



# Electrified calciner concept for CO<sub>2</sub> capture in pyro-processing of a dry process cement plant

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## ABSTRACT

Around two-thirds of the CO<sub>2</sub> emission from the cement industry comes from calcite decomposition ( $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ ), and most of this reaction happens in the calciner. So, it is possible to reduce the CO<sub>2</sub> emission significantly by electrifying the calciner. This possibility is studied in this work through a process simulation model using Aspen Plus. The model is first calibrated with experimental results for a cement calciner heated by coal firing. The validated model is then electrified with three scenarios of gas recycling. Electrifying an existing calciner will require high gas recycling, while some alternative designs require no gas recycling. The results indicate that this method could reduce the CO<sub>2</sub> emissions by as much as 78%. The total energy (including fans, calciner and kiln) required in the coal-fired calciner system is around 138 MW. The energy in the electrified system may vary between 154 MW for high gas recycling and 137 MW for no gas recycling. The net excess energy in the electrified calciner per captured CO<sub>2</sub> unit varies between 0.6 MJ/kgCO<sub>2</sub> for high gas recycling and -0.04 MJ/kgCO<sub>2</sub> for no gas recycling.

## 1. Introduction

The global cement industry has the second-largest share of the direct industrial CO<sub>2</sub> emission, emitting around 2.6 Gt of CO<sub>2</sub> in 2020 [1]. Further, cement production is expected to grow by 12–23% by 2050 due to the rising world population and urbanization [2]. The European Union (EU) aims to reduce greenhouse gas emissions by 80–95% by 2050 relative to 1990 [3]. Decarbonizing the cement industry will play a significant role in achieving this goal.

The international energy agency (IEA) considered several leading solutions<sup>1</sup> to reduce CO<sub>2</sub> emissions from the cement industry and found that the biggest lever to reach the target is using emerging and innovative technologies such as carbon capture technology [2]. Carbon capture technologies are typically categorized as post-combustion, pre-combustion, oxy-fuel, or integrated capture technology [4].

Post-combustion technology aims to capture the CO<sub>2</sub> in the exhaust gas downstream of the fuel combustion process. Amine scrubbing is an example of this and can be considered the more mature technology [5]. The main challenge with amine absorption is the relatively high energy requirement, and in most processes, there is limited waste heat available

to cover the energy requirements related to the regeneration of the solvent. Other post-combustion concepts have similar challenges related to energy consumption. However, partial CO<sub>2</sub> capture by absorption may be possible in some plants. In one of the Norwegian cement plants, an amine absorption system will be installed using only waste heat from the plant as regeneration energy in the stripper section. This process will reduce the CO<sub>2</sub> emissions from the plant by 50% [6].

Alternatively, oxy-fuel combustion may be applied. The main energy penalty in this technology arises from the need for an air separation unit (ASU) to produce high-purity oxygen [7]. Due to false air intrusion, there is also a challenge in implementing oxy-fuel combustion in a cement kiln system. The false air may intrude in the rotary kiln (as there is a small gap between the rotating kiln and the kiln inlet/outlet sections), in the calciner (where different fuels are added), and in the preheater tower. The false air may significantly reduce the CO<sub>2</sub> concentration in the flue gas; in such a case, the flue gas may require a post-combustion CO<sub>2</sub> capture unit [8].

Electrification of cement production is also an option for CO<sub>2</sub> capture if a clean source of electricity (renewable/nuclear energy) is available. A study from 2018 indicates that electrification of cement production may

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<sup>1</sup> The leading solution includes improving energy efficiency, using alternative fuels (less carbon-intensive), reducing the clinker-to-cement ratio, and using emerging and innovative technologies.

be economically feasible compared to post-combustion carbon capture technologies [9]. However, it should be mentioned that complete electrification of the most energy-intensive industries (steel, cement, glass, lime, petrochemicals, chlorine, and ammonia) in the EU is projected to increase the electricity consumption from 1000 TW h in 2010 to around 2500 TW h by 2050 [10]. The high increase in energy demand means that providing energy through renewables may be an even bigger constraint in the future than today.

In a modern cement kiln, thermal energy is supplied both in the rotary kiln and the calciner. To reduce the electricity demand, electrification of only the calciner is an option. The calciner is the most energy-intensive equipment and the highest CO<sub>2</sub> contributor in the production process. The benefits of electrifying the calciner are two-fold: It removes fuel-generated CO<sub>2</sub>, and it produces more or less pure CO<sub>2</sub> from the calcination process ( $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ ). So, the exhaust gas (clean CO<sub>2</sub>) from the calciner can be directly passed on to storage/utilization. Electrifying the calciner can thereby potentially avoid at least 70% of the CO<sub>2</sub> emission from clinker production [11].

The partial electrification concept is somewhat similar to the indirect calciner heating currently being tested in the LEILAC project at the Heidelberg Cement plant in Lixhe, Belgium [12]. In that project, the heat is indirectly transferred from hot reactor wall to the meal. Even if the reactor wall is heated by fuel combustion in the LEILAC project, the same calciner may be a good candidate for an electrified calciner if an electrical energy source heats the tube wall.

Other electrification possibilities are an electrified entrainment calciner [13], an electrified rotary calciner [14], and an electrified fluidized bed calciner [15]. The choice of reactor type will affect the mass and energy balance of the system as, for example, an entrainment calciner, or a fluidized bed calciner, would need some CO<sub>2</sub> recycling in the system for particle entrainment and fluidization, respectively. Electrical heating using plasma will also require gas recycling [9].

This study aims to demonstrate how the process is impacted by different partial electrification alternatives and thereby facilitate the comparison of different options using a common reference frame. Aspen Plus is used as a tool, and different cases are simulated.

To reach the goal, the objectives of this study are to i) establish an Aspen Plus process simulation model of clinker production, validated with results from full-scale experiments at a cement plant in Norway, and ii) apply the model as a reference for comparison with different calciner electrification concepts.

## 2. Experimental method

### 2.1. System description

A general block diagram for the cement pyro-process is shown in Fig. 1.

The pyro-processing starts with the raw meal entering the preheating towers, i.e., a two-string four-stage cyclone system, where the raw meal is suspended and heated by the hot exit gas from the calciner. The gas from the preheater is then sent to a gas treatment section for temperature reduction and dust removal, and the preheated raw meal is passed on to the calciner.

The primary process in the calciner is to decompose calcite. The energy required for this reaction ( $\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$ ) is supplied partly by burning fuels in the calciner and partly by the hot exit gas from the rotary kiln.

The calcined meal then enters the rotary kiln, where a partial melt is formed, and sintering and clinker formation occurs. The main clinkering products (clinker minerals) are alite (C<sub>3</sub>S), belite (C<sub>2</sub>S), aluminat (C<sub>3</sub>A), and ferrite (C<sub>4</sub>AF).<sup>2</sup> The energy in the kiln is supplied by fuel burning in

<sup>2</sup> Here, cement chemistry notation is used, where "C" = CaO, "S" = SiO<sub>2</sub>, "A" = Al<sub>2</sub>O<sub>3</sub> and "F" = Fe<sub>2</sub>O<sub>3</sub>.

the kiln.

The hot clinker enters the grate cooler, where it is cooled down in three stages by atmospheric air in cross-flow. The heated air from the first stage is used as secondary air, which is sent to the kiln for fuel burning. The second stage produces tertiary air, which goes to the calciner for fuel burning. The air from the third stage is vented to the environment. The cooled clinker from the grate cooler is intermediately stored in silos and will subsequently be used as the main constituent in the cement grinding process. The latter is outside the scope of this study.

### 2.2. Fuel and raw meal characteristics

The fuel and raw meal characteristics are shown in Fig. 2. The fuels include coal, animal meal (AM), and liquid hazardous waste (LHW). The proximate analyses (moisture, volatiles, fixed carbon and ash) were done by thermogravimetric analysis at an external lab; the heating values were determined by a bomb calorimeter method at an external lab; the ultimate analysis (elemental analysis of C, H, N, O, S and Cl) were also done at an external lab. The raw meal composition is based on XRF analysis at the cement plant.

### 2.3. Process values from the full-scale experiment

The experiment was conducted with the process values shown in Table 1. It is not practically possible to keep completely stable conditions during a full-scale production campaign. Hence the possible variation in process values is also indicated in the table. The value range indicates the accuracy of the results, which will also apply to the simulated electrified cases.

Constant feed rates of raw meal and kiln fuel were maintained during the experiment. The calciner temperature was maintained at 863 °C by controlling the coal supply to the calciner. Controlling the calciner temperature is essential to get a calcination degree of roughly 94%. The fuel feeding to the rotary kiln was kept almost constant during the test period.

The gas flow rates are controlled by adjusting the power of fans, but for the test, this value was kept constant. The power supplied to each fan, and the gas flow rates are summarized in Table 2.

The gauge pressure profile (pressure relative to ambient pressure) in each string is shown in Fig. 3. The values are directly measured for the kiln inlet, kiln hood, cyclone 4 inlet, cyclone 4 outlet, and cyclone 1 outlet. The other values are calculated based on previous measurements.

## 3. Modelling method

### 3.1. Approach

A steady-state model was developed in Aspen Plus to replicate the coal-fired calciner system. The model was validated against results from the full-scale experiments. The validated model is then used to simulate scenarios with an electrified calciner system.

The gas components are assumed to follow the ideal gas law, and the thermodynamic properties (specific heat, standard enthalpy, and standard entropy of formation) of each component in the model are taken from Barin's database [16], except for calcium aluminoferrite (C<sub>4</sub>AF), for which the data are taken from another source [17]. The data is fitted into three different polynomial equations for specific heat capacity. (The data and the polynomial equations are available as digital extra material).

Solids are modelled as conventional solids, and gases as conventional components. The fuel and ash are modelled as non-conventional components defined by proximate analysis, ultimate analysis, and heating values shown in Fig. 2.

The fuel combustion in the calciner and the kiln is modelled with a two-stage model [18,19]. In the first stage, the fuel is decomposed into its constituent components (found from ultimate and proximate

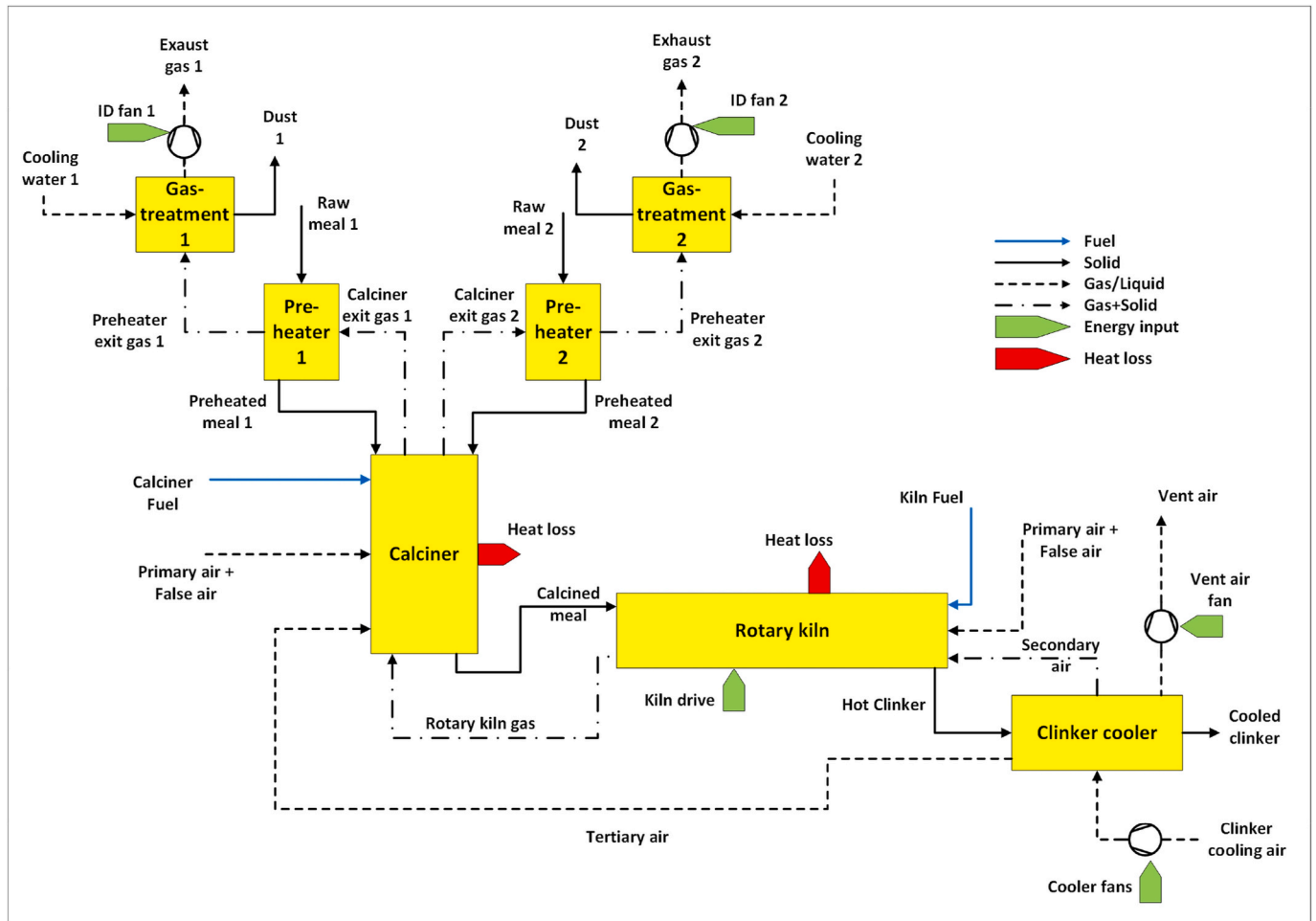


Fig. 1. General block diagram for pyro-processing cement raw meal into clinker.

analysis). In the second stage, the decomposed components are mixed with air in a Gibbs reactor, and the product is assumed to have reached the state of thermodynamic equilibrium. The heating value of the fuel is given as an input, but the enthalpy of the decomposed components in the first stage may differ from the input heating value. Aspen Plus calculates this difference in the first stage, and the difference is corrected for in the second stage. This combustion model is implemented in the sub-model of the calciner and the kiln (documented in the supplementary document).

The calcination reaction in the calciner is modelled with a stoichiometric reactor. The calcination degree is given as an input which is based on the process value. The clinkering reaction inside the rotary kiln is assumed to have reached a thermodynamic equilibrium, and this is modelled with a Gibbs reactor. Bogue's method is used to validate the kiln's equilibrium clinker composition. According to this method, the equilibrium composition of the main clinker components (weight fraction basis) is given by equations (1)–(4) [20].

$$x_{C3S} = 4.017x_{CaO} - 7.6x_{SiO_2} - 6.718x_{Al_2O_3} - 1.43x_{Fe_2O_3} \quad (1)$$

$$x_{C2S} = 2.867x_{SiO_2} - 0.7544x_{C3S} \quad (2)$$

$$x_{C3A} = 2.65x_{Al_2O_3} - 1.692x_{Fe_2O_3} \quad (3)$$

$$x_{C4AF} = 3.043x_{Fe_2O_3} \quad (4)$$

here,  $x_{C3S}$ ,  $x_{C2S}$ ,  $x_{C3A}$  and  $x_{C4AF}$  are the mass fractions of the main clinker components, and the other weight fractions ( $x_{CaO}$ ,  $x_{SiO_2}$ ,  $x_{Al_2O_3}$ ,  $x_{Fe_2O_3}$ ) are given for the main raw meal minerals.

### 3.2. Coal-fired calciner system

The process overview of a coal-fired calciner system built in Aspen Plus is shown in Fig. 4. The process overview contains only the main blocks described in section 2.1. The main blocks are developed as a hierarchical model containing sub-models. (The sub-models are described in the supplementary document.)

### 3.3. Electrified calciner system

The process overview of clinker production with an electrified calciner is shown in Fig. 5, and the CO<sub>2</sub> cooling model is shown in Fig. 6. The coal-fired calciner system is modified by.

1. Cutting off the fuel supply to the calciner. Instead of fuel, electrical energy is supplied.
2. Modifying the geometry of cyclone 4 to increase its efficiency from 80% to 95%. The rotary kiln receives either a hot calcined meal from cyclone 4 or cold dust from the electrostatic precipitator (see point 6). Improving cyclone efficiency is crucial to increasing the calcined meal fraction going to the kiln. Further, since an improved efficiency will reduce the particles transported with CO<sub>2</sub> exit gas from the calciner, potential blockages in the CO<sub>2</sub> heat exchanger placed downstream can be minimized.
3. Re-routing the calciner exit gas to a new CO<sub>2</sub> cooler section. The heat from the CO<sub>2</sub> gas is extracted in a gas-to-gas heat exchanger. One could have used this gas for preheating in one of the preheating

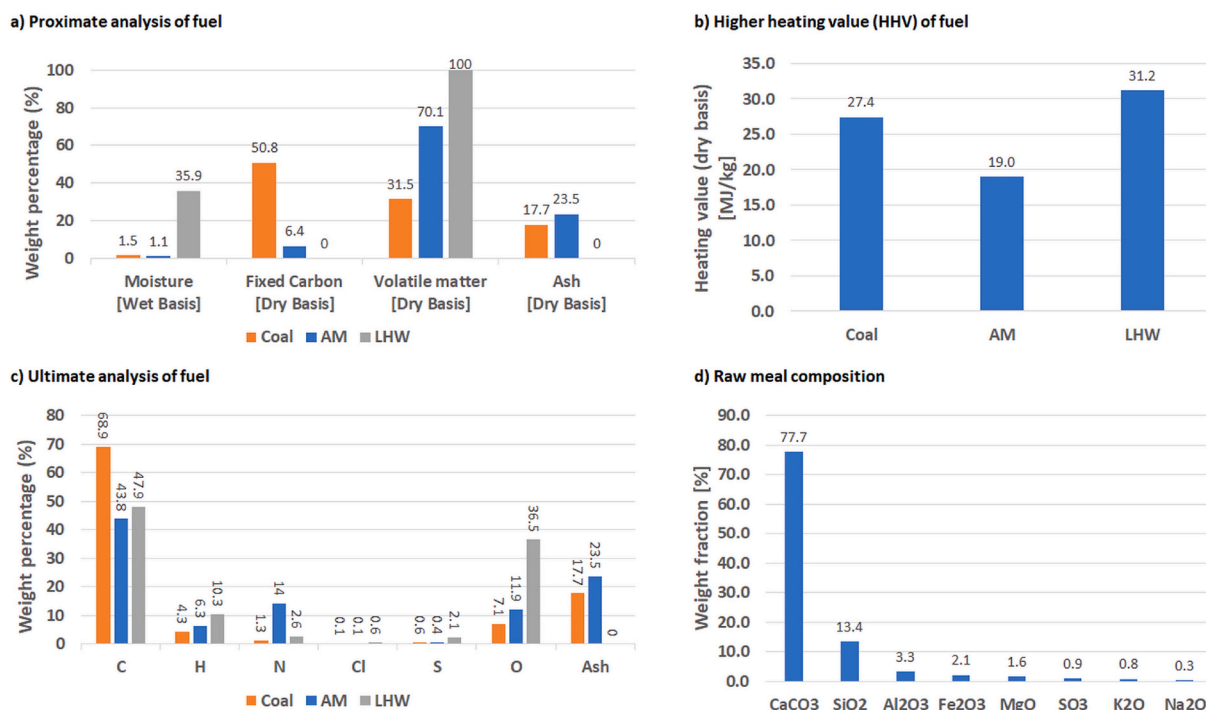


Fig. 2. Fuel and meal characteristics. a) Proximate analysis (AM = Animal meal, LHW = Liquid hazardous waste), b) heating value, c) ultimate analysis, and d) raw meal composition.

Table 1

Measured process values for the full-scale experiment.

Process variables	Unit	Value
Raw meal feed rate	t/h	220 ± 4
Raw meal inlet temperature	°C	30 ± 10
Calciner temperature	°C	863 ± 7
Coal feed rate in the rotary kiln	t/h	5.5 ± 0.2
Animal meal feed rate in the rotary kiln	t/h	2.5 ± 0.1
Liquid hazardous feed rate in the rotary kiln	t/h	1 ± 0.1

Table 2

Measured fan power values and gas flow rates.

Process parameter	Unit	Value
Power supplied to the ID fan in string 1	kW	1052 ± 50
Power supplied to the ID fan in string 2	kW	1023 ± 50
Total power supplied to all cooling air fans	kW	700 ± 50
Power supplied to the vent air fan	kW	333 ± 50
Total flow rate of cooling air	t/h	405 ± 15
Total flow rate of tertiary air	t/h	106 ± 5
Total flow rate of vent air	t/h	208 ± 5

towers, but this would have reduced the CO<sub>2</sub> purity due to false air ingress in the preheating towers.

- Re-routing a fraction of the vent air to the CO<sub>2</sub> cooler section. This fraction of vent air is preheated in the gas-to-gas heat exchanger. The re-routed fraction of vent air and CO<sub>2</sub> stream are calculated in Aspen Plus such that:
  - The inlet temperature of the preheater gas is maintained at 863 °C (as in the reference system and not to risk early calcination in the preheater).
  - The preheater gas flow rate is the same as in the reference system (to avoid significant changes in pressure drops in the preheater cyclones and thereby the need to redesign the cyclone separator).
- The cooled CO<sub>2</sub> from the heat exchanger is mixed with the fraction of CO<sub>2</sub> not sent to the heat exchanger. The mixed CO<sub>2</sub> stream is then

sent for waste heat recovery (cooling the gas down to 150 °C). One could alternatively handle both fractions of the CO<sub>2</sub> stream separately. Since the fraction of CO<sub>2</sub> not sent to the heat exchanger has a higher temperature, it could be used to produce high-pressure steam. However, such an analysis is outside the scope of this study and may be done in a future study.

- Placing a new electrostatic precipitator downstream of the gas-to-gas heat exchanger to remove the dust from the CO<sub>2</sub> gas. The dust is sent to the kiln as it contains calcined meal.
- Mixing tertiary air and rotary kiln gas with the heated vent air. The resulting gas mixture is next sent to the preheater tower for preheating the meal.
- Adding two new fans; one to convey the cooled CO<sub>2</sub> to the section for intermediate on-site CO<sub>2</sub> storage, and another one for CO<sub>2</sub> recycling to the calciner.

### 3.3.1. CO<sub>2</sub> heat exchanger details

The details of the gas-to-gas heat exchanger depend on the heat exchanger type and topology, as shown in a previous study [21]. The parameters are taken from the study for a shell-and-tube heat exchanger with four heat exchangers, each with two shells and four tubes. The design parameters are summarized in Table 3.

### 3.3.2. Thermodynamic constraints

In addition to the modifications mentioned above, some thermodynamic conditions should be considered. Operating the calciner in pure CO<sub>2</sub> reduces the rate of reaction. The calcination rate ( $r_{calc}$ ) at different partial pressures of CO<sub>2</sub> ( $p_{CO_2}$ ) and temperatures ( $T$ ) can be found by solving equation (5) [22].

$$r_{calc} = 5 \times 10^7 e^{\left(\frac{-24500}{T[K]}\right)} - 1.22 \times 10^{-5} e^{\left(\frac{-4026}{T[K]}\right)} p_{CO_2} [\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}] \quad (5)$$

In the coal-fired calciner system, the calciner exit gas temperature is typically at 863 °C with a CO<sub>2</sub> concentration of around 28%. However, an electrified calciner is expected to operate at 100% CO<sub>2</sub>. A comparison

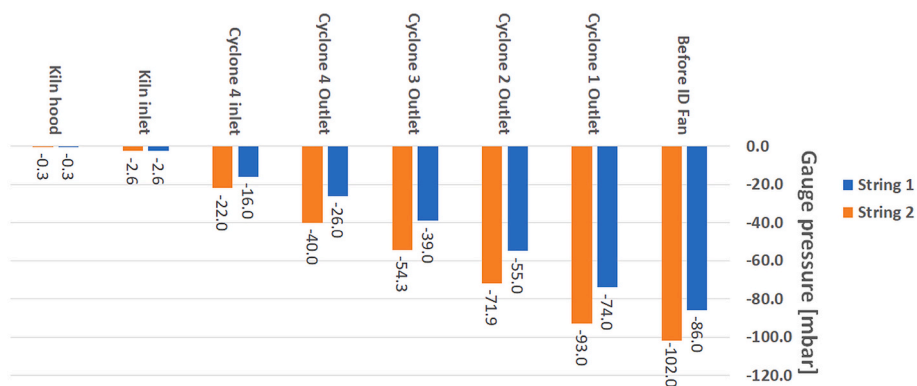


Fig. 3. Approximate relative pressure profile in the process.

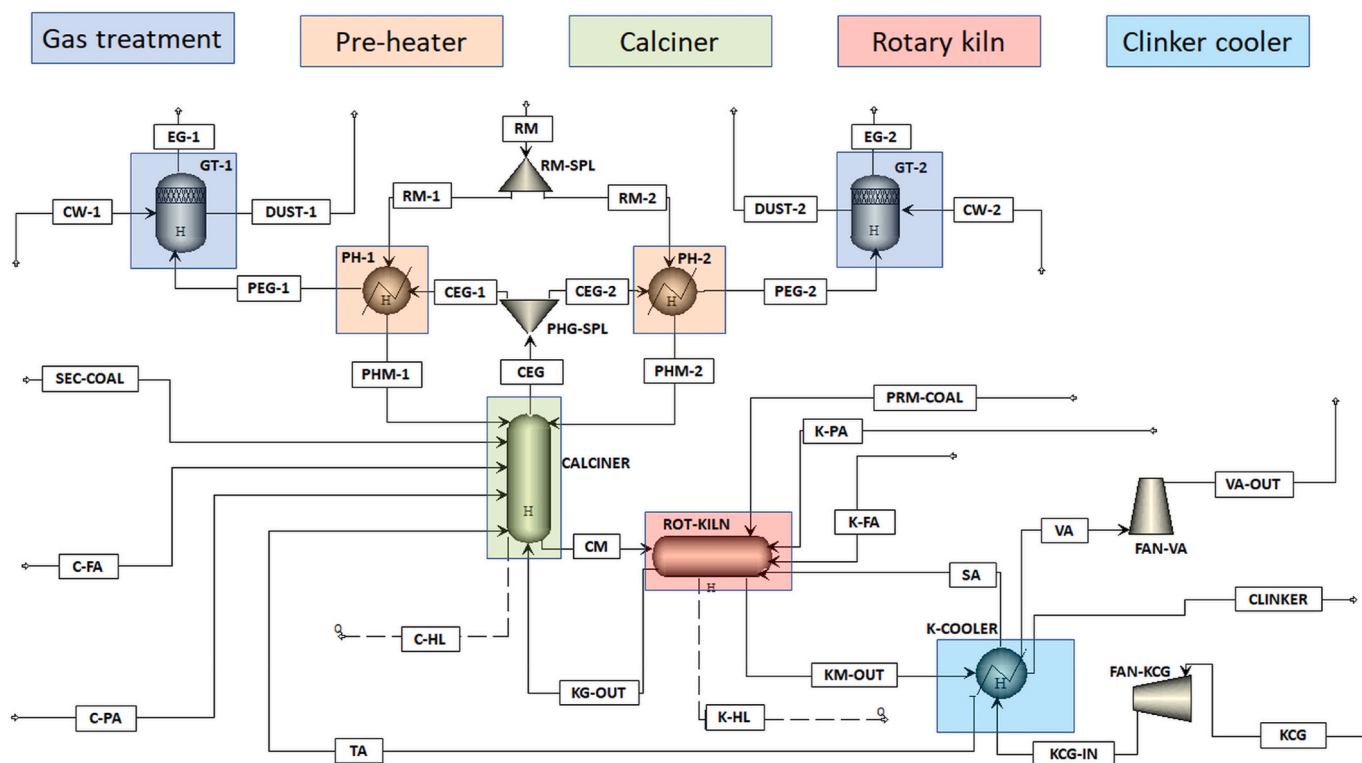


Fig. 4. Process overview of clinker production with a coal-fired calciner system in Aspen Plus.

of the calcination rate at 28% CO<sub>2</sub> and 100% CO<sub>2</sub> is shown in Fig. 7. As shown in the figure, to maintain the same kinetics as with 863 °C, the calciner should be operated at 912 °C.

### 3.3.3. Electrification cases considered

The amount of gas being recycled and the pressure drop across the calciner depend on the calciner design. The simulations are performed for three cases.

1. High recycling of 70 t/h, assuming a pressure drop of 20 mbar, which signifies an entrainment calciner.
2. Low recycling of 15 t/h, assuming a pressure drop of 200 mbar, which signifies a fluidized bed calciner.
3. No recycling, assuming a pressure drop of only 2 mbar, which signifies a rotary calciner.

## 4. Results and discussions

### 4.1. Model calibration using data from the coal-fired calciner system

The model is calibrated within the uncertainty limits of the experimental results. (The heat and energy balance of the process is shown in the supplementary document.) The experimental results used as inputs for model calibration are shown in Table 4. Based on the fuel feeding rate and heating value, the total energy to the calciner is around 77 MW, and around 58 MW to the kiln. Further, the total electrical energy supplied to all the fans within the simulation scope is 3 MW. The total exit gas amounts to 582 t/h; out of this, the exiting CO<sub>2</sub> amounts to 113 t/h.

The validation of the model is done by comparing model predictions against experimental results for three different variables not given as inputs, more specifically, the secondary coal supply in the calciner, the CO<sub>2</sub> concentration in the calciner exit gas, and the CO<sub>2</sub> concentration in the preheater exit gas. The validation of the model is summarized in Table 5, and there appears to be quite a good correspondence between



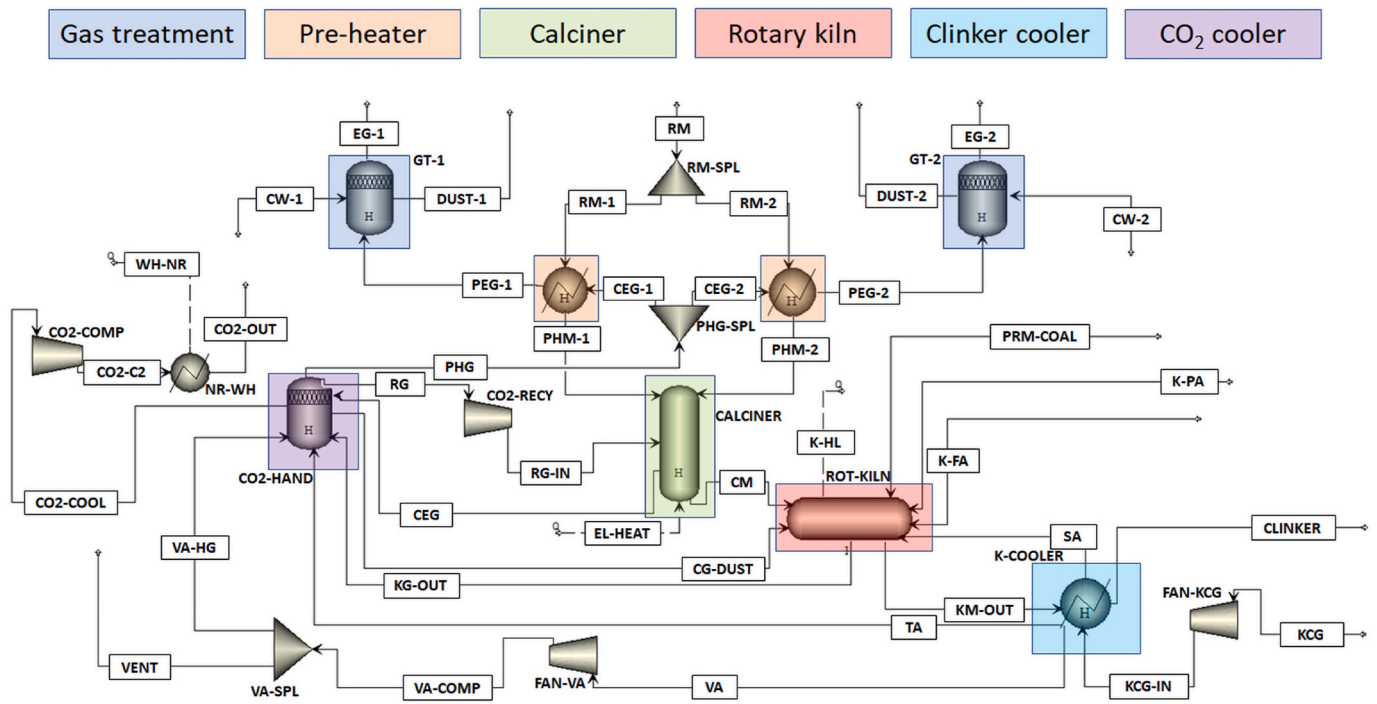


Fig. 5. Process overview of clinker production with an electrified calciner in Aspen Plus.

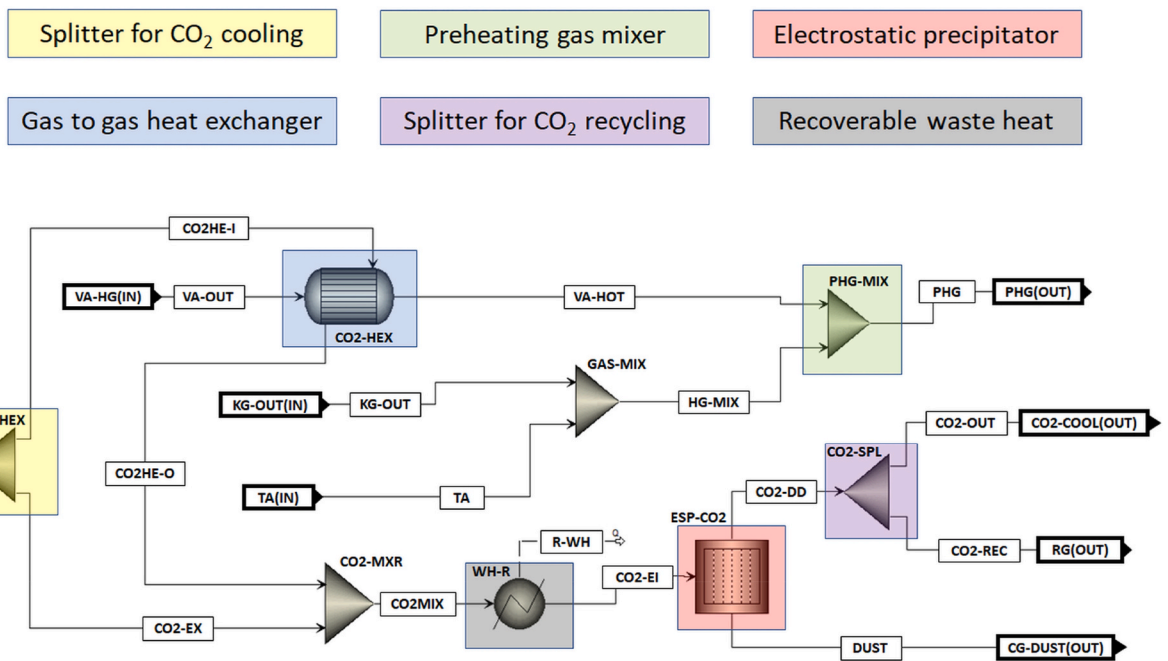


Fig. 6. Process flow chart of the CO<sub>2</sub> cooler section in Aspen Plus.

**Table 3**  
Design parameters of the gas-to-gas heat exchanger used for CO<sub>2</sub> cooling.

Parameters	Unit	Value
Minimum temperature difference	°C	200
Pressure drop in the hot fluid	mbar	43
Pressure drop in the cold fluid	mbar	36

modelled and measured values. The false air in the preheater was calculated to be 12 t/h from each preheater string, and the calculated heat transfer coefficients are summarized in Table 6. The UA values are used as constant input values in the electrified cases.

The equilibrium clinker composition predicted by Aspen Plus and the composition calculated by Bogue's method is shown in Table 7. The sum of the components is not 100% as some components are not included in the calculation. The predicted composition from Aspen Plus matches well with the results from applying Bogue's calculation method.

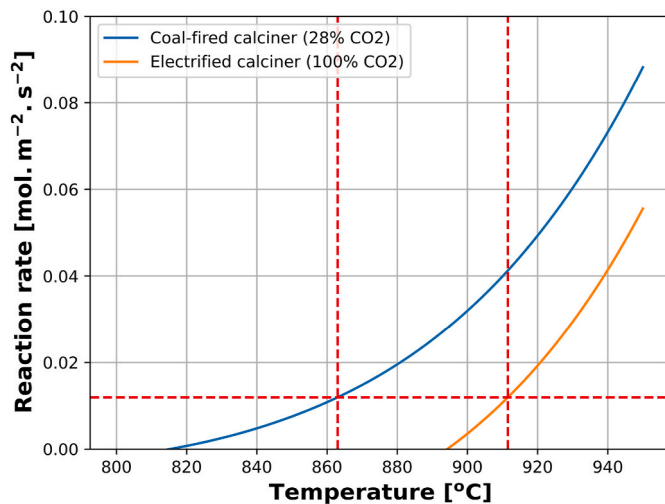


Fig. 7. Comparison of reaction rate for coal-fired (28% CO<sub>2</sub>) and electrified (100% CO<sub>2</sub>) calciner system.

Table 4  
Experimental results used for model calibration.

Measured parameters	Unit	Experimental result as Aspen Plus inputs
Degree of calcination	%	92 ± 2
Free lime content in the clinker	wt%	2.5 ± 0.5
Tertiary air temperature	°C	525 ± 30
Vent air temperature	°C	203 ± 10
Secondary air temperature	°C	950 ± 50
O <sub>2</sub> concentration of rotary kiln gas	vol% (dry)	6.5 ± 0.3
O <sub>2</sub> concentration at calciner exit gas	vol% (dry)	5 ± 0.5
O <sub>2</sub> concentration at preheater exit gas	vol% (dry)	6.8 ± 0.4
Preheater exit gas temperature from string 1	°C	370 ± 20
Preheater exit gas temperature from string 2	°C	400 ± 20
Part of calciner exit gas entering preheater string 1	wt%	50.76 ± 0.2

Table 5  
Validation of Aspen Plus model.

Measured parameters	Unit	Experimental result	Aspen Plus prediction
Coal feed rate in the calciner	t/h	10.5 ± 2	10.2
CO <sub>2</sub> concentration at calciner outlet gas	vol% (dry)	27 ± 2	28.2
CO <sub>2</sub> concentration at preheater exit gas	vol% (dry)	24 ± 2	24.4

Table 6  
Calculated heat transfer coefficients for the heat exchangers in the model.

Heat exchanger	Heat transfer coefficient (UA) [W/K]
Each exchanger in preheater string 1	55 000
Each exchanger in preheater string 2	34 000
Meal preheating in the kiln	36 993
Clinker cooler stage 1	37 259
Clinker cooler stage 2	32 414
Clinker cooler stage 3	36 615

Table 7  
Equilibrium clinker composition [wt%].

Main clinker components	Bogue's method	Aspen plus prediction
Alite (C <sub>3</sub> S)	75.8	75.8
Belite (C <sub>2</sub> S)	1.2	1.0
Aluminate (C <sub>3</sub> A)	7.9	7.9
Ferrite (C <sub>4</sub> AF)	9.7	9.7

#### 4.2. Electrified calciner system

The implications of the results are discussed in this section. (The mass and energy balance for the electrified calciner system for each simulation case is given in the supplementary document.)

##### 4.2.1. Impact on production rate

The clinker production rate reduces by 1.8 t/h due to the absence of ash from the fuel burnt in the calciner.

##### 4.2.2. Impact on pressure drop

The pressure profile in the preheater changes for the electrified scenario and is shown in Fig. 8. Even though the pressure drops are the same in each cyclone, the gas at the inlet of cyclone 3 is now coming from the gas-to-gas heat exchanger. This gas is at a higher absolute pressure due to the push from the vent air fans, and there is a reduced downstream pressure drop as the gas now bypasses the calciner and cyclone 4. The direct effect of the increased absolute pressure near the ID fans is a reduced ID fan power, as seen in Fig. 9.

The reduced ID fan power when operating with an electrified calciner could possibly be utilized for increased clinker production (as ID fans are often bottlenecks in cement kiln systems), but pursuing that possibility is outside the scope of this article.

##### 4.2.3. Impact on CO<sub>2</sub> emissions

The electrified calciner system produces around 63 t/h of relatively pure CO<sub>2</sub> from the calcination process for direct capture. A high CO<sub>2</sub> purity is required for the downstream processing and storage of the gas, which is why a separate gas-to-gas heat exchanger is required to cool down the CO<sub>2</sub>. Using one of the preheater towers as a CO<sub>2</sub> heat exchanger is not an option due to false air ingress in the preheater. (False air is calculated to be 12 t/h in section 4.1, and with this amount of false air, the CO<sub>2</sub> purity would have dropped from ~100% to around 84%). Additionally, the extra CO<sub>2</sub> produced by fuel burning in the calciner is avoided in this system.

Some CO<sub>2</sub> is still being produced from fuel burning in the kiln, which amounts to around 25 t/h. So, overall, the emitted CO<sub>2</sub> reduces from 113 t/h in coal-fired to 25 t/h in the electrified calciner system, i.e. a reduction of 78%.

##### 4.2.4. Impact on energy demand

A comparison of the total energy demand in each case is shown in Fig. 10. The total recoverable waste heat from the CO<sub>2</sub> cooler section is shown in Fig. 11.

The energy demand in the kiln is not affected significantly. A higher temperature of the calcined meal coming directly from the calciner should reduce the energy demand, while the cold dust coming from the CO<sub>2</sub> cooler should increase the energy demand. The net effect is that the energy demand of kiln in the electrified calciner system is lower than the coal-fired system by 1–2 MW.

The energy demand in the calciner increases from 77 MW to 78–95 MW in the electrified calciner. The energy demand in the electrified calciner includes a heat loss of 0.8 MW but doesn't account for the electricity-to-heat conversion efficiency. The energy demand in the calciner is affected by the following factors.

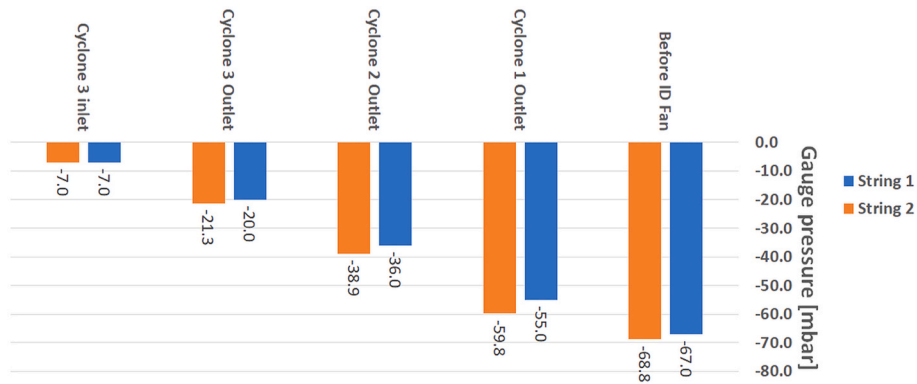


Fig. 8. Relative pressure profile in the preheater for the electrified calciner scenario.

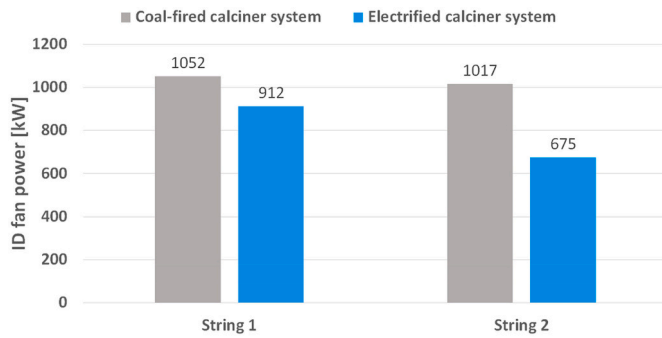


Fig. 9. Comparison of ID fan power between coal-fired and electrified calciner system.

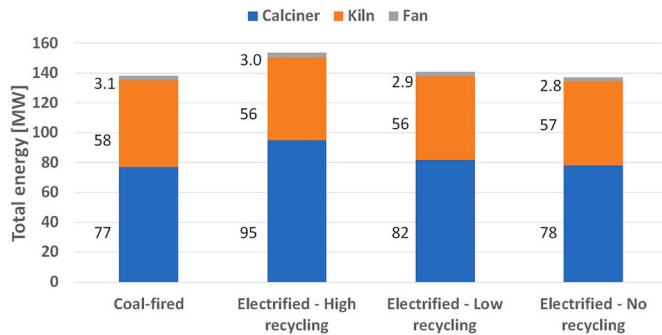


Fig. 10. Total energy required for each simulation case.

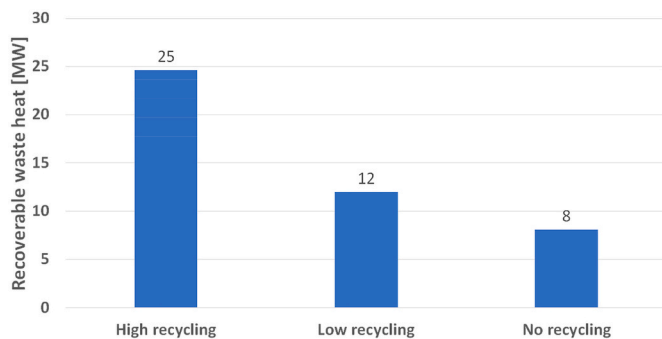


Fig. 11. Recoverable waste heat from the CO<sub>2</sub> cooler section for different electrified cases.

- 1 Calcination temperature:** The calcination temperature was increased from 863 to 912 °C in the electrified calciner. The energy demand in the electrified calciner should therefore increase.
- 2 Recycle gas preheating:** High recycling gas requires higher energy for gas preheating. So, the case with high recycling requires the highest energy.

If the waste heat is recovered in the CO<sub>2</sub> cooler section (shown in Fig. 11), the net energy demand in the calciner becomes 70 MW for all the cases. This energy is lower than in the system with a coal-fired calciner. The total exit gas reduces from 582 t/h in the coal-fired case to 559 t/h in the electrified calciner system (i.e., a reduction of 4%). A reduced exit gas represents a lower heat loss as less thermal energy stored in the gas is lost to the environment. So, the heat efficiency is improved in the electrified calciner system.

However, there is a quality difference between electrical and thermal energy. The second law of thermodynamics limits the amount of electrical energy that can be produced from thermal energy, which must be considered when comparing the energy demand. The breakdown of energy in electrical and thermal energy is shown in Fig. 12. The effective thermal energy for each case is calculated by assuming a thermal-to-electrical energy efficiency of 40% [23], and the result is shown in Fig. 13.

Fig. 13 reveals that the effective thermal energy requirement is significantly higher in the electrified scenario, even with the lowest gas recycling case (81% higher effective thermal energy). Moreover, the thermal energy source of electricity may have further CO<sub>2</sub> emissions. This means that electrification is only a good idea if renewable electrical energy sources are used. When the electrical energy is not generated by thermal power stations, heat-to-power losses are not relevant.

#### 4.2.5. CO<sub>2</sub> capture vs energy use

The captured CO<sub>2</sub> is 63 t/h. Some CO<sub>2</sub> is also reduced as the fuel

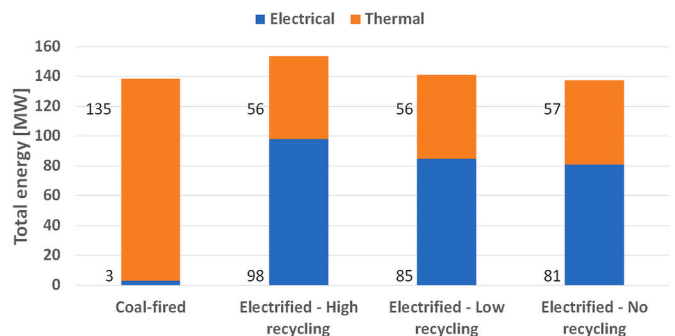


Fig. 12. Comparison between electrical and thermal energy demand for each scenario.



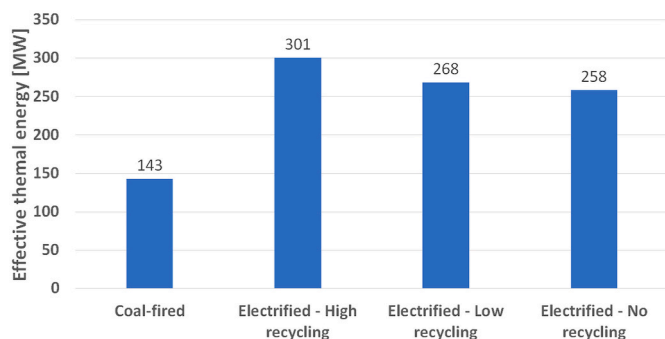


Fig. 13. Effective total thermal energy requirement assuming a thermal-to-electrical energy efficiency of 40%.

source is switched to electricity. Overall, the total saved CO<sub>2</sub> amounts to 88 t/h if all the CO<sub>2</sub> is captured and the electricity source is renewable. The excess energy per CO<sub>2</sub> captured in each electrified scenario compared to the coal-fired calciner system is shown in Fig. 14. The excess energy per CO<sub>2</sub> captured reduces to  $-0.4$  MJ/kgCO<sub>2</sub> if all the waste heat from the exit CO<sub>2</sub> is recovered.

## 5. Conclusions

This study developed a model of a coal-fired calciner system in Aspen Plus. The model was successfully calibrated by comparing the modelling results against a full-scale test conducted at a cement factory. The predictions from the model matched well with the experimental results. The results showed a CO<sub>2</sub> emission of around 113 t/h in a coal-fired calciner system. The results also showed a false air inlet of about 24 t/h in the preheating tower. The energy demand in a coal-fired calciner is around 77 MW.

The model was then modified to include an electrified calciner. The calciner exit gas was re-routed to a separate cooler as false air ingress in the preheater would have reduced the CO<sub>2</sub> concentration at the outlet from the preheater if the calciner exit gas was sent to a preheater string. Three simulation cases with high, low and no gas recycling rates were studied.

The results showed that the clinker production was reduced by 1.8 t/h due to reduced ash in the process by cutting off the calciner fuel. The clinker composition was only slightly affected by the reduced ash content. The results showed a potential to reduce CO<sub>2</sub> emissions by up to 78% compared to a coal-fired calciner system.

The existing calciner is an entrained flow calciner and requires high CO<sub>2</sub> recycling if it is directly electrified. The simulation results show that the electrical energy required is as high as 95 MW, and thus the operational cost of the system will be high. Using a design with low gas recycling can reduce the required energy to 82 MW, while a design with no gas recycling reduces the energy demand to 78 MW. If all the energy from the CO<sub>2</sub> stream is recovered, the net energy required in all the electrified calciner scenarios reduces to 70 MW (i.e., lower than a coal-fired calciner system). The reduced energy demand in an electrified system is mainly due to the reduced gas entering/exiting the system. However, if the electricity is produced from a thermal source, the effective thermal energy becomes very high compared to the fuel-fired system. So, the project is only viable if the electricity source is renewable.

## Credit author statement

**Ron M Jacob:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Lars-André Tokheim:** Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

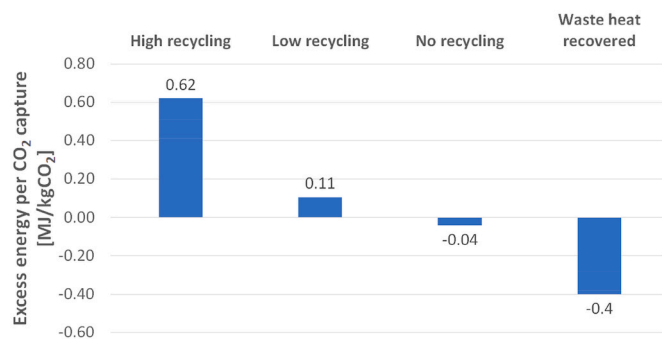


Fig. 14. Excess energy per unit of captured CO<sub>2</sub> for each electrified scenario assuming the electrical energy source is renewable.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.energy.2023.126673>.

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