avoided CO<sub>2</sub> (CAC) is the primary economic KPI. Since cryogenic capture is a post-combustion technology, only the additional cost of clinker ( $\Delta COC$  [€/t<sub>clinker</sub>]) due to capture implementation is considered.  $\Delta COC$  is derived from the sum of fixed and variable operating expenses, along with the annualised total overnight cost (TOC) normalised by the annual clinker production rate ( $\dot{m}_{clinker}$  [t<sub>clinker</sub>/y]). The annualisation assumes a 91.3 % plant capacity factor, a 25-year operational lifespan, and an 8 % discount rate. The cost formulations are as follows:

$$CAC \left( \frac{\epsilon}{t_{CO_2}} \right) = \frac{\Delta COC}{e_{eq}^{ref} - e_{eq}^{decarb}} \quad (3)$$

$$\Delta COC \left( \frac{\epsilon}{t_{clinker}} \right) = \left( FO + VO + TOC \frac{0.08(1 + 0.08)^{25}}{(1 + 0.08)^{25} - 1} \right) / \dot{m}_{clinker} \quad (4)$$

### 3. Results

Table 3 summarises the technical results of the cryogenic capture plant. The process captures 90 % of the CO<sub>2</sub> in the flue gas, relying solely on electrical energy. The total power demand amounts to 29.89 MW<sub>el</sub>, resulting in an energy penalty of 1.14 MJ<sub>el</sub>/kg<sub>CO<sub>2</sub></sub>. This is promising when compared to MEA-based carbon capture, which incurs both a thermal energy penalty of 3.76 MJ<sub>th</sub>/kg<sub>CO<sub>2</sub></sub> and an electrical energy penalty of 0.52 MJ<sub>el</sub>/kg<sub>CO<sub>2</sub></sub> for a flue gas with a similar CO<sub>2</sub> concentration (Voldsgaard et al., 2019). With more conservative assumptions for the polytropic efficiency of compressors and blowers, reduced to 85% and 75% respectively, the total power consumption would increase to 32.01 MW<sub>el</sub>, resulting in an energy penalty of 1.22 MJ<sub>el</sub>/kg<sub>CO<sub>2</sub></sub> (+7 %).

Table 3: Electrical power consumption and key performance indicators for the cryogenic capture process.

Variable	Unit	Value	
Power consumption blower	MW <sub>el</sub>	4.14	13.8 %
Power consumption refrigerant 1 compressor	MW <sub>el</sub>	23.24	77.8 %
Power consumption refrigerant 2 compressor	MW <sub>el</sub>	0.59	2.0 %
Power consumption CO <sub>2</sub> compressor	MW <sub>el</sub>	1.27	4.2 %
Power consumption pumps	MW <sub>el</sub>	0.66	2.2 %
<b>Total power consumption</b>	<b>MW<sub>el</sub></b>	<b>29.89</b>	<b>100.0 %</b>
<b>Energy penalty (<math>\gamma</math>)</b>	<b>MJ<sub>el</sub>/kg<sub>CO<sub>2</sub></sub></b>	<b>1.14</b>	
Equivalent CO <sub>2</sub> emissions	kg <sub>CO<sub>2</sub>,eq</sub> /t <sub>clinker</sub>	160.9	
Carbon capture rate	%	90.0	
<b>Equivalent CO<sub>2</sub> avoidance rate (AC<sub>eq</sub>)</b>	<b>%</b>	<b>81.3</b>	

The compression power for the first refrigeration cycle represents the main contributor to overall power consumption, accounting for 77.8 % of the total. Additionally, the blower contributes almost 14 %, primarily to offset the pressure drop of the gas throughout the drying section. Considering the substantial increase in electrical demand, capturing 90 % of the direct CO<sub>2</sub> emissions results in an equivalent CO<sub>2</sub> avoidance rate of 81.3 %, due to the higher indirect emissions.

The sensitivity of the energy penalty to the molar concentration of CO<sub>2</sub> in the flue gas was analysed across a range between 10 % and 31 % in order to assess process efficiency under variable flue gas concentrations (Figure 2). The overall process design was maintained, including key parameters such as flue gas mass flow rate, refrigerant composition, and distillation column configuration. However, minor adjustments were made to meet pinch temperature constraints in heat exchangers and ensure process feasibility on CO<sub>2</sub> product purity. Within the 10-31 % mol CO<sub>2</sub> range, the energy penalty exhibits a decreasing trend, varying from 1.70 to 1.07 MJ<sub>el</sub>/kg<sub>CO<sub>2</sub></sub>. The process performs particularly well at CO<sub>2</sub> concentrations above 19 %, with an energy penalty below 1.20 MJ<sub>el</sub>/kg<sub>CO<sub>2</sub></sub>, while for concentrations below this threshold, performance deteriorates. Also, it should be noted that at CO<sub>2</sub> inlet concentrations between 10 % and 13 %, the trend of energy penalty slightly deviates due to the high N<sub>2</sub> and O<sub>2</sub> content in the flue gas. This results in a significant portion of these gases dissolving in isopentane, which prevents achieving the same product purity as for CO<sub>2</sub> concentrations greater than 13 % (99.9 % by mass). Figure 3a presents the total plant cost (TPC) breakdown, estimated in 203.2 M€. The first refrigerant compressor dominates capital expenses, accounting for approximately 50 % of the total cost,

followed by heat exchangers, including the multi-stream unit, and the blower, accounting for 16.7 % and 9.5 % of the total cost, respectively.

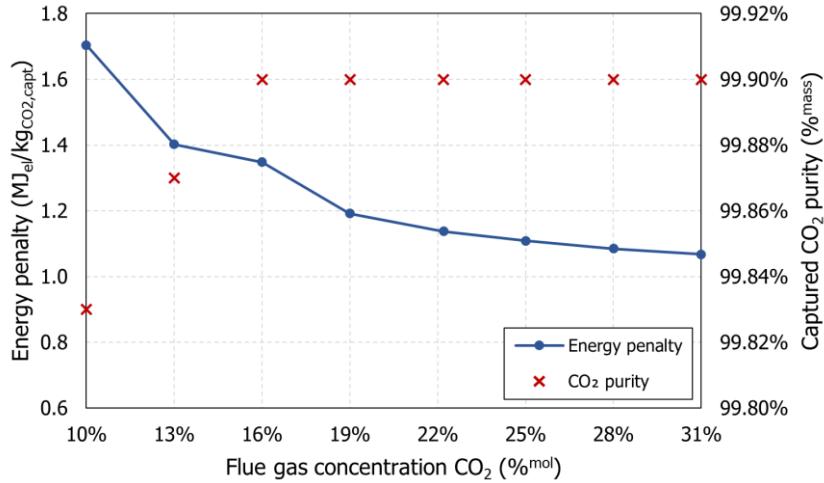


Figure 2: Sensitivity analysis of process energy penalty and CO<sub>2</sub> purity against CO<sub>2</sub> concentration in flue gas.

Figure 3b illustrates the cost of avoided CO<sub>2</sub> for the cryogenic capture process, estimated at 118.2 €/t<sub>CO<sub>2</sub></sub>. The main cost drivers are variable OPEX, including electricity, cooling water and transportation and storage, which together constitute nearly 61 % of the overall cost, while the annualised CAPEX accounts for 25 %. Notably, transport and storage (31.8 %) and electricity (28.7 %) are the largest contributors to the CO<sub>2</sub> avoidance cost. The economic performance of cryogenic capture was benchmarked against MEA-based capture, oxyfuel process, and tail-end calcium looping. The cost values were sourced from Gardarsdottir et al. (2019) and Voldsgaard et al. (2019) and recalculated using the same economic assumptions outlined in Section 2. Transport and storage costs were included to ensure a consistent comparison, particularly with tail-end calcium looping, which produces and captures more CO<sub>2</sub> and incurs higher associated costs.

Cryogenic capture outperforms MEA-based capture being significantly less OPEX-intensive, but it shows a CO<sub>2</sub> avoidance cost 16 % larger than oxyfuel technology due to greater CAPEX and electricity expenses. It also exhibits comparable CO<sub>2</sub> avoidance costs to tail-end calcium looping, which, despite higher CAPEX and CO<sub>2</sub> transport/storage costs, benefits from electricity export. However, it is important to note that both oxyfuel and calcium looping technologies generate a lower purity CO<sub>2</sub> outlet stream.

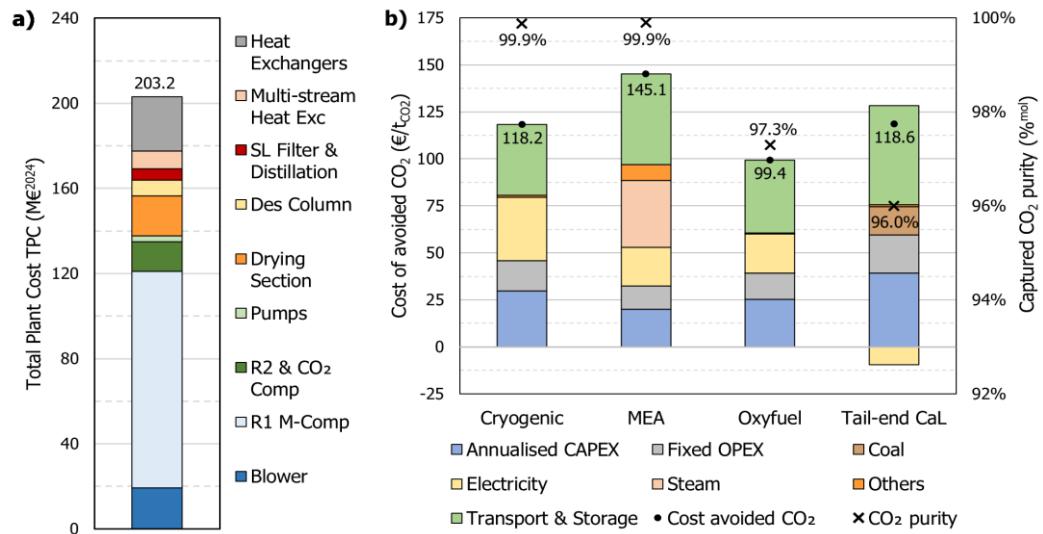


Figure 3: (a) Breakdown of total plant cost (TPC) for the cryogenic capture process and (b) comparison of cost of CO<sub>2</sub> avoided between cryogenic capture, MEA-based capture, oxyfuel cement process, and tail-end calcium looping. Results are adapted from Voldsgaard et al. (2019) and Gardarsdottir et al. (2019) recomputed using the same economic assumptions as this study.

## 4. Conclusions

This study presented a techno-economic analysis of cryogenic CO<sub>2</sub> capture applied to a coal-fired cement plant, highlighting its potential as a viable alternative to more established capture technologies. The simulations demonstrated competitive performance from both an energy and economic perspective, exhibiting an energy penalty of 1.14 MJ<sub>el</sub>/kg<sub>CO2</sub> and a cost of avoided CO<sub>2</sub> of 118.2 €/t<sub>CO2</sub>. While the economic performance of cryogenic capture is less favourable than oxyfuel and comparable to tail-end calcium looping, it offers the advantage of a higher purity in the captured CO<sub>2</sub>. These results provide a benchmark for future research aimed at enhancing process design and efficiency. Future studies should prioritise optimisation of the refrigeration cycles and drying section to improve energy performance and reduce both capital and operating costs.

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