

COMBINED CALCINATION AND CO₂ CAPTURE IN CEMENT CLINKER PRODUCTION BY USE OF ELECTRICAL ENERGY

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Abstract

The technical feasibility of electrifying the calcination process in a precalciner cement kiln system was assessed by studying different electrification concepts. Resistance-based heating was selected as it requires no CO₂ recycling, has a high electricity-to-heat efficiency and has no major safety concerns. Resistance-based heating may be implemented in different types of calcination reactors. In this study, a rotary calciner was selected because the material flow can be readily controlled, it appears to be technically feasible to implement heating elements with a sufficiently high surface temperature to perform calcination, and rotary kilns are already in use in the cement industry, hence can be regarded as well-known technology. It is possible to integrate the electrified calciner with an existing cement kiln system in such a way that minimum disturbance of the production process is obtained. Hence, no negative impacts on the process, product quality or emissions are expected. The required electrical energy input for calcination in a kiln system producing 1 Mt of clinker per year, is about 85 MW. An early-phase cost estimate was conducted resulting in total annualized costs of 67 € per ton of CO₂ avoided. The net avoided CO₂ emission was 72 % (using a CO₂ footprint of 47 g/kWh for electrical energy). The described CO₂ capture concept was technically and economically compared with amine-based absorption of CO₂ from the preheater exhaust gas. Two amine-based cases were calculated, one using electrical energy as the source of solvent regeneration (85 % net CO₂ reduction) and another one using only available waste heat as the energy source (48 % net CO₂ reduction). The annualized costs of these two cases were 75 and 40 € per ton of CO₂ avoided, respectively. Hence, in cement plants where large amounts of waste heat are available, amine-based absorption appears to be the least expensive option for reduction in CO₂ emissions. However, in systems with no such waste heat available, electrified calcination, for example in the form of electrified rotary calciners, may be a competitive alternative to post-combustion capture technology.

Keywords: CO₂ capture, Calcination, Electrification, Clinker production

1. INTRODUCTION

Today, cement clinker is produced by combustion of fuels. There are two main sources of CO₂ in the process: Calcination (decarbonation) of the limestone-based raw materials ($\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$), accounting for about 65 % of the CO₂ emissions, and fuel combustion, accounting for about 35 %. In a modern kiln system, there are two combustion zones; the calciner, where the decarbonation occurs at approximately 900 °C, and the rotary kiln, where clinker minerals are formed at material temperatures around 1400 °C. About 60 % of the fuel energy is fed to the calciner, whereas the remaining 40 % is fed to the rotary kiln.

The thermal energy requirement is relatively high, so a medium size cement plant may typically have CO₂ emissions around 1 Mt per year. And as there are thousands of cement plants in the world, and the production is increasing, the CO₂ emissions from the cement industry (including CO₂ from calcination and fuel combustion) likely constitute around 8 % of the global man-made emissions [1].

In a green future, when renewable energy sources have replaced most of the fossil energy, industrial production

processes such as cement clinker production will largely have to be run by electricity instead of fuel combustion. With that in mind, the purpose of the current study was to:

- investigate the technical feasibility of electrifying part of the cement kiln process
- suggest a promising technical solution for combined electrification and CO₂ capture
- determine the impact on the clinker production process
- perform an early-phase estimate of the CO₂-specific costs of implementing the selected concept
- compare the results with those from implementing post-combustion amine absorption technology, which is the most mature method for achieving significant reductions in CO₂ emissions today

2. ELECTRIFICATION OF THE KILN PROCESS

Figure 1 shows different alternatives for combined electrification and CO₂ capture. The length of each area in the figure reflects the approximate CO₂ emission

contribution. The reference case (Alt 0) shows the CO₂ emission contributions from a regular kiln system, with combustion in the precalciner (dark red) and rotary kiln (light red) as well as pre-calcination in the calciner (dark grey) and post-calcination (light grey) in the rotary kiln.

Pure electrification without any CO₂ capture (Alt 1 and 3) will only eliminate the fuel related CO₂ emissions. But if the electrification is combined with capture of the CO₂ (Alt 2, 4, 5 and 6), more significant reduction levels may be achieved.

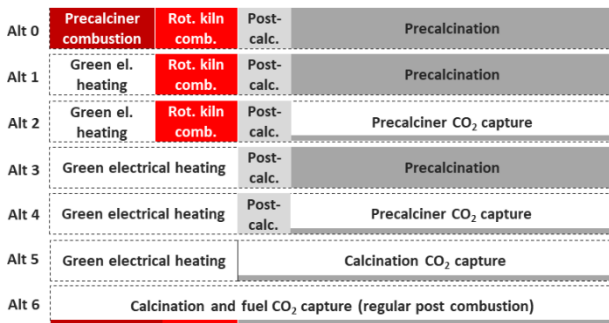


Figure 1: Different ways of reducing CO₂ emissions using CO₂-neutral (“green”) electrical heating in combination with CO₂ capture.

By replacing the fuel combustion with electrical energy as the energy source for calcination in the calciner, two simultaneous effects are obtained:

- The CO₂ formation from the calciner fuel combustion is eliminated, which reduces the total CO₂ formation from the clinker production process.
- The exhaust gas from the calciner is (almost) pure CO₂, meaning that this gas can be routed directly to a CO₂ processing unit without the need for a CO₂ separation plant.

Applying electrification and CO₂ capture to the calciner only (i.e. not to the rotary kiln), corresponding to Alt 2 in Figure 1, is attractive because of the following reasons:

- A relatively high CO₂ reduction rate (in the order of 70 %) may be achieved.
- It is sufficient to supply heat to a zone of ~900 °C; the very high temperature required in the rotary kiln does not have to be considered.
- Only one of the main equipment units in the kiln system (the calciner) needs to be modified.

2.1 Reference kiln system

A regular cement kiln system is illustrated in Figure 2. The raw meal enters at the top of the preheaters, where it is heated to about 700 °C by hot gases coming from the calciner. In the calciner, most of the preheated meal is calcined at ~900 °C by direct contact with hot gases generated by fuel combustion in the calciner. In the rotary kiln the precalcined meal is first completely calcined, then heated further until partial melt phase and clinker minerals are formed at a temperature of 1400-1450 °C. This rotary kiln heating process also requires fuel combustion. Finally, the clinker is cooled by ambient air in the clinker cooler.

A large fraction of the air heated in the cooler is used as combustion air in the rotary kiln (“secondary air”) and in the calciner (“tertiary air”), hence recuperating a significant part of the heat. Some low-temperature heat (at about 200 °C) is, however, lost to the surroundings (“cooler vent air”). The hot exhaust gas from the kiln mixes with the calciner gas, hence contributing with some of the energy required for precalcination. Some fuel conveying air and/or cooling air (“primary air”) is supplied in both the rotary kiln and the calciner, and there may be some air inleakage (“false air”) in the rotary kiln, calciner and preheater tower.

This system, applying pulverized coal as the fuel in both the rotary kiln and the calciner, is used as the reference process in the current study.

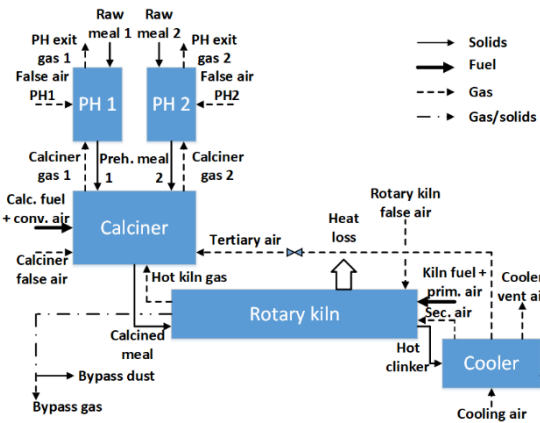


Figure 2: A regular cement kiln system with two preheater (PH) strings.

2.2 Kiln system with electrified calciner

A conceptual implementation of calciner electrification combined with CO₂ capture is shown in Figure 3. All calciner fuel is now replaced by heat provided indirectly from electrical energy. The tertiary air is no longer needed in (nor allowed to flow into) the calciner. Instead, its sensible heat is utilized in the preheater. The hot rotary kiln exit gas bypasses the calciner, i.e. it is routed to the preheater, where its sensible heat can be utilized. This means that the only major gas component in the exit gas stream from the calciner is the CO₂ from the decarbonation.

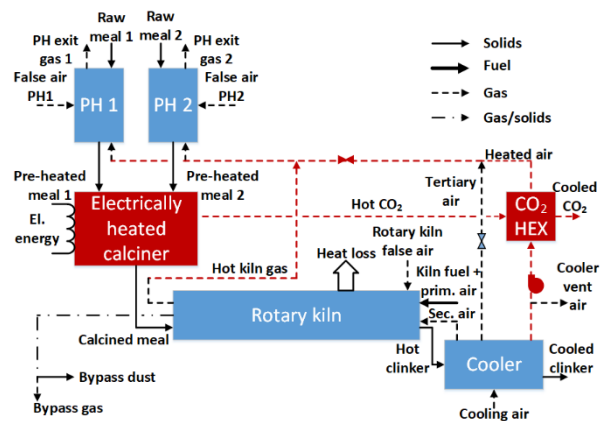


Figure 3: Cement kiln system with two preheater (PH) strings equipped with an electrified calciner. (Red-colored units are new/modified, whereas existing units are blue/black.)

A gas-to-gas heat exchanger (“CO₂ HEX”) is installed to utilize the heat in the hot CO₂ exiting from the calciner. A fan (not shown in Figure 3) placed downstream of the CO₂ HEX pulls the CO₂ out of the calciner and through the heat exchanger. A fan is also needed to blow the cooler air from the cooler, via the CO₂ HEX, to the preheater tower.

Direct-contact heating of the preheated meal with the hot CO₂ was considered, but was discarded. One reason for this is that the pure CO₂ stream would be too low to entrain (and to sufficiently heat) the meal in the preheater tower. Hence, using direct heat exchange between CO₂ and (a fraction of) the meal would require a significant modification of the preheater construction, which is a disadvantage. Another reason for not using direct heat exchange is that the suspension preheater is operated with a slight under-pressure (induced draft fans are placed downstream of the preheater towers, not shown in Figure 2 or Figure 3), and due to wear during normal operation of the preheaters, the preheaters are not completely airtight. This means that it is almost impossible to avoid inleakage of some ambient air, meaning that the CO₂ would be polluted with O₂ and N₂, which should also be a disadvantage.

2.3 Calciner electrification concepts

Different electrical heat transfer concepts were considered in the study. One may distinguish between different electricity-based energy transfer concepts in the way the energy is transferred to the meal, see Table 1. A few concepts may involve direct transfer of electrical energy to the meal in one step (“direct transfer”), but most concepts involve typically two or three transfer steps, i.e. an overall “indirect transfer” process.

Table 1: Potential electricity-based energy transfer concepts.

Energy transfer process	Concept	Number of energy transfer processes	Energy transfer type	Energy medium required?
El → Meal	Microwaves	1	Direct	No
	Induction ^b			
El → Gas → Meal	Plasma	2	Indirect	Yes
	Electrical resistance heating			
	Ultrasound ^a			
El → Solid → Meal	Electrical resistance heating	3	Indirect	Yes
	Induction ^c			
El → Solid → Gas → Meal	Electrical resistance heating	3	Indirect	Yes
	Induction ^c			
	Electrolysis of water followed by H ₂ combustion in O ₂			

^a Sonification medium needed, ^b Direct induction heating of the raw meal; ^c Induction heating of a solid material used as an intermediate heating medium.

Different types of radiation/waves may be possible to utilize in direct transfer of energy to the meal. In such radiation/wave-based methods, no heat transfer medium is required, which may be a big advantage as only one

(direct) energy transfer process is required. If such a scheme is possible, then the calciner exit gas will be only the CO₂ from the decarbonation. As no heat medium is required, there is no need for CO₂ recycling. This category includes microwaves and electromagnetic (direct) induction.

Another possibility is to use a gas, i.e. recycled CO₂, as a heat medium. The gas is heated by electricity and the sensible heat in the hot gas is then transferred to the meal. The heating of the medium may take place by plasma generation or by resistance-based heating. In both cases, recycled CO₂ is heated to a (very) high temperature and will subsequently transfer heat to the meal by radiation and convection.

A gas may also act as a medium for transferring mechanical energy in the form of pressure waves. This is the ultrasound transfer mechanism.

Instead of using a gas as a heat medium, it may be possible to use a solid. In such cases, the solid will be heated by electricity, and then the meal is brought into contact with the hot solid. This may or may not require motion of the solid heat medium, depending on the concept. The solid medium may be heated by induction or by resistance heating. In both cases, the solid must be electrically conducting. The heat transfer will be a combination of direct contact (conduction) and radiation heat transfer.

An even more complex energy transfer concept would be to introduce still one more medium, i.e. a gas (recycled CO₂) which is heated by the hot solid. The heated gas is next used to calcine the meal. The same electrical heating concepts could be applied as in the previous category, i.e. induction heating or resistance-based heating. The solid heat medium could be the walls in a heat exchanger or possibly internals inside a vessel.

Finally, electricity could be used to electrolyse water to form hydrogen and oxygen. Hydrogen is combusted, generating heat required for calcination, which takes place by direct contact between the meal and the hot steam generated in the combustion process. This may require a recycle stream to control the temperature and the combustion properties of the burnable gas. Even though this concept involves combustion, and in that respect is quite similar to the regular calcination process, it is still different in the sense that electricity is the energy source and no CO₂ is generated.

The concepts listed in Table 1 are described in some more detail below.

2.3.1 Microwave heating

It is possible to perform calcination of CaCO₃ by radiation from a microwave source [2, 3], usually called a magnetron. General descriptions of different technologies are available for example in a paper from the company Ceralink [4] and in a book from Intech [5]. The company Microwave Research and Applications Inc. can deliver technology and equipment for microwave calcination [6]. Another company involved in development of microwave calcination is C-Tech Inc. [7].

The main advantage of the concept is that it applies direct transfer of energy (in the form of electromagnetic waves) to the meal. Hence, the relatively high heat transfer resistance found in systems with indirect heat transfer may be avoided. Furthermore, due to the nature of the energy form, it is expected that the energy input can be adjusted quickly, giving efficient process temperature control. The paper from Ceralink [4] claims that microwave technology needs less energy consumption than conventional heating. In the documentation from C-Tech Inc. [7] it is claimed that a combination of traditional heating with convection or radiation and microwave heating is advantageous. One paper [8] describes the calcination of mega-crystalline calcite at 950°C and compares a microwave oven with an electric furnace. The authors claim that a microwave oven gives faster calcination.

A review article from Buttress et al. [9] gives a critical review of the potential of microwave processing in the cement industry. The paper indicates a large energy consumption of the microwave technology, likely related to energy losses. This may in turn be related to CaCO₃ not exhibiting good properties for absorption and transformation of microwave energy into heat. Moreover, there may be safety concerns for personnel operating the system. Besides, superheating of materials might be a challenge. The goal is to heat the materials to about 900°C, but it is possible that local hot spots could occur, and that the minerals in the raw meal in such hot spots start to decompose or melt.

2.3.2 Plasma heating

Plasma is considered to be the fourth aggregate state. However, a gas is required for generation of plasma. This gas is commonly referred to as plasma gas. In a plasma, many of the particles are charged, i.e. electrons, protons, and ions. The ratio between electrically charged and neutral particles indicates the degree of ionisation of the plasma. In a plasma, forces will be generated between the electrically charged particles, and this will affect the organisation and movement of the particles. The plasma will be able to conduct electricity, and both influence and be influenced by electromagnetic fields. This allows for manipulation of the plasma externally using electric and magnetic fields [10, 11].

One of the uses for plasma is heat generation for industrial processes. When plasma is formed through interaction between a gas and an electric arc, the gas becomes ionised and consequently both thermally and electrically conductive. This enables the transfer of energy from the arc to the process gas and then to the process or furnace [12]. Such an installation is often called a plasma torch.

According to Westermoen [13], further expansion of plasma technology in industry is dependent on improving the characteristics of plasma torches and electric arc reactors. The main factors to consider are increased operating life of electrodes (currently relatively short due to the high thermal stress) to several hundreds and further to thousands of hours, increased thermal efficiency, working gases of different chemical composition, and increased yield of product.

According to Zhukov and Zasytkin [14], multi-jet plasma chemical reactors with mixing chamber are widely used for waste treatment and production of ultrafine powders. Nyrstar Høyanger operates a high temperature plasma furnace for metal processing [15] and claim that thermal plasma torches could be an alternative to conventional fossil fuel burners in the industry to provide heat in a process.

Advantages include lower operating cost, lower gas volumes, reduced need for flue gas cleaning, and lower greenhouse gas emissions (assuming renewable sources for electricity generation). A relatively high thermal efficiency can be achieved [12, 14]. According to Jensen [16], a 3 MW rotating plasma furnace achieved 90% overall heat efficiency in laboratory testing. Moreover, the response time is short, with good process control and temperature regulation [12, 16]. It has been confirmed experimentally in the CemZero project [17] that CO₂ can be used as a plasma gas.

As mentioned above, a disadvantage of the plasma technology is a relatively short operating life for the electrodes (reportedly 600–1000 hours [12]). Besides, water cooling is required, giving some energy loss, and unwanted reactions may potentially occur in the high temperature arc [13].

2.3.3 Electrical resistance heating

A metal surface can be heated by resistance heating (also called ohmic heating or Joule heating) and in turn transfer heat i) to a gas by convection (and the gas will in turn heat and calcine the meal through convection), ii) directly to the meal by radiation through the gas medium (CO₂) or iii) directly to the meal by conduction, provided that the meal is brought into direct contact with the hot surface.

Calcination via heat transfer from heating elements is well known from lab-scale muffle furnaces used in the cement industry, typically operating up to 1100°C. But in such cases, only a small amount of material is calcined, and the material is not moving.

In an industrial application, the material has to flow through the calciner while being decarbonated. One may implement this in different types of calcination reactors, such as a drop tube [17, 18], a fluidized bed [19] or a rotary kiln [20]. For the concept to work, one has to use heating element materials that are suitable for use at sufficiently high temperature and that can withstand the impacts from the flowing meal.

2.3.4 Ultrasound heating

Ultrasound is a form of vibrational energy (more than 18000 cycles/s) that is propagated as a mechanical wave by the motion of particles within the medium. The wavelengths of ultrasound are in the order of millimetres [21]. Ultrasound does not involve molecular level vibration, such as the heat generation in metals due to induction energy or microwaves. The wave causes compressions and rarefactions of the medium, thus propagating a pressure wave along with the mechanical movement of the particles in the medium.

Apparently, ultrasound has never been used in high-temperature applications or for heating purposes and has

not been tested widely. It has mainly been used at small-scale for low-temperature heating, e.g. drying food [22].

A disadvantage of ultrasound is that using a gas as the sonication medium is inefficient as the heat transfer is low [23]. This is a big disadvantage of the method and suggests that the method is not suitable. The method could also create local hot spots. Furthermore, the absorption of ultrasound energy into porous solids is high, and reflection back to the sonication media may lead to high energy losses as it is not absorbed by the solids.

2.3.5 Induction heating

In induction heating, an electrically conducting object is heated through electromagnetic induction. An electronic oscillator passes a high-frequency alternating current through an electromagnet. A rapidly alternating magnetic field will then penetrate the object to be heated and generate eddy currents inside the conductor, and these currents heat the material by Joule heating [24]. Joule heating is the same as resistance heating, which has already been described above. Hence, the difference between induction heating and electrical resistance heating in this study is mainly the way the electrical energy is transferred.

Induction heating, which is known as an efficient way to reach local high temperatures fast, is applied for example in induction welding [25] and in induction furnaces [26] used for melting different types of metals.

To use induction, the object to be heated must be electrically conducting. And if the object is also made of a magnetic material, such as steel, the induction heating process is more efficient.

As indicated in Table 1, one may envision one of the following energy transfer concepts: i) direct induction heating of the meal, ii) induction heating of a solid, which in turn will heat and calcine the meal through radiation or conduction and iii) induction heating of a solid, which in turn will heat a gas, which in turn will be brought into direct contact with the meal so that it is heated and calcined.

Direct heating of the meal using induction (point i above) appears to be not viable as the meal has a poor electrical conductivity and is also non-magnetic. The next two options (point ii and iii), both involving induction heating of a solid, could be possible if the solid is made of steel, which is electrically conducting and ferromagnetic.

Induction heating of granular media, which are subsequently heating a fluid, is a method described in a technical book published for designers, manufacturers and users of industrial equipment involving induction [27]. One may envision a packed bed of meal containing metallic susceptors disseminated in the meal bed. The susceptors would then be heated by induction and transfer heat to the meal by conduction. Such a process has been tested on preparation of activated carbon. However, it seems to be a challenge obtaining a homogeneous temperature distribution in such a system [27].

A disadvantage of the indirect heating via a hot gas is that a very high gas flow rate is required, contributing to heat

losses in the system. Moreover, the induction heating equipment must be cooled, meaning that there may be significant energy losses from an induction system, reducing the efficiency of the calcination process.

2.3.5 Electrolysis of water followed by hydrogen combustion in oxygen

The main idea of this concept is to keep a direct combustion process in the calciner, but avoid CO₂ formation by combusting hydrogen. This has the big advantage that direct heat transfer between the combustion products and the meal is maintained, and no additional heat transfer surfaces are required. Instead, the electrical energy is spent on dissociating liquid water into hydrogen gas and oxygen gas. This mixture is subsequently combusted in the calciner. To control the temperature in the process and to prevent explosions, the mixture of H₂ and O₂ may be mixed with recycled CO₂.

There are several different water electrolysis cell technologies, the three main ones being Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cell (PEMEC), and Solid Electrolysis Cells (SOEC). Ogawa et al. [28] and Schmidt et al. [29] provide a review of the current trends and merging technologies, and an expert elicitation study on future cost and performance, respectively. In addition, Schmidt et al. [29] gives an overview of the main characteristics of the three technologies; operational, input and output parameters, lifetime, and investment cost.

2.3.6 Selection of heat transfer concept

The resistance-based heating concept was selected for the following reasons:

- It requires no (or very little) CO₂ recycling, hence losses related to waste heat from a hot CO₂ stream can be minimized.
- It has a high efficiency, i.e. low losses related to conversion of electrical energy into thermal energy.
- It is a relatively simple and well-proven heat transfer technology, hence the costs are likely to be low compared to more sophisticated concepts.
- There are no major safety concerns.

2.4 Rotary calciner with resistance-based heating

As explained above, there are different ways to implement the resistance-based heating concept. In this study, a rotary kiln was selected as the reactor type. There are several reasons for that:

- The meal flow and its residence time in the calciner can be readily controlled in a rotary calciner.
- It appears to be technically feasible to implement heating elements with a sufficiently high surface temperature to perform the heating and calcination of the raw materials.
- Rotary kilns are already in use in the cement industry and can be regarded as well-known technology.

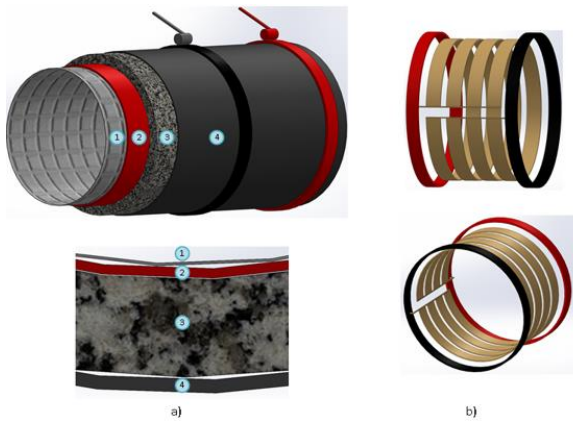


Figure 4: Suggested rotary calciner design (a, with 1: protective layer, 2: heating elements, 3: refractory and 4: steel shell) and arrangement of the heating elements (b).

A potential implementation of the heating system is shown in Figure 4. The rotating cylinder is equipped with a slip ring for transfer of electrical energy to the heating elements. The elements are covered by a thin protective layer on the inside (exposed to the hot meal flowing through the rotary calciner). Outside the heating elements there is a refractory layer to minimize the heat loss to the surroundings. The cylinder itself is made of carbon steel, similar to a regular clinker kiln.

3. MODELLING OF THE MODIFIED SYSTEM

The electrified calciner is integrated with an existing cement kiln system in such a way that minimum disturbance of the production process is obtained, i.e. the material streams (gases and solids) in the preheater, rotary kiln and cooler are kept close to the flow rates in the regular system (cf. Figure 1).

3.1 Mass and energy balance

A mass and energy balance for steady state conditions was conducted, so that relevant temperatures, flow rates and duties in the modified system (cf. Figure 2) could be calculated and compared with the values in the regular system (cf. Figure 1). A set of altogether 176 equations (not shown here) constitutes the mass and energy balance for the kiln system. The equations were implemented and solved in Excel.

3.2 Design basis

The design basis values are summarized in Table 2. The values are selected to cover typical process conditions in a modern precalciner cement kiln system producing 1 Mt of clinker per year.

3.3 Calculation results

Selected calculation results for both systems are shown in Table 3. The calciner exit gas flow rate is reduced from 270 to 67 t/h because the calciner fuel, the tertiary air and the kiln gas streams are no longer entering the calciner (cf. Figure 3). However, the preheater exit gas is only slightly reduced (from 316 to 306 t/h) because the kiln gas, the tertiary air and some of the vent air from the cooler has been routed to the preheater tower. Hence, the vent air is reduced from 177 to 106 t/h. Moreover, the

preheater exit gas is only slightly reduced (from 446 to 399 °C), and this is also the case for the preheated meal temperature (from 700 to 658 °C). This ensures minimal impact on the kiln process and means that no modification of the preheater tower, rotary kiln or cooler is required.

The net CO₂ emissions from the kiln system is reduced from 114 to 32 t/h. This is due to the elimination of calciner fuel CO₂ generation and the capture of the CO₂ from the precalcination process. The only extra CO₂ contribution from the electrified calciner system is coming from the electricity generation. A CO₂ footprint of 47 g/kWh (corresponding to the Norwegian energy mix in the period 2011-2015) [30] has been assumed for the electrical energy.

The net CO₂ emission reduction in the electrified calciner case is 72 % when compared to the regular coal-fired plant.

Table 2: Design basis values.

Parameter	Unit	Regular system	System with el-calciner
Clinker production	t/y	1 000 000	1 000 000
Operation time	h/y	7 315	7 315
Specific thermal energy cons.	MJ/kg_cli	3.40	Calculated
Calciner CO ₂ capture rate	-	0 %	90 %
CO ₂ footprint of electricity	gCO ₂ /kWh _{el}	47	47
Mass fraction of CaCO ₃ i raw meal	kg/kg	0.77	0.77
Cyclone 1 efficiency	-	94 %	94 %
Calciner thermal energy fraction	-	62 %	Calculated
Calcination degree in the calciner	-	94 %	94 %
Primary air supply in the rot. kiln	-	8 %	8 %
Purged bypass gas	-	5 %	5 %
Primary air supply in the calciner	-	5 %	5 %
O ₂ in the rotary kiln exit gas (dry)	vol%	3 %	3 %
O ₂ in the calciner exit gas (dry)	vol%	3 %	3 %
Bypass dust ratio	kg/kg_cli	0.02	0.02
False air in the rotary kiln	kg/kg_cli	0.03	0.03
False air in the calciner	kg/kg_cli	0.01	0
Specific clinker cooling air supply	Nm ³ /kg_cli	2.0	2.0
Mass fraction of C in fuel	kg/kg	0.722	0.722
Mass fraction of H in fuel	kg/kg	0.040	0.040
Mass fraction of O in fuel	kg/kg	0.057	0.057
Mass fraction of S in fuel	kg/kg	0.012	0.012
Mass fraction of N in fuel	kg/kg	0.016	0.016
Mass fraction of moisture in fuel	kg/kg	0.018	0.018
Mass fraction of ash in fuel	kg/kg	0.135	0.135
Lower heating value of fuel	MJ/kg	28.0	28.0
Specific rotary kiln heat loss	MJ/kgcli	0.15	0.15
Ambient temperature	°C	20	20
Hot clinker temperature	°C	1 400	1 400
Minimum temp. diff. in HEX	°C	NA	100
Calcination temperature	°C	900	900
Meal inlet temperature	°C	50	50
Calciner fuel inlet temperature	°C	30	30
Calciner primary air inlet temp.	°C	30	30
El-to-heat efficiency	-	NA	90 %
Rotary kiln fuel inlet temperature	°C	30	30
Rotary kiln primary air inlet temp.	°C	30	30

3.4 Impacts on the cement kiln process

No negative impacts on the process, product quality or emissions are expected. This is because the mass flow rates and temperature profiles in the system are identical to or kept very close to the values in the regular system. There are no changes at all in the cooler or in the rotary

kiln and only minor changes in the preheater tower. The calciner is of course different in many respects, but the meal exiting the calciner has the same temperature and degree of calcination as in the regular system.

One may expect somewhat lower emissions of combustion related components, such as CO and VOC, as there is no longer any combustion going on in the calciner. This is a potential positive side-effect of the new system.

The following modifications to the system are required:

- a new calciner, equipped with an electrically driven heating system
- a new electrical power supply system of ~85 MW
- a new CO₂/air heat exchanger (HEX)
- a new CO₂ processing system
- a new gas duct from the kiln inlet to the preheater tower
- a new gas duct for conveying of the air into and out of the CO₂ HEX
- re-routing of the tertiary air duct

Table 3: Comparison of selected process values.

Parameter	Unit	Regular system	System with el-calciner
Secondary air	t/h	61	61
Rotary kiln exit gas	t/h	79	79
Tertiary air	t/h	114	114
Calciner exit gas	t/h	270	67
Preheater inlet gas	t/h	270	260
Preheater exit gas	t/h	316	306
Air heated in CO ₂ HEX	t/h	0	71
Cooler vent air	t/h	177	106
Gross raw meal feed rate	t/h	221	223
Net raw meal feed rate	t/h	207	210
Gross precalcined meal (w/ ash)	t/h	143	143
Clinker production	t/h	137	137
CO ₂ from raw meal decarbonation	t/h	70	71
Fuel-gen. CO ₂ in the rotary kiln	t/h	17	17
Fuel-gen. CO ₂ in the calciner	t/h	27	0
CO ₂ from precalcination	t/h	66	67
CO ₂ from precalcination captured	t/h	0	60
CO ₂ from precalcination emitted	t/h	66	7
CO ₂ from postcalcination	t/h	4	4
Net fuel-gen. CO ₂ in the rotary kiln	t/h	17	17
Net fuel-gen. CO ₂ in the calciner	t/h	27	0
CO ₂ from electricity production	t/h	0	4
Net CO ₂ emissions	t/h	114	32
Secondary air temperature	°C	881	881
Kiln gas exit temperature	°C	1 150	1 150
Tertiary air temperature	°C	684	684
Preheater gas inlet temperature	°C	900	860
Preheater exit gas temperature	°C	446	399
Raw meal exit temp. preheater	°C	700	658
Clinker temp. vent air zone	°C	97	97
N ₂ in the PH exit gas	vol%	65 %	78 %
CO ₂ in the PH exit gas	vol%	26 %	4 %
H ₂ O in the PH exit gas	vol%	3 %	1 %
O ₂ in the PH exit gas	vol%	6 %	17 %
Calciner fuel energy	MW	80	0
Calciner el-to-heat energy	MW	0	76
Electrical power loss	MW	0	8
Rotary kiln fuel energy	MW	49	49
Net CO ₂ emission reduction	%	0 %	72 %

4. CO₂ COMPRESSION

Downstream of the kiln system, the CO₂ is compressed to 70 bar and 25 °C. Liquefaction is not included. Figure 5 shows the CO₂ processing section.

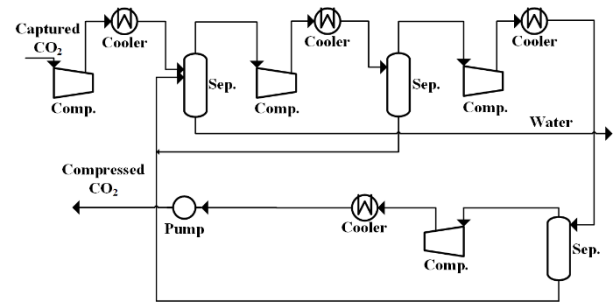


Figure 5: CO₂ compression plant.

The CO₂ entering the compression and liquefaction section has been taken as a pure stream. In reality it may contain some impurities, such as O₂ and N₂ from false air entering into the calciner along with the the raw meal. However, the concentrations are on ppm levels, so have not been included in the process calculations.

5. COMPARISON WITH POST-COMBUSTION AMINE ABSORPTION CO₂ CAPTURE

When evaluating the electrified calcination and CO₂ capture concept it is compared with CO₂ capture by amine absorption as this can be considered the most mature capture technology today [31].

A generic amine absorption plant is shown in Figure 6. The flue gas entering the absorption plant is the preheater gas from the kiln system shown in Figure 2. The CO₂ from the capture plant (“CO₂ to compressions” in Figure 6) is routed to a CO₂ processing plant as shown in Figure 5.

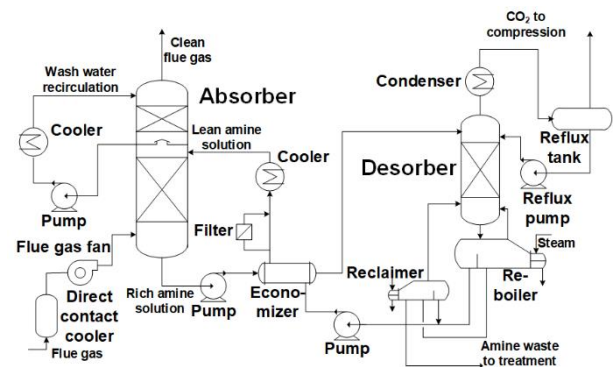


Figure 6: Amine absorption plant.

Three different scenarios are compared, as shown in Table 4. Case 1 can be seen as a "standard" post-combustion absorption process implemented to obtain around 90 % CO₂ capture. Such a process requires a significant amount of thermal energy for regeneration of the solvent (3.7 MJ/kg_{CO₂} in this study). The thermal energy can be provided in different ways, for example by combustion of fuels (which would give an extra on-site

CO₂ footprint), such as natural gas, but to facilitate comparison it has been assumed that this energy is provided via an electric boiler.

In Case 2, an advanced proprietary amine with a lower specific solvent regeneration energy (3.0 MJ/kg_{CO2}) is applied, and all the energy required for the regeneration is provided by waste heat available in the kiln exhaust gases (33 MW in this study) and by process integration (13 MW in this study) inside the battery limit of the capture plant (hence a partial capture case). Such waste heat utilization is possible because the solvent regeneration occurs at a relatively low temperature (~120 °C), which is a big advantage of the amine-absorption process both when it comes to energy consumption and operational costs. However, significant amounts of waste heat are only available in some cement plants.

Case 3 is the electrified calciner case, which is also a partial capture case because the CO₂ from the rotary kiln is not captured.

Table 4: Compared CO₂ capture cases.

Case	Concept	CO ₂ capture	Cement plant waste heat
1	Absorption using an optimized standard MEA solvent	Full (post-comb.)	Not used
2	Absorption using an advanced proprietary amine solvent	Partial (post-comb.)	The only source of energy for solvent regeneration
3	Rotary calciner applying electric resistance heating	Partial (integrated)	Not used

The energy consumption in the three cases is shown in Figure 7. Both in the standard MEA case and in the electrified calciner case, the electricity consumption makes the biggest contribution. In the MEA case, this is due to the electrical power consumption required for providing energy to the reboiler in order to regenerate the solvent (cf. Figure 6).

The advantage of the waste heat scenario is very clear from the graph; the electrical energy is almost eliminated because all energy required for regeneration of the solvent is provided by waste heat. However, as mentioned, waste heat is not available in all cement plants, at least not to the same extent as in the plant used in this study. Several factors impact the waste heat availability, such as the fraction of exhaust gas utilized for drying the raw materials, the excess air levels in the combustion zones and false air leakage in the preheater tower.

An advantage of the electrified calciner case, however, is the significant reduction of fuel energy in the calciner. For a coal-fired calciner, this means a significant reduction in fuel costs and hence operational costs of the cement kiln system.

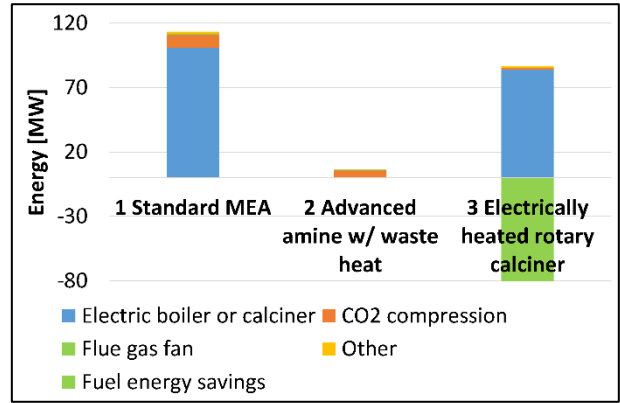


Figure 7: Electrical energy consumption and fuel energy savings in the three compared scenarios.

6. COST ESTIMATION

The new process equipment units in the electrified calciner system (cf. Figure 3) and all the required units in the CO₂ processing system were designed and sized.

With all components identified and sized, a detailed factor estimation method [32] was applied to make a cost estimate for the capital expenditure (CAPEX). This method normally has an uncertainty of $\pm 40\%$ (80% confidence interval). The equipment costs are for the most part calculated using the “Aspen In-Plant Cost Estimator” v10. It was assumed that the CO₂ capture plant built is the nth of a kind (NOAK; i.e. the technology is mature), hence the costs reflect that maturity level. Further cost input data, including inputs for the operational expenditure (OPEX), are given in Table 5. The annual costs are calculated based on a utility and personnel unit price list, and maintenance cost. It should be noted that the electricity cost is set as low as 0.033 EUR/kWh as the installation of transformers are included in the investment cost. The reduced coal consumption in the calciner in the el-calciner case is included in the cost calculation as a fuel saving.

Table 5: Cost calculation input data.

Parameter	Unit	Value
Operating hours	h/y	7 315
Electricity price	EUR/kWh	0.033
Coal price	EUR/t	111
Cooling water	EUR/m ³	0.02
Personnel (operators)	kEUR/y	650
Maintenance (% of CAPEX)	%	4
Interest	%	7.5
Number of years for depreciation	-	25
Contingency	%	20
Cost data reference year	-	2018

The costs per mass of avoided CO₂ are illustrated in Figure 8. The advantage of the low electrical energy consumption in the waste heat scenario is evident, giving a total cost of 40 € per ton of avoided CO₂. The electrified calciner case is, however, less costly (67 €/t_{CO2}) than the amine case operating without waste heat utilization (75 €/t_{CO2}).

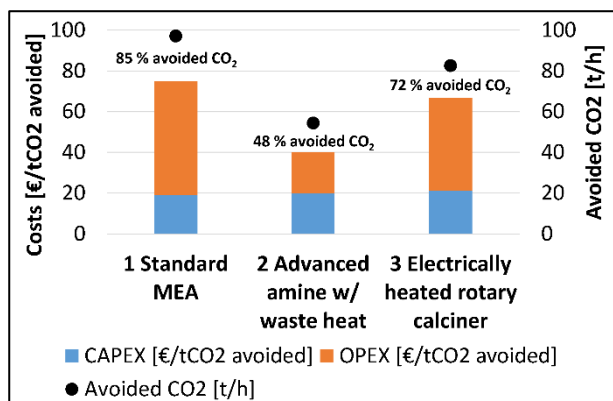


Figure 8: CO₂-specific operational costs (OPEX) and capital costs (CAPEX) and avoided CO₂ emissions.

A sensitivity analysis was also made to investigate the impact of changes in the input parameters (which may be different in the future). The details are not shown here, but the main outcome is that the strong dependence of Scenario 1 and 3 on electrical energy make them very sensitive to variations in electricity price and CO₂ footprint.

7. CONCLUSIONS

Calcination based on electric heating appears to be possible. Different energy transfer concepts may be applied, but heat transfer based on ohmic resistance seems to be a good solution when only the calciner is considered. It is possible to implement such a system in an existing kiln system without any negative impacts on the process, emissions or product quality.

In cement plants where large amounts of waste heat are available, amine-based absorption appears to be the least expensive option for reduction in CO₂ emissions. However, in systems with no such waste heat available, electrified calcination, for example in the form of electrified rotary calciners, may be a competitive alternative to post-combustion capture technology.

Acknowledgements

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