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Assessment of different carbon capture and electrification configurations for low-carbon cement

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Abstract

This study explores the potential for decarbonising the cement sector through calciner electrification combined with amine-based carbon capture for rotary kiln emissions. A techno-economic analysis, based on process simulation, was conducted for two alternative configurations, differing in the calciner technology – entrainment (Ent) vs. drop tube (DT) – and in the heat recovery strategy for the hot CO_2 produced. The heat content of the CO_2-rich stream can either be used to preheat the raw materials (RMP case) or transferred to a fraction of the vent air from the clinker cooler via a gas-gas heat exchanger (GGHX case). The two alternative configurations, labelled Ent-RMP and DT-GGHX, were benchmarked against a reference plant without mitigation measures and an oxyfuel cement plant.

Across different energy mix scenarios, DT-GGHX demonstrates better energy efficiency than Ent-RMP, although their environmental performances are similar. Under an EU-27 energy mix, the specific primary energy consumption for CO_2 avoided (SPECCA) ranges between 5.14-5.72 MJ_{LHV}/kg_{CO2}, with a CO_2 avoidance rate of 70-72%, making these options less competitive compared to oxyfuel cement plants. However, when powered by renewable energy, both configurations showed significant performance improvements making them competitive with oxyfuel technology. Ent-RMP emerges as the most economically favourable configuration with a cost of avoided CO_2 of 217.4 €/t_{CO2}, while this is equal to 233.6 €/t_{CO2} for DT-GGHX.

Keywords: cement industry; decarbonisation; carbon capture; electrification, techno-economic analysis.

1. Introduction

The cement industry is a significant contributor to global CO_2 emissions, responsible for approximately 7% of the total [1]. These emissions are predominantly process-related, originating from the calcination of calcium carbonate ($CaCO_3 \rightarrow CaO + CO_2$), which accounts for 60% of emissions, while the remainder arises from the combustion of fossil fuels to provide the heat duty in the calciner and rotary kiln [2]. In modern cement plants, calcination largely occurs in the calciner (~90%), with clinker formation taking place in the rotary kiln.

Carbon capture, utilisation, and storage (CCUS) technologies are widely recognised as crucial for addressing process emissions [3]. A promising short-term solution to reduce emissions from fuel combustion is the electrification of the calciner, supplied with renewable energy [4]. Electrifying the calciner heat duty has the potential to avoid at

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least 70% of the CO_2 emission [5] by avoiding fuel-related CO_2 emissions and producing a pure CO_2 stream that can be captured and directed to storage or utilisation. However, addressing emissions from the rotary kiln, which include residual calcination and fuel combustion emissions, is necessary for deeper decarbonisation.

This work evaluates the techno-economic feasibility of combining calciner electrification with amine-based carbon capture to target rotary kiln emissions. Two different configurations are assessed, differing in the calciner technology – entrainment (Ent) vs. drop tube (DT) – and their strategies for recovering heat from the CO_2 stream exiting the electrified calciner. These configurations are benchmarked against a reference plant without mitigation measures and an oxyfuel cement plant.

Nomenclature

CCUS	Carbon capture, utilisation, and storage
COP	Coefficient of performance
CPU	CO_2 compression and purification unit
DT	Drop tube
Ent	Entrainment
GGHX	Gas-gas heat exchanger
MEA	Monoethanolamine
RMP	Raw meal preheating

Sub-/Superscripts

clk	Clinker
decarb	Plant with decarbonisation measure
el	Electric
eq	Equivalent
LHV	Lower heating value
ref	Reference unabated plant

2. Methods

The analysis was performed using gPROMS Process 2023.2.0 software [6], by solving steady-state material and energy balances for the analysed configurations.

The reference cement plant is based on a state-of-the-art, highly efficient dry process employing a five-stage preheater-calciner kiln system equipped with a grate cooler. The plant is coal-fired, producing approximately 1 Mt/y of clinker, typical of mid-sized European facilities. This process represents the Best Available Technique as outlined in the European BREF document [7].

2.1. Low-carbon cement plants description

The low-carbon configurations are modelled to maintain the same clinker production capacity as the reference plant but replace the coal-fired calciner with electrified alternatives:

- Ent-calciner: a vertical tube where calcination occurs as solids are carried upwards by a gas flow. This calciner is directly electrified using heating rods, with the gas flow generated by recycling a portion of the pure CO_2 produced.
- DT-calciner: inspired by the LEILAC design [8], this calciner features calcination inside an inner tube, with heat transferred indirectly through the calciner walls via an external electrical source. In this design, solids move downward, avoiding the need for CO_2 recycling.

Another key distinction between the configurations lies in the strategy for recovering heat from the hot CO_2 exiting the electrified calciner. Based on the approaches proposed in [5, 9], two heat recovery designs are explored:

- Using the heat from the CO_2-rich stream to preheat the raw meal (RMP configuration).
- Transferring the heat to a portion of vent air from the clinker cooler via a gas-gas heat exchanger (GGHX configuration), with the heated vent air subsequently used to preheat the raw meal.

The two process alternative, referred to as Ent-RMP and DT-GGHX, are detailed in the following sections.

To address rotary kiln emissions, an amine-based carbon capture unit using monoethanolamine (MEA) is employed. MEA-based capture is chosen due to its maturity and the significant available waste heat for solvent regeneration in the low-carbon configurations. This process is modelled as a black-box unit with a 90% CO_2 capture rate, based on the work of [10]. The heat required for solvent regeneration is primarily supplied by low-pressure steam recovered from waste heat. If additional steam is needed, it is provided by an electrical heat pump (exchanging with ambient air) with a coefficient of performance (COP) of 2 [11], ensuring consistency with the electrification approach. The CO_2 from the calciner and the MEA absorption process is processed by a CO_2 compression and purification unit (CPU), which ensures the CO_2 meets the required quality specifications for transportation and storage.

The Ent-RMP configuration (Fig. 1) features an electrified Ent-calciner with the pure CO_2 stream exiting the calciner (stream #16 in Fig. 1) preheating part of the raw meal in the calciner preheating tower. A fraction of this CO_2-rich stream is recycled to the Ent-calciner (stream #18) to lift the solid particles, while the remaining CO_2 (stream #19) undergoes waste heat recovery before being sent to the CPU. A portion the of tertiary air (stream #11) is mixed with the exhaust gas from the rotary kiln to preheat the remaining raw meal in the kiln preheating tower. The heat content of the flue gas from the kiln tower (stream #20) is recovered before final stages involving MEA capture and the CPU. Finally, the mixture of vent air and remaining tertiary air (stream #14) is used to dry the raw meal, after which it is discharged into the atmosphere.

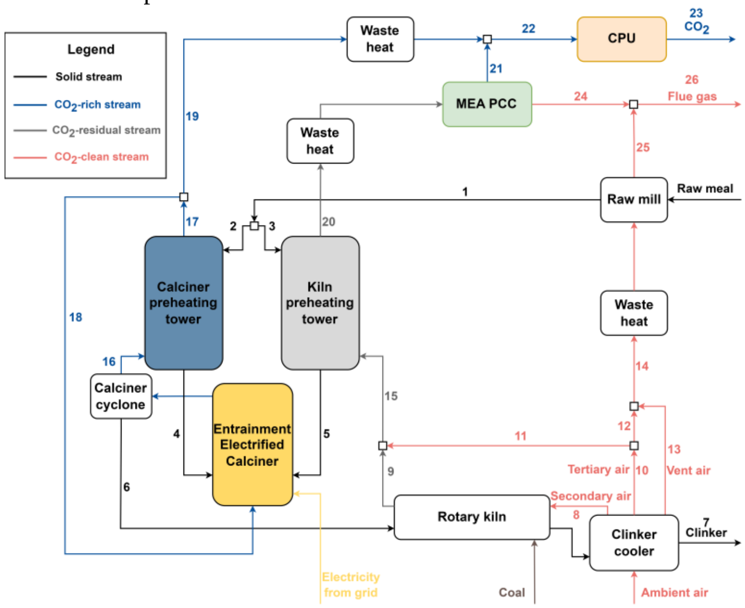

Fig. 1. Ent-RMP configuration scheme: entrainment calciner with pure CO_2 preheating raw meal.

The DT-GGHX alternative (Fig. 2) includes an electrified DT-calciner, in which the CO_2-rich stream exiting the calciner (stream #13 in Fig. 2) transfers heat to a portion of the vent air from the clinker cooler (stream #9) via a gas-gas heat exchanger. After heat recovery, the CO_2 stream is routed to the CPU, while the heated vent air is mixed with kiln exhaust gas and tertiary air, forming a hot gas mixture (stream #12) that preheats the raw meal in a standard four-stage cyclone tower. The flue gas exiting the preheating tower (stream #15) is then used to dry the raw meal before proceeding to the MEA capture stage and then to the CPU.

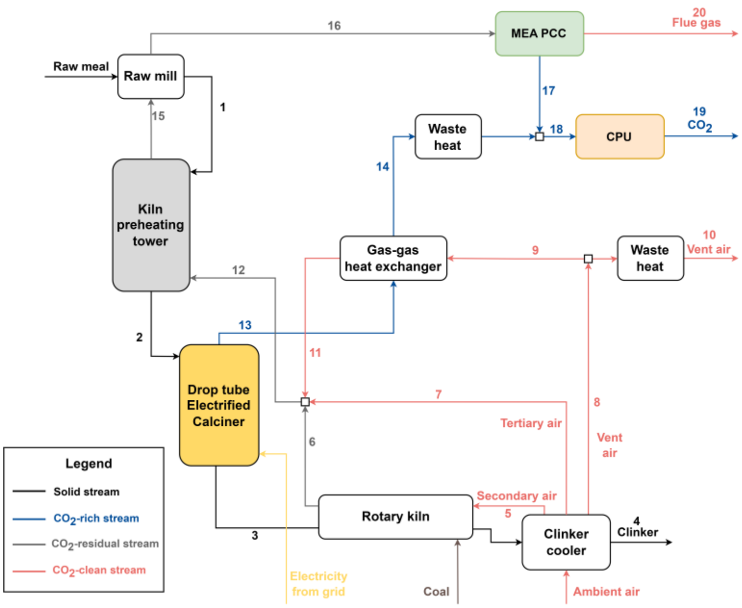

Fig. 2. DT-GGHX configuration scheme: drop tube calciner with pure CO_2 preheating vent air via a gas-gas heat exchanger.

2.2. Technical and economical key performance indicators

A technical and economic comparison of the two low-carbon configurations was conducted using key performance indicators (KPIs), as outlined in Eqs. 1-8. The equivalent specific fuel consumption (q_{eq} [GJ_{LHV}/t_{clk}]) and the equivalent specific CO_2 emissions (e_{eq} [kg_{CO_2}/t_{clk}]) are calculated as:

$$q_{eq} = q + q_{el} \tag{1}$$

$$e_{eq} = e + e_{el}. \tag{2}$$

In Eqs. 1-2, q and e are the direct fuel consumption and direct CO_2 emissions (Scope 1), respectively. On the other hand, q_{el} represents the indirect fuel consumption, while e_{el} reflects the indirect specific CO_2 from the electricity imported from the grid (Scope 2). These are computed as:

$$q_{el} = \frac{P_{el,clk}}{\eta_{el}} \tag{3}$$

$$e_{el} = P_{el,clk} \cdot e_{el,grid} \tag{4}$$

where P_{el} [MWh_{el}/t_{clk}] is the electrical energy consumption of the process, η_{el} [%] is the efficiency of electricity generation, and $e_{el,grid}$ [$kg_{CO_2,eq}/MWh_{el}$] is the carbon intensity of the imported electricity.
The specific primary energy consumption for CO_2 avoided (*SPECCA* [MJ_{LHV}/kg_{CO_2}]) is calculated as follows through these variables, to quantify the increase in fuel consumption needed to avoid CO_2 emissions in a cement plant with carbon capture relative to an unabated reference plant:

$$SPECCA = \frac{q_{eq}^{decarb} - q_{eq}^{ref}}{e_{eq}^{ref} - e_{eq}^{decarb}} \tag{5}$$

where the superscript "decarb" refers to the plant with decarbonisation measure, and "ref" to the reference plant. The equivalent CO_2 avoided AC_{eq} [%] metric evaluates CO_2 reduction by comparing the equivalent emissions between the low-carbon plant and the reference plant:

$$AC_{eq} = \left(1 - \frac{e_{eq}^{decarb}}{e_{eq}^{ref}}\right) \cdot 100. \quad (6)$$

This study compares two electricity generation scenarios, as shown in Table 1. The first scenario reflects the EU-27 energy mix, based on the most recent data from 2022 (EEA, 2024; Eurostat, 2024a). The second scenario assumes electricity generated solely from non-combustible renewables (wind, solar and hydro), with an assumed efficiency of 100% (IEA, 2019).

Table 1. Electricity generation scenarios analysed.

Scenario	**Electricity generation efficiency (%)**	**Electricity carbon intensity ($kg_{CO_2,eq}/MWh_{el}$)**
EU-27 energy mix (2022)	50.7[a]	258
Non-combustible renewables	100	0

[a] Computed from [12] for European electricity-only producers (combined heat and power plants not included) in 2022.

The economic KPIs considered in this study are the cost of clinker (*COC* [€/t_{clk}]) and the cost of avoided CO_2 (*CAC* [€/t_{CO_2}]), calculated as:

$$COC = \frac{TAC + OPEX}{\dot{m}_{clk}} \quad (7)$$

$$CAC = \frac{COC^{decarb} - COC^{ref}}{e_{eq}^{ref} - e_{eq}^{decarb}} \quad (8)$$

where *TAC* [€/y] is the total annualised capital cost, *OPEX* is the plant operating cost and $\dot{m}_{clk}$ [t_{clk}/y] is the annual clinker production. The total capital cost is quantified as the total overnight cost (TOC), estimated using a bottom-up approach and following best practices for cost estimation in CCS projects [13]. The methodology starts by estimating the cost of individual equipment units, with additional allocations for installation, engineering, owner's costs, and contingencies. TOC is then annualised to *TAC* assuming a plant operational life of 25 years and a discount rate equal to 8%.

3. Results and discussion

Table 2 presents a comparison of *SPECCA* and AC_{eq}, calculated for two electricity generation scenarios described in Section 2. These results are benchmarked against an oxyfuel cement plant, widely regarded as a promising decarbonisation strategy.

Table 2. Summary of technical and environmental key performance indicators for reference cement plant and low-carbon configurations under different electricity generation scenarios. Ent-RMP = entrainment calciner with pure CO_2 preheating raw meal; DT-GGHX = drop tube calciner with pure CO_2 preheating vent air via a gas-gas heat exchanger;

Scenario	**Ent-RMP**	**DT-GGHX**	**Oxyfuel**
EU-27 energy mix in 2022 ($\eta_{el} = 50.7\%$, $e_{el} = 258\,kg_{CO_2,eq}/MWh_{el}$)			
SPECCA	5.72	5.14	1.52
AC_{eq}	70.8%	72.2%	81.5%
Non-combustible renewables ($\eta_{el} = 100\%$, $e_{el} = 0\,kg_{CO_2}/MWh_{el}$)			
SPECCA	0.92	0.77	0.74
AC_{eq}	98.1%	98.1%	89.4%

Under the EU-27 energy mix scenario, the DT-GGHX configuration demonstrated greater energy efficiency compared to Ent-RMP, achieving a *SPECCA* of 5.14 MJ_{LHV}/kg_{CO_2} versus 5.72. This performance advantage arises primarily from the higher electrical power demand of the Ent-RMP configuration, which is associated to the energy penalty incurred when reheating the recycled CO_2 flow to lift solid particles in the calciner. This additional demand increases both indirect fuel consumption and emissions, thereby negatively impacting *SPECCA*. While the AC_{eq} values for both configurations are relatively close, in the range of 70–72%, the Ent-RMP configuration performs slightly worse due to higher indirect emissions. However, when compared to the oxyfuel cement plant, both configurations exhibit substantially higher SPECCA values (1.52 MJ_{LHV}/kg_{CO_2} for oxyfuel) and lower AC_{eq} values (81.5% for oxyfuel) [14].

The energy and environmental KPIs change substantially in a scenario where the plant electrical demand is supplied by renewable energy. *SPECCA* drops below 1 MJ_{LHV}/kg_{CO_2} for both alternatives, with DT-GGHX remaining slightly advantageous from an energy perspective. However, the results are more balanced due to the absence of indirect emissions. For the same reason, AC_{eq} values are maximised, achieving 98.1% for both configurations. In this scenario, the improved KPIs enable the low-carbon processes to rival oxyfuel technology, with comparable *SPECCA* (0.74 MJ_{LHV}/kg_{CO_2} for oxyfuel) but significantly higher AC_{eq} (89.4% for oxyfuel) [14].

Fig. 3 highlights the breakdown of the cost of clinker (*COC*) for the reference cement plant and the low-carbon configurations. The additional capital costs associated with the electrified calciner, MEA capture unit, and CPU, along with the increased electrical energy expenses, result in a dramatic rise in *COC* (+267% for Ent-RMP and +283% for DT-GGHX). Variable *OPEX*, which includes the costs of fuel, electricity, transportation, storage, and other utilities, emerges as the dominant contributor, accounting for 63–70% of the total *COC* depending on the configuration. The annualised capital expenses represent approximately 18% of the *COC* in Ent-RMP design and around 22% in DT-GGHX process, while the remaining share is attributed to fixed *OPEX*. Electricity cost clearly dominate the total *COC*, due to significant electrical energy demand of the processes accounting for 54% and 48% of the total *COC* for Ent-RMP and DT-GGHX, respectively.

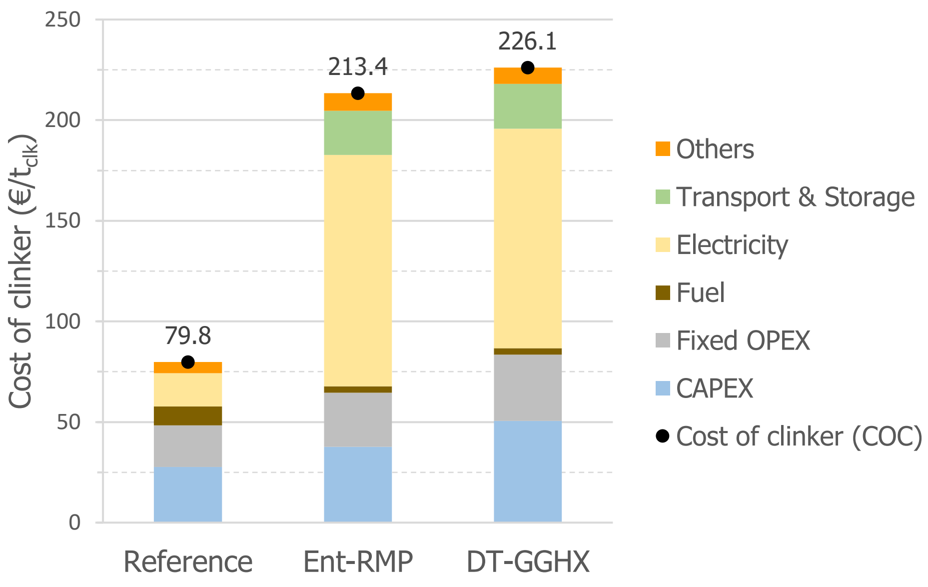

Fig. 3. Breakdown of cost of clinker for reference cement plant and low-carbon configurations. Ent-RMP = entrainment calciner with pure CO_2 preheating raw meal; DT-GGHX = drop tube calciner with pure CO_2 preheating vent air via a gas-gas heat exchanger.

The cost of avoided CO_2 (*CAC*) breakdown in Fig. 4 resembles that of *COC*, leading to similar observations. In this case, the dominance of electricity costs is even more pronounced, representing 74% and 63% of the total *CAC* for Ent-RMP and DT-GGHX, respectively.

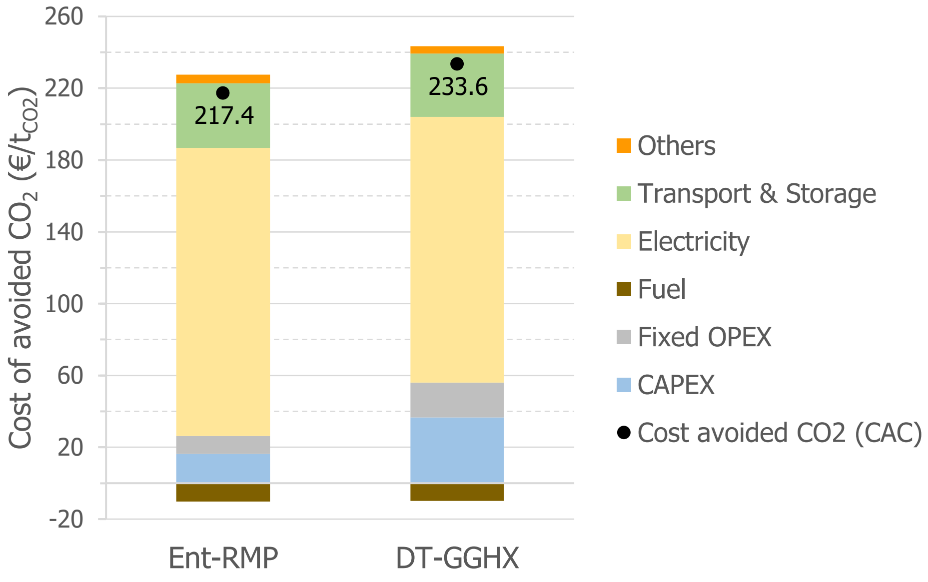

Fig. 4. Breakdown of cost of avoided CO_2 for the low-carbon configurations. Ent-RMP = entrainment calciner with pure CO_2 preheating raw meal; DT-GGHX = drop tube calciner with pure CO_2 preheating vent air via a gas-gas heat exchanger.

Overall, the Ent-RMP configuration outperforms the DT-GGHX design in terms of both *COC* and *CAC*, making it the more economically viable option. The *CAC* reflects the carbon tax required to break even with the production costs of the reference plant without mitigation measures. Compared to the EU Emission Trading System price of approximately 70 €/t_{CO_2} in August 2024 [15], the *CAC* for all configurations is notably high. This is driven by the high electricity costs in Europe, with a nominal value of 125 €/MWh_{el} assumed in this analysis.

4. Conclusions

This study explored the potential for decarbonising the cement sector through calciner electrification combined with amine-based carbon capture for rotary kiln emissions. A techno-economic analysis, based on process simulation, was conducted for two process alternatives, differing in the calciner technology – entrainment vs. drop tube – and in the heat recovery strategy for the hot CO_2 produced.

The configuration with a drop tube calciner showed better energy efficiency than the entrainment calciner alternatives across various energy mix scenarios, although their environmental performance is comparable. When renewable electrical energy is supplied to the plants, the specific primary energy consumption for CO_2 avoided ranges from 0.74 to 0.92 MJ_{LHV}/kg_{CO_2}, with CO_2 avoidance rates exceeding 98%, making these options competitive with other promising decarbonisation technologies such as oxyfuel.

From an economic perspective, the introduction of CO_2 abatement measures in the low-carbon scenarios drastically increased the cost of clinker. Entrainment calciner with raw materials preheating emerged as the most favourable configuration with a cost of avoided CO_2 (*CAC*) of 217.4 €/t_{CO_2} against a *CAC* of 233.6 €/t_{CO_2} for the process with the drop tube calciner and the heat content of the CO_2 stream transferred to the vent air via a gas-gas heat exchanger. The high *CAC* values observed revealed that these technologies are not yet economically viable, mainly due to the current electricity price in the EU.

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