

CemZero

A feasibility study evaluating ways to reach sustainable cement production via the use of electricity.

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Sammanfattning

Syftet med förstudien är att undersöka hur elektrifiering kan bidra till att sänka växthusgasutsläpp (koldioxid, CO₂) från cementproduktion. Syftet är att svara på vilka tekniskt möjliga lösningar det finns, hur elsystemet påverkas samt vilka affärsmässiga förutsättningar det finns för elektrifiering. Som randvillkor förutsätts att elektricitet i framtiden framställs på ett helt och hållet fossilfritt sätt.

En litteraturstudie har utförts för att finna teknologier för elektrifiering samt riktade praktiska försök har utförts för att utvärdera funna möjligheter och om möjligt avgöra om de ska behandlas vidare. Konsulter och universitet har stött projektet med kunskap och försöksuppställningar.

Studien drar följande huvudslutsatser:

- Elektrifiering av värmningen i cementprocessen, exempelvis med hjälp av plasmateknik, ser ut att vara tekniskt möjlig men behöver verifieras i test i större skala,
- Produktionskostnaden för cement i en elektrifierad process ser ut att ungefär fördubblas jämfört med dagens teknik, men är konkurrenskraftig i jämförelse med andra teknologialternativ för radikala utsläppsminskningar,
- Simuleringar har indikerat att en eventuell framtida elektrifiering av Cementas fabrik i Slite skulle fungera väl tillsammans med planerad utbyggnad av vindkraft på Gotland, dels genom förbättrad energibalans men också genom minskande av det maximala effektöverskottet som vindkraften annars skulle ge upphov till,
- Det tvärssektoriella tillvägagångssättet i samarbetet mellan industri och universitet med stöd från Energimyndigheten har varit viktigt för projektets framgång,
- Cementa och Vattenfall fortsätter nu samarbetet in i nästa fas där pilottester av teknik ska göras för att reducera tekniska risker och ge viktig information inför kommande uppskalning och implementation.

Teknologierna som är möjliga att använda för elektrifiering har olika mognadsgrad och effektivitet. Förstudien visar på att koncentrationen av koldioxid blir mycket hög om uppvärmning sker med elektricitet. Mängden koldioxid minskar dessutom avsevärt när förbränning av bränslen exkluderas. Om uppvärmning sker på annat sätt än med hjälp av varma gaser förväntas ytterligare minskning av rökgasvolymen. Detta leder till en betydligt enklare infångning och rening av koldioxid ur rökgaserna. För att nå nollutsläpp krävs lagring eller användning av koldioxiden, så kallad CCS eller CCU.

En ekonomisk analys ger att produktionskostnaden för en elektrifierad cementprocess är ungefär dubbelt så hög jämfört med en referenscementfabrik där referensfabriken inte har någon infångning av koldioxid installerad. Studien visar också att elektrifiering står sig väl ekonomiskt jämfört med andra koldioxidavskiljningsteknologier. Produktionskostnaderna för avskiljning med aminmetod är högre. Elektrifiering har också signifikant lägre total energiförbrukning än aminmetoden. Summerat ger resultaten från studien, tillsammans med de prognostiserade priserna på råmaterial, energi och koldioxidutsläpp, att en fossilfri elbaserad cementprocess är ekonomiskt genomförbar.

Förstudien förordar, utifrån erhållna resultat, att en fortsatt utredning av konceptet med 'förvärmartorn, kalcinering och roterugn' där värmekällan är plasmageneratorer bör göras. Nästa steg är att i pilotskala utreda detta teknologiska koncept. Syftet med pilotförsöket är att verifiera slutsatser från tidigare utförda försök i mindre skala. Bevakning av utvecklingen av andra tekniker, så som DSR-tekniken som appliceras inom EU Horizon 2020 pilot projektet LEILAC där HeidelbergCement är medverkande, bör också inkluderas. För att lyckas med en

ekonomisk genomförbar omställning till en elektrifierad cementtillverkning integrerat i ett starkt fossilfritt kraftnät kommer stora ansträngningar av företag, myndigheter och samhälle att krävas.

Nyckelord: Elektrifiering, cementklinker-tillverkning, koldioxid, CO₂, klimatmässig hållbarhet.

Abstract

The aim of the prefeasibility study is to investigate the possibility of electrification to reduce greenhouse gas emissions (carbon dioxide, CO₂) from cement production. The purpose is to answer what possible technical solutions are available, how the electrical system is affected and what business conditions are available for electrification. In the future, electricity is expected to be 100% fossil free.

A literature study has been conducted to find electrification technologies, as well as targeted practical attempts have been made to evaluate found opportunities and, if possible, decide whether to be further processed. Consultants and universities have supported the project with knowledge and practical tests.

The main conclusions of the study are:

- Electrification of the cement production process, for example by means of plasma technology, appears to be technically possible but needs to be verified in larger scale tests,
- The production cost of cement in an electrified process appears to be doubled compared to today's technology, but is competitive compared to other technology options for radical emission reductions,
- Simulations have indicated that possible future electrification of Cementa's plant in Slite would work well together with planned expansion of wind power on Gotland, partly through improved energy balances, but also by reducing the maximum power surplus that wind power would otherwise give rise to,
- The cross-sectoral approach with cooperation between industry and universities supported by the Swedish Energy Agency has been important for the success of the project,
- Cementa and Vattenfall are continuing the collaboration into the next phase where pilot tests of technology will be made to reduce technical risks and provide important information for future upscaling and implementation.

The possible technologies for electrification of cement clinker production have different degrees of maturity and the efficiency varies.

The preliminary study shows that the concentration of carbon dioxide becomes very high if heating is done with electricity. The amount of carbon dioxide also reduces significantly when the combustion of fuel is excluded. If heating occurs without hot gases further reduction of flue gas volumes is expected. This leads to a much easier capture and purification of carbon dioxide from the flue gases. To reach zero emissions a need for storage or utilization of carbon dioxide (CCS or CCU) is necessary.

The outcome from this economic analysis indicates that the production costs for an electrified cement process are approximately twice the costs of a reference cement plant operating as of today, the latter meaning a fossil-based combustion process with no carbon capture technology installed. However, the study also shows that electrification as a carbon capture technology compares economically well to other carbon capture technologies of today. A detailed comparison indicates higher production cost for a post combustion amine method. Also, the electrification scenario has significantly lower total energy consumption than the post combustion amine method. All this, together with the forecasted prices for raw material, energy and carbon dioxide emissions, means that a fossil-free electricity-based cement process appears to be economically viable.

Based on obtained results, the prefeasibility study advocates further investigations of the selected concept with 'preheating tower, calcination and rotary kiln' with heating sources of plasma generators. The next step is to investigate the technology with this concept in a pilot scale plant for verification of previous tests. Following the development of other technologies,

such as the DSR technology applied in the EU Horizon 2020 pilot project LEILAC, where HeidelbergCement is involved, should also be included. To succeed in an economically feasible conversion to an electrified cement production integrated into a strong fossil-free power system will require great efforts by companies, government and society.

Keywords: Electrification, cement clinker production, carbon dioxide, CO₂, environmental sustainability

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1. Introduction

The Swedish climate law passed by the Swedish parliament in June 2017 declares that Sweden shall have zero net emissions of greenhouse gases by 2045. The framework agreement on Swedish energy policy from 2016 sets the target of 100% fossil free electricity production by 2040. These ambitions are in line with the Paris Agreement.

Cement is one of the most abundantly produced materials in the world. It is wide spread, used for most construction purposes, it enables cost-efficient construction and its main raw material, limestone, is abundant and geographically available in almost every country.

The cement industry is today responsible for about 7% of anthropogenic carbon dioxide globally (Pales and Leung 2018) and the Swedish cement industry is responsible for 5% of total national emissions (Naturvårdsverket 2018). The Swedish cement industry is continuously improving its efficiency and also successively phasing out fossil based fuels in favor for biofuels. The rapid increase of global warming places extra demand on switching to a low carbon dioxide-emitting production and the big challenge is to totally eliminate the carbon dioxide emissions. The cement industry will need to undertake a major shift in technology. Several initiatives have been initiated in the area of CCS (Carbon Capture and Storage) and CCU (Carbon Capture and Utilization). These initiatives are typically clusters of industrial partners, universities and authorities in different parts of the world and HeidelbergCement, in which Cementsa is an affiliate, is participating in several activities.

An electrification of the cement making process in total or in parts will reduce the demand of fuels, lessen the amount of carbon dioxide released and (potentially) increase the concentration of carbon dioxide in the process gases. This results in the simplified capture of carbon dioxide. However, further analysis is needed on how an electrified cement making process could work.

During 2016 Cementsa emitted 2,5 Mt of carbon dioxide. One third of these emissions originate from combustion of fuels and could thereby potentially be reduced to zero with either the use of biofuels or if the process were completely electrified.

Research focusing on a future, electrified cement making process is in line with Cementsa's official vision of zero carbon dioxide emissions during the life cycle of cement products by 2030. The future industrial cement process is based on sustainable energy where Swedish fossil free electricity production could be used which is also in line with Vattenfall's owner's directives. This symbiosis makes the situation in Sweden unique with the connection between fossil free electricity production and a large scale downstream industry segment. The long term goal of the cooperation between Cementsa and Vattenfall, CemZero, is to establish a sustainable cement making process. An underlying prerequisite is that electricity is an important step towards the goal.

Sweden has a unique situation given the availability of nearly fossil free electricity, competence in the areas concerned and a tradition of networking in order to solve the major challenges like the one CemZero is addressing. A disruptive technology shift like this will place emphasis on research and development with the actors involved and will also need strong support from the government and society. However, a future sustainable cement making process has great potential to mark a new era globally and will create great

opportunities for new technologies to be developed, business opportunities to be strengthened, and the development of know-how and competence.

During 2018, Cementsa and Vattenfall, together with external expertise, have studied the feasibility of an electrified and fossil free cement making process. This report summarizes the findings which have been partly financed by the Swedish Energy Agency.

The results have been compiled through literature studies, collaboration with universities, discussions with manufacturers and suppliers of potential technologies, on-site study visits at production facilities, laboratory tests and theoretical calculations.

The report starts with some basic facts about the cement industry and the cement production process, in particular the inherent release of CO₂. Certain aspects of the Swedish power system, with focus on the power system on the island Gotland, are examined. A short overview of the CemZero project is followed by a survey of electricity-based technologies for heat generation and of cement production technologies and/or concepts suitable for electrification. Some chemical aspects related to the electrification of the cement production process are studied. Conceptual designs, including mass and energy balances, are presented for two selected production processes. The consequences for the future power production and power consumption of a fully electrified production plant at Slite, Gotland, are analyzed. Following that, the capital and operating costs of an electrified cement plant are discussed.

2. Background

2.1. The cement and concrete industry

The annual demand for concrete is today about 30 billion tons worldwide. Concrete is today a fundamental construction material and will remain so in order to meet the constant demand from society on sustainable infrastructure and buildings. Concrete enables secure energy supply, functional water supply, effective transport opportunities and sustainable solutions for new buildings and infrastructure.

By the year 2050, the global population is expected to have increased from the current level of 7.6 billion to almost 10 billion (UN 2017). Twice as many people are expected to be living in metropolitan regions. This means that we need sustainable, robust and functional construction materials. Construction must be done in a resource-efficient, long-term manner using the recycling of construction materials and the conversion to sustainable manufacturing processes for construction materials.

Portland cement is the most common type of cement in general use around the world as a basic ingredient in concrete. Natural elements in cement are calcium, silica, alumina and iron. Materials used to manufacture cement are limestone, marlstone, clay, slate, blast furnace slag, silica sand, and iron oxides.

Cement production plants are mostly localized close to limestone quarries and the industry is driven by a constantly increasing demand in construction activities and infrastructure development projects globally. The major driver in this increasing demand of cement is India and China, the two fastest growing economies in the world, see Figure 1. Even if exact numbers are hard to verify, China alone claims to contribute to more than 50% of global cement production and India is following thereafter.

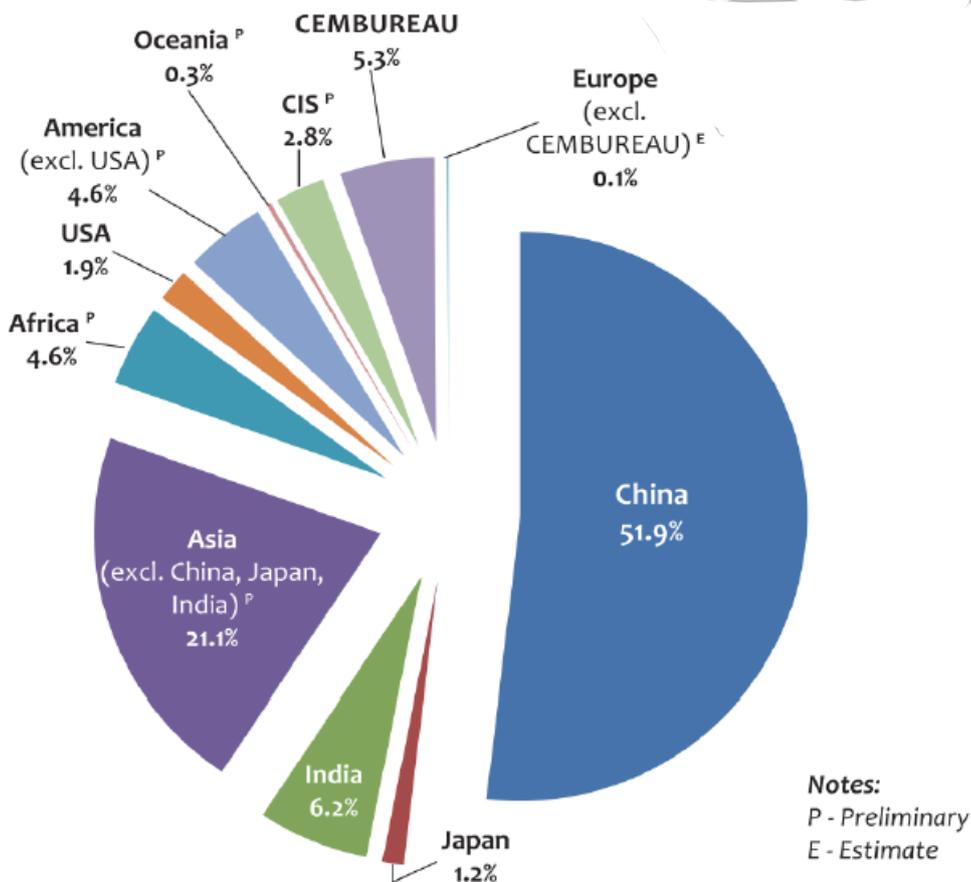


Figure 1. World cement production 2016, by region and main countries, % (Cembureau 2017).

The cement manufacturing sector in Sweden has a long history and is today a modern high technology business performing very well in an international market with a focus on quality, knowledge and sustainability. Cementa AB is the sole cement producer in Sweden and is an affiliate company to the international company HeidelbergCement. Cementa has three production sites, located in Slite, Skövde and in Degerhamn – strategic locations in regards to raw material resources and transportation of material by ship. The customers are in the concrete sector and entrepreneurs in the building business.

2.2. The cement manufacturing process

Production of cement involves several unit operations as well as chemical conversions. A general process scheme is shown in Figure 2.

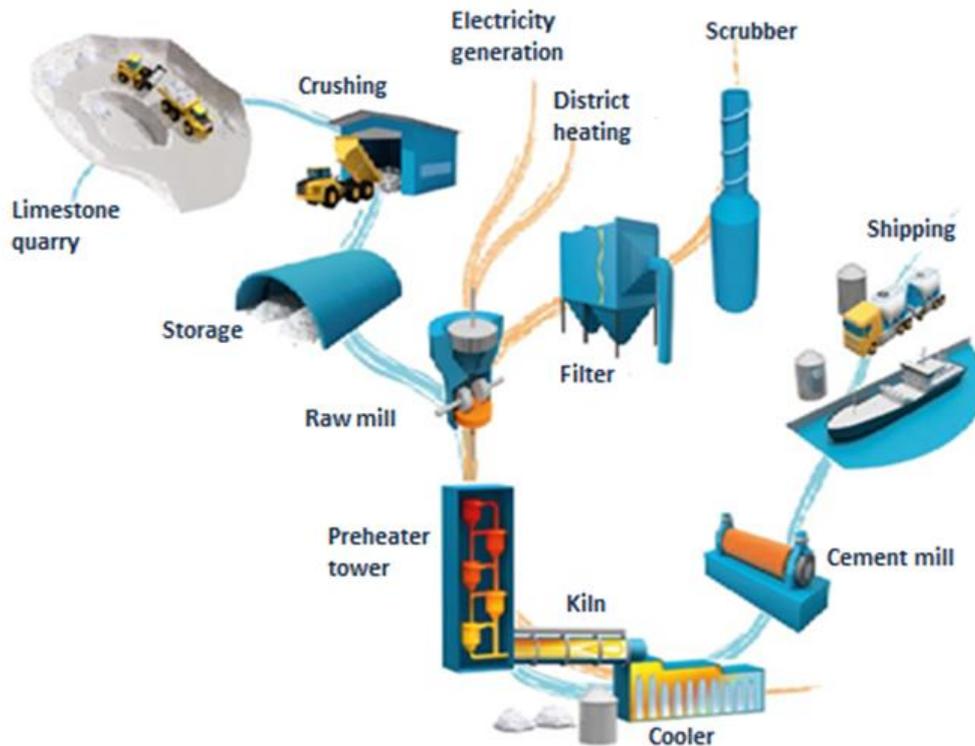


Figure 2. General process of a cement manufacturing plant (www.cemta.se).

The process starts in the lime- and marlstone quarry which generally is located nearby the cement plant. Raw materials are extracted from the quarry and transported to the cement plant. Other corrective raw materials added are silica sand, blast furnace slag, alumina and iron oxides. These are added to achieve the correct chemical composition.

After transportation of raw materials to the cement plant, large size rocks are crushed into smaller size rocks with the help of a crusher in the quarry. The crusher reduces the size of large rocks to the size of maximum 80 mm.

Before the raw materials are stored in pre-homogenization piles, it is ground together with additives to form the raw mix desired by analysis and proper proportioning. Generally, limestone and marlstone constitute 80% of the raw mix.

After the primary crusher, the raw materials are stored in pre-homogenization piles. The limestone and marlstone are then mixed to form the raw mix desired by analysis and proper proportioning. Generally, limestone and marlstone constitutes 80% by weight.

The raw mix enters the next process step where it is ground in the raw mill to a very fine meal, with the approximate size of less than 0,09 mm. To ensure high cement quality, the chemistry of the raw materials and the subsequent raw meal is carefully monitored and controlled.

Hot exhaust gases coming from the kiln preheater dries the powdered raw meal before it enters the raw meal silos as an energy efficiency measure. The raw meal is then transported with the exhaust gases through a filter where dust is separated from the gases.

The dust in the flue gas, originating from different parts of the process is separated in either high-efficiency electro filter or in fabric bag filters.

The flue gases are washed with mild limestone and water in a wet scrubber. The residual product becomes gypsum that is recycled. It is used as an additive in the cement grinding step.

Hot exhaust gases coming from the kiln, preheat the powdered raw meal before it enters the kiln. A preheater consists of a series of cyclones through which the raw meal is passed by swirling hot flue gases in the opposite direction of the material flow. By this thermal energy is recovered from hot flue gases with the benefit that the raw meal is preheated which in turn means that efficiency of the plant has increased and less fuel is needed. The heat recovery increases by the number of stages of cyclones in the plant. A pre-heater tower may have up to 6 stages.

Free, crystalized and chemical water is driven out in the pre-heater tower and the temperature is in the range of ambient temperature to 900°C.

In the calciner, which is a combustion chamber at the bottom of the preheater tower, about 95% of the calcination takes place. The temperature in the calciner reaches about 900°C, which is needed to reach the aimed calcination degree of the calcium carbonate. Higher temperatures will create problems such as sticking and it is, therefore, the main reason for stopping at 95% calcination degree in the calciner. The rest of the carbon dioxide from the limestone is released in the rotary kiln.

Almost fully calcined raw meal enters the rotary kiln at temperatures of around 900°C. Fuel, such as coal, petroleum coke, gas, oil and alternative and biofuels, is fired directly into the rotary kiln. Fuels are added to reach sufficient temperatures to ensure sintering, which means raw material reaching temperatures of 1450°C. The kiln, which is a brick-lined metal tube 4-5 meters wide and 60-80 meters long, rotates about 3-5 times per minute and the raw material flows down through progressively hotter zones of the kiln towards the flame. The intense heat causes the chemical reaction between calcium and silicon dioxide compounds to form the primary constituents of cement i.e. calcium silicate. A liquid phase is formed based mainly on calcium, alumina and iron that will improve the reaction between calcium and silica.

From the kiln, the hot cement clinker is cooled rapidly to keep the calcium silicates minerals formed which define the quality and performance of cement. Large quantities of air are used for cooling and generally, the cooling system can be divided into two parts, one hot and one cool. The hot part exhaust gas is of high-grade heat in the range of 1000°C which thereby is very attractable to re-use in the process.

In the cement mill, clinker is ground into a fine powder. During grinding, gypsum is added together with other possible additives.

From storage in silos the end product cement is loaded in closed systems on boats, rails or trucks for transportation to customers.

Due to the complex chemical nature of cement, abbreviations are used to explain the chemical compounds. The shorthand for the basic cement clinker minerals are shown in Table 1 (Hewlett 2003).

Table 1. Cement clinker compounds, their chemical composition and their subsequent abbreviation.

Cement clinker compound	Abbreviation
Tricalcium silicate ($3\text{CaO}\cdot\text{SiO}_2$)	C_3S
Dicalcium silicate ($2\text{CaO}\cdot\text{SiO}_2$)	C_2S
Tricalcium aluminate ($3\text{CaO}\cdot\text{Al}_2\text{O}_3$)	C_3A
Tetracalcium aluminoferrite ($4\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Fe}_2\text{O}_3$)	C_4AF

Ideal composition of raw material is shown in Table 2. Together with cement clinker composition from the dry raw material assuming no fuel ash absorption.

Table 2. Ideal composition of raw meal (weight-%) (Hewlett 2003).

	Dry raw material	Clinker made from the dry raw material
SiO_2	14,0	20,9
Al_2O_3	4,1	6,1
Fe_2O_3	1,6	2,3
CaO	43,2	64,5
Free lime		1,0
C_3S (Bouge)*		55
C_2S (Bouge)		18
C_3A (Bouge)		12,2
C_4AF (Bouge)		7,0

*). The Bogue calculation is used to calculate the approximate proportions of the four main minerals in Portland cement clinker.

The chemical reactions taking place from ambient temperature to maximum temperature of the material is shown graphically in Figure 3 and in Table 3 is the main chemical reactions and corresponding temperature interval described in brief.

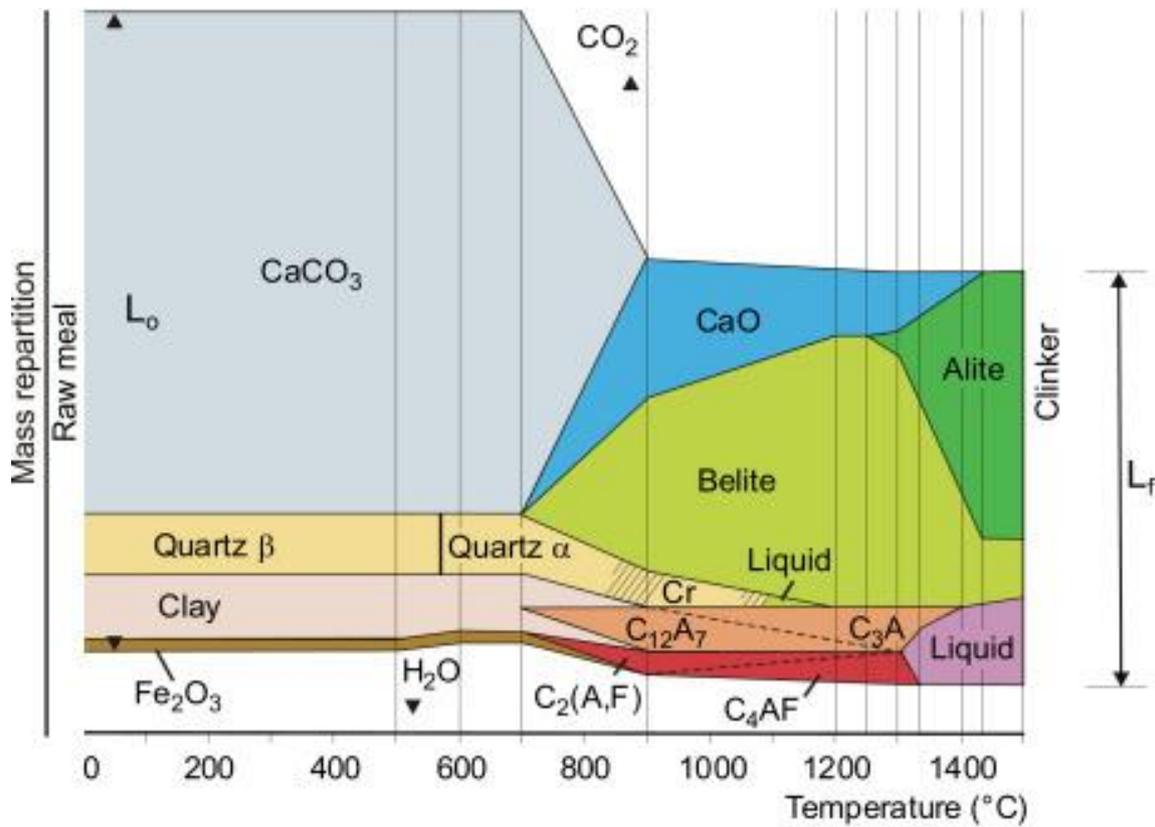


Figure 3. Schematic diagram showing the typical chemical phases during the formation of cement clinker (Aïtcin and Flatt 2015)

Table 3. Main chemical reactions during formation of cement clinker.

Process	Reaction	Temperature (°C)
Drying / pre-heating	Water driven out	20 - 900
Calcining	CO ₂ driven out,	600 - 900
Clinkering / sintering	CaCO ₃ → CaO + CO ₂ Liquid phase, formation of alite and belite. Exothermic process	1450
Cooling	Crystallization of aluminates and ferrites	1300 - 1240

A typical cement raw meal used as basis for the calculations described in chapter 5 and 6 is found in Table 4. The cement raw meal composition constitutes the chemical properties of interest.

Table. 4. Chemical composition of cement raw meal used for calculations in this study.

Chemical composition	Mass-%
CaCO₃	79,62
SiO₂	13,37
Al₂O₃	3,61
Fe₂O₃	1,73
K₂O	1,02
FeSO₄	0,58
CaCl₂	0,07

2.2.1. CO₂ from the cement manufacturing process

Like many other limestone based processes, cement clinker production includes thermal decomposition of minerals in the limestone followed by the release of gaseous CO₂ to the atmosphere.

The dominant CO₂ emissions from cement production are categorized according to direct and process emissions. For cement clinker production, the direct emissions, or combustion emissions, emerge from the use of carbon carrying fuels used in the kilns and calciners. The process emissions relate to CO₂ emitted from non-combustion processes, here the decomposition (calcination) of carbonate minerals. As described in Table 3.

For clinker production, approximately 62 % are process emissions and 38 % combustion emissions (Schorcht et al. 2013).

Since the combustion emissions vary with the energy consumption, energy efficiency measures will reduce emissions. The production technology influences the energy consumption. With a given raw material, the process emissions are constant with the production volume. Changing the raw material will affect the emissions.

Calcination is the central chemical reaction in the cement clinker process. Alternative calcium sources are sought for and used but their use is limited due to small quantities and the overall chemical composition. Accordingly the use of limestone is foreseen to be the most common feedstock for a very long time. This focuses the agenda to develop efficient and reliable carbon captures technologies together with storage and utilization of the captured CO₂.

2.3. Other CCS/CCU activities in the cement industry

A number of ongoing varying initiatives exist to investigate different possibilities to capture CO₂ from the cement production process and subsequently find solutions avoiding CO₂ being emitted into the atmosphere. They range from more mature solutions close to full-scale implementation to technology concepts at an earlier innovation stage such as CemZero. A non-exhaustive illustration of activities in the industry follows below.

On the mature side; the post-combustion amine-based carbon capture project connected to HeidelbergCement's plant in Brevik, Norway has come closest to full scale CCS-implementation. The project connects to transportation and geologic storage solutions in the North Sea. A decision on full-scale implementation is expected in 2020 with the potential of a full-scale CCS solution in place in 2024.

The European Cement Research Association has investigated the potential of creating gas-tight production by retrofitted solutions in existing facilities in order to enable an oxy-fuel

process with the intention of simplifying carbon capture over the past several years. Calcium looping and the Leilac-project are other concepts of interest and further described in Chapter 4 in this report.

In parallel and complementing CemZero, the Norwegian ELSE-project is also investigating aspects of electrifying cement production.

Geological storage of CO₂ has taken place in the oil- and gas industry for more than a decade. From a technical standpoint, this type of handling is mature. Using this possibility connected to industrial emissions is however not in place at full-scale but seen as a key to manage climate change (IPCC, IEA). The most mature and geographically closest opportunity relating to Swedish industrial emissions is currently being developed in the Northern Light project as a part of CCS-ambitions in Norway. Important and complementary CCU measures connected to the cement industry can be seen at several places, for example, a large scale algae plant being established in Morocco using CO₂ from cement manufacturing as a raw material for the algae photosynthesis. A pilot scale algae CCU-solution has also been tested at Cementa Degerhamn in collaboration with Linné University in Kalmar.

2.4. The Swedish power system

The power system in Sweden is today almost fossil-free and the reliability is, in general, high. Since 2011, there has been an excess of power generation and during the period of 2012 - 2016 the yearly power export has been on average 15.9 TWh (SCB 2017). This represents approximately 10% of the domestic power generation. The power system is however currently under considerable changes. The amount of renewable power generation is increasing whilst nuclear generation is anticipated to be phased out. The main reason for this is the framework agreement on Swedish energy policy which was concluded in 2016 (Regeringskansliet 2016), where one main goal is to achieve 100% of electricity supply in Sweden from renewable power sources by 2040. Also, the agreement aims to ensure that the transaction of the Swedish power system will be robust also in the future, has high security of supply, low environmental impact and competitive prices for electricity. The agreement will increase the current amount of electricity certificates with additional 18 TWh of renewable power generation by 2030. This means that even if some of the nuclear reactors in Oskarshamn and Ringhals are expected to be phased out by approximately 2020, the overall energy balance is foreseen to continue to be robust in Sweden. The average electricity generation each year from 2012 – 2016 for those four reactor in Oskarshamn och Ringhals has been 12 TWh, which corresponds to 20% of the total generation from nuclear in Sweden. Additionally, during 2030-2040 an additional 34 TWh wind and 7 TWh solar are assumed to be added to the power system in Sweden (SVK 2018). Sweden is therefore foreseen to be relatively well adapted to the new energy landscape regarding energy supply. However, the Transmission System Operator (TSO), Svenska kraftnät, which is responsible for the power balance in Sweden, has announced that there will be lack of power during the winter at periods with maximum power demand. Furthermore, it is estimated that the power balance will continue to be deteriorated and the power imports will be requested more often in the coming years. The occasions with local power unbalance in Sweden is also estimated to increase due to insufficient transmission capacity from the northern to the southern part of Sweden, since hydro power cannot be transmitted. Therefore, increasing investments in transmission capacity may partly counteract the negative trend of increasing situations with power unbalance.

2.4.1. The power system on Gotland

The yearly electricity production on Gotland is almost 0.5 TWh and thus accounting for about half of the total electricity consumption, which is about 1 TWh per year. Currently 180 MW of

wind power capacity is installed on Gotland which is approximately the same as the highest load demand on the island. Additionally, installed solar capacity on the island is about 3 MW and also some negligible power capacity comes from hydro power. The vision of the municipality of Gotland is to increase annual wind power generation to 2.5 TWh, corresponding to an increase of approximately 600 MW of installed wind power capacity (Region Gotland 2018). However, in May 2017, the Swedish transmission system operator, Svenska kraftnät, decided to cancel the plan of installing a new high-voltage connection to Gotland (SVK 2017). Based on the decision from Svenska kraftnät to not install a new high-voltage connection to Gotland the Distribution System Operator (DSO) on Gotland concluded that it was no longer possible to increase wind power capacity on the island without jeopardizing the security of supply (SVT 2017).

Increasing renewable power on Gotland by 600 MW does not only require additional transmission capacity to the mainland but also the reinforcement of the internal grid on the island. Today the internal grid on Gotland consists of cables and overhead line with the highest voltage of 70 kV. To be able to cope with the vision of comprehensive growth of wind power capacity on Gotland the voltage level needs to be increased to for example 130 kV (Johansson and Gadea 2018). An investigation of the estimated future power import and export is shown in chapter 7.

Today, Cementsa has production sites in Slite, Skövde and Degerhamn. Slite, on the island of Gotland in the Baltic Sea, is by far the largest cement plant which produces the majority of the Swedish domestic cement demand and all of Cementsa's production that is exported. Thus, when looking into the possibilities on electrifying Cementsa's process, the Slite plant is prioritized. Therefore, this study will set up a number of scenarios showing the dependencies between production/consumption and the need for additional transmission capacity from Gotland to the mainland of Sweden.

3. CemZero

3.1. Pre-feasibility study

During 2016, Cementa emitted 2,5 Mt of carbon dioxide. One third of these emissions come from fuels and could thereby potentially be reduced to zero if the process were to be fully electrified. However, there are still many uncertainties regarding how an electrified cement making process could work.

An electrification of the cement making process in total or in parts will reduce the demand of fossil fuels and thereby concentrate the CO₂ coming from the process, which makes it more suitable for, amongst other things, carbon capture.

As prerequisites, it is assumed that the electricity in the future is 100% fossil free.

Cementa and Vattenfall have started the joint project CemZero with the aim to electrify the cement production process and have studied the feasibilities during 2018. This report summarizes the study. The results have been compiled through literature studies, collaboration with universities, discussions with manufacturers and suppliers of potential technologies, on-site study visits at production facilities, laboratory tests and theoretical calculations.

3.1.1. Studies within the project

The following studies were performed during the project:

I). Mapping of technologies:

There is limited information available on how an electrified cement making process could look. Hence, the project started with performing a mapping of heat transfer technologies and reactor designs to support such a process. The study does not claim to have identified all potential technologies.

II). Conceptual design:

The most promising technologies and concepts were studied further and analyzed in more detail. Description and process designs, heat transfer, mass and energy balance, cost analysis and analysis of product properties are covered in this section.

III). Power supply:

This section highlights the consequences and possibilities of introducing an electrified cement making process in a future 100% fossil free and renewable power system in Sweden and on the island of Gotland.

IV). Cost and sensitivity analysis:

Cost analysis of the most promising concept and a cost comparison of one of the most developed carbon capture technologies. Sensitivity analyses were performed to highlight the impact of, for example, prices and efficiency.

V). CemZero road map:

Present a road map of CemZero defining a transition plan towards full conversion to an electrified cement production.

3.2. Specific considerations for cement production

For the classical process of cement manufacturing, there are some demands and limitations that have to be addressed. In this report, the focus is on clinker production.

The raw material is a mix of natural material as limestone and sand and rest material with alumina and iron. All of this material has impurities as trace elements, chlorides, sulphur etc. that can affect the process and the quality of the product. This means that the design must handle vaporization, circulations and variations of these impurities which also include the balance of oxidation and reduction of different elements. At the same time, the calcinations and mineralization of the clinker have to be separated. If the calcination of the raw material goes too far in the cyclone tower the risk of clogging will be high. If there is too much non-calcinated material left in the kiln, the clinker formation needs to be stressed and the required heat will increase.

As has been described, the clinker process is a stepwise process where the material meets the hot gas from the kiln outlet to minimize the heat consumption. To optimize the process, some process parameters are controlled and examples are given in the Table 5.

Table 5 gives example of process parameters that are controlled to optimize the clinker production.

Parameter	Unit	Comment
Feeding rate	t/h	Always maximal
Fan speed	rpm	Limited to the maximal under pressure
Fuel	t/h	Regulated by target values on the product
Kiln speed	rpm	Regulated by target values on the product and the filling degree of the kiln
Burner		Designed to be controlled in several ways to give the best flame depending of fuel mix
Cooler		Air fans the can be controlled independent of itch other to get the best heat recover and product quality

The clinker that exits from the kiln have a temperature around 1450°C and are instable and will decompose if it is not cooled down to under 800°C. The cooler should cool down the clinker, and at same time, produce high temperature combustion air to the main burner. The rest of the recovered heat from the clinker goes via the tertiary duct to the calciner burner and to the coal mill. The waste heat goes to the filter or in some plants through a boiler for further heat recovery before the cooler.

4. Chemical aspects related to electrification

Some major changes are to be addressed when electrifying cement production. These include practical aspects of production, changed chemical atmospheres in the process steps and new demands related to efficient carbon capture.

4.1. Replacement of conventional fuels

The replacement of conventional and alternative fuels will lead to several changes, both practical and chemical. The handling of fuels will be excluded, leading to less process equipment utilization and manpower, no extraction of fuels, either fossil or alternative. This means further that no ash from fuels will serve as raw material for the production and there will be less input of foreign trace elements derived from fuels in the cement production.

4.2. CO₂ in flue gases

The heat consumed in conventional cement clinker production originates from the combustion of fuels. Combustion needs oxygen and air is used as combustion gas. With the oxygen comes nitrogen as it constitutes 79% of the air. Electrical heating systems based on heating without combustion will give an off-gas composition from the production mainly constituting CO₂. This will give technical and economic advantages for carbon capture. Theoretical calculations of gas composition and volume for non-combustion and combustion with coal are shown in Figure 4. Depending on chemical composition of the raw meal as well as the fuel used; the exhaust gas composition is formed. 1 kg of a typical cement raw meal was used as input for the calculations. Calculations were made with FactSage 7.2 (Bale et al. 2016).

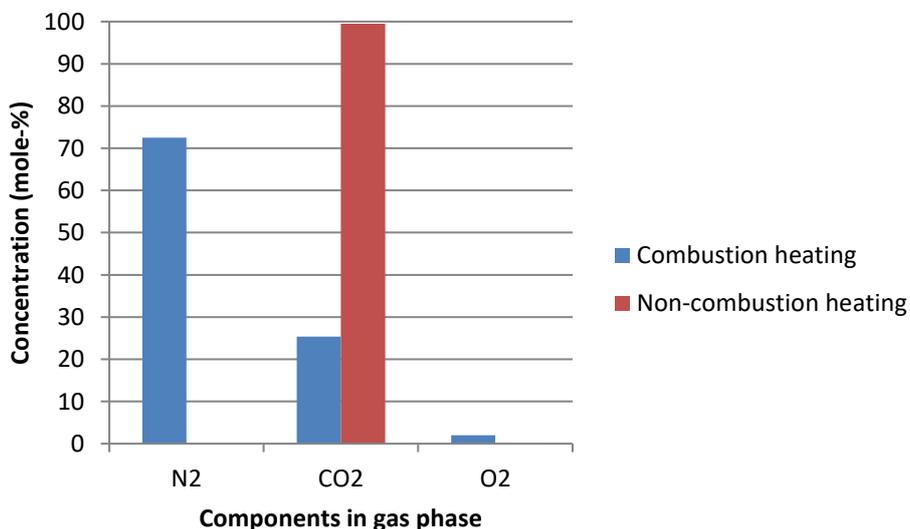


Figure 4. Concentration of gas phase composition from heating a typical cement raw meal with and without combustion with coal.

As shown in Figure 4, the concentrations of the off-gas from non-combustion compared to combustion off-gas are different. The concentration of CO₂ with combustion heating is 25,3 mole-% and without combustion heating is 99,5 mole-%. Calculating gas volumes from coal combustion to heating with non-combustion technology indicate that the volume decreased by more than 70%.

4.3. Heating and cooling in CO₂ rich atmospheres

A change in atmosphere from approximately 25 to close to 100 mole-% CO₂ may influence the chemistry in the process, from heating of raw material, calcination, clinkering and further to cooling.

The aspects of increased calcination temperature due to increased CO₂ partial pressure have been examined and are described elsewhere. Other issues of importance are; how volatile elements are affected, with related accumulation phenomenon, reactivity of middle products and final product, etc.

Some laboratory testing have been conducted with various CO₂-concentration in the gas phase during burning and cooling related to oxy-fuel combustion (ECRA 2012). No changes in mineral phases due to changed atmosphere were determined.

4.4. Gas tight production

Of utmost importance is to achieve a high concentration of CO₂ in the exhaust gases, therefore, it is essential that production is gas tight so that no dilution of the gas composition will occur. Process equipment will need to be re-designed to cope with the new demands, in particular handling intake of material, the linings at the inlet and outlet of the rotary kiln and the clinker cooler, provided that this equipment will be used in the future.

In other applications, like oxy-fuel combustion, the demand is similar. In the CEMCAP-project, a clinker cooler has been tested under oxy-fuel conditions through a prototype oxy-fuel cooler (Rugstad Knudsen, Ruppertand and Hoenig 2018).

5. Results from mapping of technologies possibly supporting an electrified cement production process

The mapping of heat transfer technologies to support an electrified cement making process has resulted in several possibilities. Both single heat transfer technologies as well as concepts for the whole process are described below.

5.1. Heat transfer technologies

5.1.1. Plasma

Plasma is a fundamental state of matter that occurs when a gas is heated sufficient to form an ionized gas. Plasma is a mixture of electrons, ions and neutral particles and is the fourth aggregation state a material may have. Others are solid, liquid and gaseous. In industrial applications, mainly two different types of plasma are used; "thermal plasma" and "non-equilibrium plasma".

Thermal plasma is typically generated in a plasma generator. In an AC/DC current plasma generator, electrons accelerate between two electrodes, anode/cathode, to the extent that an electric arc occurs, which in turn heat up the carrier gas so that plasma is formed. Mostly DC is used since the plasma torch tends to be more stable and easier to control than with AC.

There are two types of plasma generators; non-transferred and transferred. The difference is that in a non-transferred generator, the anode and cathode are placed inside the housing of the generator and are water cooled, whereas in a transferred generator, one electrode is placed outside the housing.

Examples of application where plasma technology are used is in the destruction of ozone depleting substances, complete degradation of organics in process gases, recycling of dusts collected in dust filters, and recycling of fly ash generated by waste incineration.

ScanArc Plasma Technologies AB is a Swedish company offering solutions for high temperature metallurgical processes based on the plasma technology mainly for extraction of valuables from industrial and hazardous waste.

ScanArc develops DC current non-transferred plasma generators mainly with tubular copper electrodes generating an arc which effectively heat the plasma gas to temperatures ranging between 3000-5000 °C. The construction has no moving parts or segments which make it easy to maintain, see Figure 5. Approximate 3 bars pressure drop in the generator and the velocity is very high, near sound velocity.

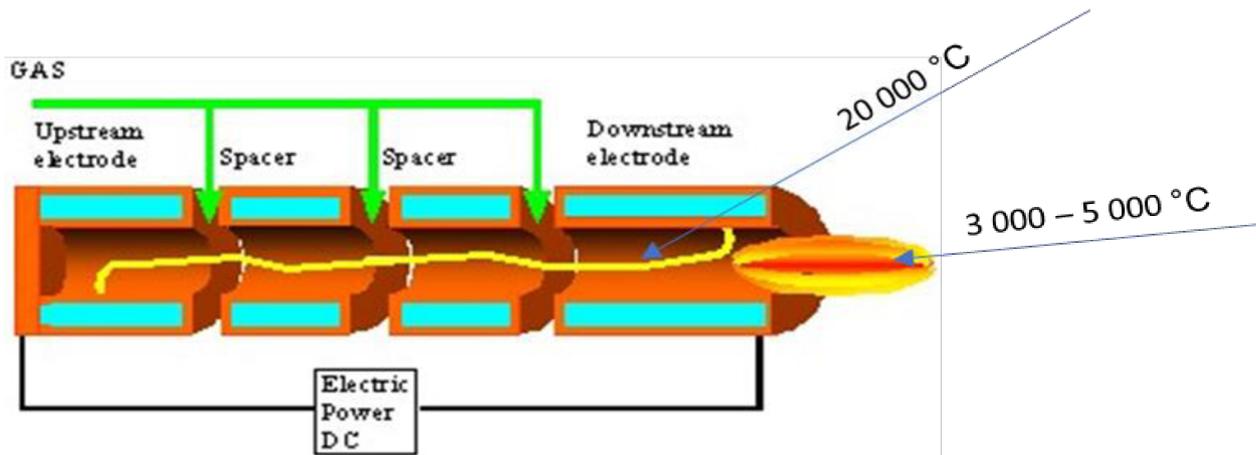


Figure 5. Design of a ScanArc plasma generator.

There are no larger commercial plasma generators than 7 MW that we know of today on the market. There has been tests conducted with significant larger generators but results showing among others abnormal wearing of the electrodes. However, it is fully possible to have multiple plasma generators operating in parallel to fulfill the power needed for the application. The efficiency varies with enthalpy in the gas, i.e. with increased power the more cooling is needed and the efficiency declines. If the generator is operated at too low temperatures, the gas loses its plasma properties. Typical efficiency is between 85-90%.

The relatively small gap (~1mm) between the electrodes makes it more sensitive for dusty environments. This typically means that the continuous operating time is about 200-300 hours before maintenance is required. The overall lifespan of an electrode is about 700 operating hours. Typically redundant systems are offered, which means that in a continuous process a switch of plasma generators is done in minutes when maintenance is needed.

A typical plasma system consists of the following components:

Electric power:

For torches > 1 MW a medium voltage distribution with one dedicated circuit breaker for each torch.

Power converter:

A power converter that transforms the medium voltage to a regulated DC current is needed to operate the torch. An inductor connected in series with the torch is required to further stabilize the current inside the electric arc.

There are mainly two converter topologies; thyristor rectifier and chopper rectifier.

Starting system:

A starting system is required to initialize the electric arc. There are two methods that can be used stand alone or in combination; electric starter and gas starter.

Cooling system:

The plasma torch requires water cooling to keep the electrodes from overheating. A closed loop cooling system with clean, low conductive water is required to minimize galvanic corrosion and stray currents in the water channels.

Gas distribution system:

The gas distribution system consists of flow meters and control valves to control the flow of gas through the plasma torch. A stable pressure from the gas supply and a precise and consistent flow regulation gives a precise and consistent power output from the torch. The pressure drop over the plasma torch is about 3 bars at maximum power.

Recommended properties of the gas are;

Temperature	10 - 60 °C
Supply pressure	4 - 8 bar (g)
Humidity	0 - 30 % RH

Particle size 0 - 0.1 mm
Particle density 0 - 1 g/nm³

From a process point of view the use of CO₂ as a plasma gas has many advantages, such as being chemically compatible with the cement process and eliminating formation of NO_x without addition of hydrocarbons. Therefore, the project together with ScanArc has conducted laboratory tests in ScanArc laboratory in Hofors on using CO₂ as a plasma gas.

The results are very positive indicating uplift in almost each parameter in comparison with air as a plasma gas. Power output is increased by megawatts, not changing the maximum 2 kA. Wearing of the electrodes is potential lower and thermal efficiency of CO₂ is higher than for air. When using air as carrier gas in the plasma generator, thermal NO_x is generated. The amount of NO_x needs to be on a minimum level. Therefore, tests measuring NO_x with various amounts of air in CO₂ as a carrier gas as well as at different power outputs have been conducted and will be evaluated.

Tests with a plasma generator of 300 kW were conducted to evaluate if it is possible to produce cement clinker of regular quality with plasma gas as heating source, see laboratory configuration in Figure 6.



Figure 6. Test configuration of plasma generator from ScanArc together with rotary batch kiln from Cements Research.

The process efficiency regarding energy usage was not possible to evaluate. The carrier gas was air. Cement raw nodules were heated to reach cement clinker quality. Samples were analyzed by XRD and XRF and compared to industrial used clinker, see Table 6 and 7.

Table 6. Clinker minerals analyzed with XRD-Rietveld. Heated with plasma and industrial produced

	Plasma clinker	Reference clinker
C₃S M1	39,4	25,1
C₃S M3	22,0	39,8
C₂S alpha	0,8	-
C₂S beta	12,0	15,0
C₂S gamma	0,2	-
C₃A cubic	4,9	3,2
C₃A orthorombic	0,0	0,7
C₄AF	12,6	11,1
Alphitalit	0,0	0,7
Arcanit	0,3	0,9
Ca-Langbeinit	0,0	0,3
Quarts, SiO₂	0,0	0,0
Periklas, MgO	2,4	1,5
Free lime, CaO	5,2	1,6
Portlandite	0,1	0,0
Anhydrite	0,0	-

Table 7. Clinker minerals analyzed with XRF. Heated with plasma and industrial produced.

	Plasma clinker	Industrial clinker
CaO	66,7	65,2
SiO₂	19,8	20,7
Fe₂O₃	3,1	3,1
Al₂O₃	4,8	5,1
MgO	3,1	3,3
SO₃	0,1	0,9
K₂O	0,0	0,9
Na₂O	0,1	0,2
Cl	0,0	0,0
LSF	105,5	98,8
SR	2,51	2,5
AR	1,57	1,6
DoS	-	108,9
Liquid phase	-	26,9

Retention time during the test was long resulting in alkali and sulphur had been vaporized. This is found in XRD results when compared with industrial clinker. Cubic C₃A is formed but no orthorhombic (Na-stabilized) is formed due to lesser alkali and sulphur contents.

LSF is high due to non-optimized raw meal composition. No quartz is present in the clinker which is positive and a proof of that the predicted chemical reactions have taken place.

Content of free lime decreased during the course of heating with plasma gas, as seen in Figure 7, which proves that chemical reactions have taken place. In Figure 8, the heated raw meal nodules are shown at various temperatures.

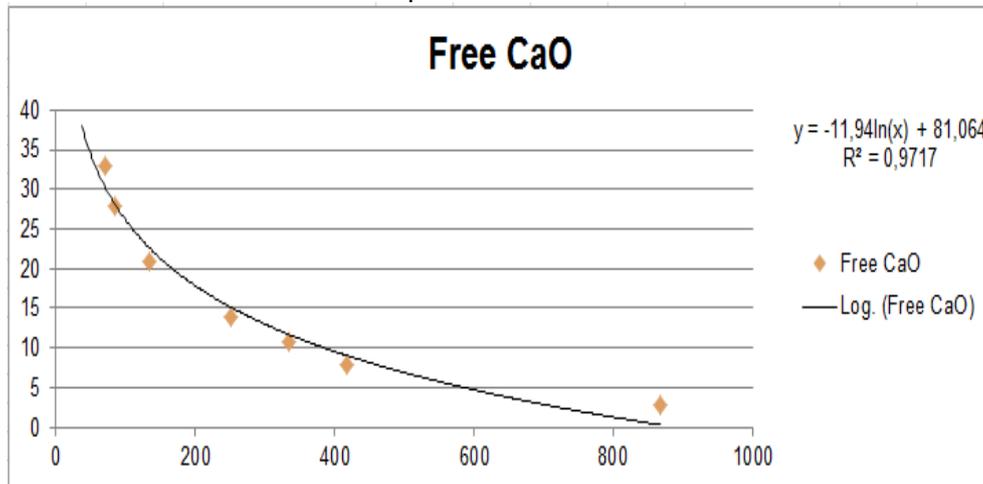


Figure 7. Amount of free lime (% CaO) analyzed in samples during heating versus energy (kWh).



Figure 8. The heated raw meal nodules shown at various temperatures.

A deeper understanding on the effects of the plasma heat source on heat transfer in the rotary kiln has been started together with Chalmers. One of the major concerns is how the heat transfer in the kiln will be maintained. When the pulverized fuel flame is replaced by the hot gas stream, the substantial amount of radiation from the fuel and ash particles are omitted, which should be made up for by gas radiation from either air or CO₂, both with varying degrees of dissociation depending on the operation of the plasma torch. The radiative heat transfer to the clinker bed would obviously be affected, and the impact must be quantified to ensure the product quality. More specifically the following specific topics will be considered in relation to the change of heat source; 1). Rate of heat transfer to clinker bed, primarily in the burning zone, 2). Design and operational parameters for controlling the net heat flux from a hot plasma gas to the clinker bed, and 3). NO formation.

5.1.2. Electrical flow heaters

Electrical flow heaters are available from several manufacturers. Detailed designs differ but they all have in common that heat is generated by running a current through a resistive element, which usually is protected by a shroud, and transferred to a gas flow through high-velocity convection. Maximum gas outlet temperatures of 1100–1200°C are quoted, which

make electrical flow heaters a potential heat source for calcination. To look closer into this, the company NyCast was commissioned to perform an evaluation of the possible use of their equipment in a calcination process. In CemZero a gas heater based on a patent were examined. The patent describes heating of a compressed gas (Olsson 2018).

5.1.3. Microwave heating

Microwave energy is possible to use for heating of material due to the unique way it interacts with materials. The property of the material, its dielectric constants, which is the electronic structure, decides if energy absorption is successful. The electronic structure of a material is phase specific. A cement raw meal during heating undergoes numerous phase changes including different polymorphs of each phase see for example (Hewlett 2003).

Early trials with using microwaves for producing cement clinker were made more than 35 years ago. The quality of the microwave produced cement clinker were similar to the laboratory made ditto (Quéméneur et al. 1983). Even so no realization of industrial scale system for pyro-processing of cement clinker production is available today.

Production of ordinary Portland cement with microwaves was done reducing the clinkering temperature with 100°C. The improvement was due to the iron content in the material. The cement clinker phases formed were as expected (Fang, Roy and Roy 1996).

Test on laboratory scale were conducted in a microwave furnace operating at 2.45 GHz with 900 W at 1150°C. Due to the too low maximum temperature of the microwave furnace, an electric furnace was used to reach higher temperatures needed for the cement clinker minerals to form. With this two-step approach a cement clinker of proven quality was produced. It was also found that the maximum temperature could be reduced by at least 100°C (Kaewwichit et al. 2017).

Another test in small scale used electrical heating to reach 1000-1100°C of the material and then put the sample in a microwave furnace (700 W, 2.45 GHz with power density of 30 kW/m³). Cement clinker of expected quality was formed. It was noted that using Fe₂O₃ in the material mix increased the microwave absorption efficiency (Long, Yan and Dong 2002). Little or no work has been undertaken on how the changing composition of the cement raw meal during heating changes the microwave absorption efficiency, i.e. its dielectric properties (Buttress, Jones and Kingman 2015).

Besides dielectric material properties of due importance for efficient heating with microwaves are material bulk density, microwave effect, wavelength and consequently frequency and the geometry and the cavity of the process equipment. Microwave heating described in literature have used microwaves of 2,45 GHz, with a few exception. Due to national legislation, a certain frequency is allowed, the ISM band in Sweden, controlled by PTS (Post och Telestyrelsen) is 2,45 GHz.

A combination of radiant heating together with microwave energy for production of lime has been shown through lab-scale tests to together with dielectric measurements to have advantages. Three limestone of exceeding impurity grade were tested. The impurity in lime production is similar to components other than calcium carbonates like silica, alumina and iron oxides, which for cement production is essential. The size of the tested limestone was larger than cement raw meal. With increased impurity rate and above 800°C the microwave absorption were found to be good. The enhance reaction rate is found to give reduced energy consumption with more than 15% (Fall et al. 2011).

Cement production is done in large scale applications, 200 tonnes/hour feed of raw material is common. The magnitude of the material flow is a challenge, hence the needed power

density. (Buttress et al. 2017) have designed a scalable pilot for processing ore of 150 tonnes/hour throughput in continuous mode.

The main challenges are connected to the high process temperature and especially the high volume flow required which calls for a high number of microwave energy sources. At relatively low temperatures, the material microwave absorption properties are low, which has been shown to be possible to counteract using the magnetic material of magnetite. The calcination stage appears most promising overall, but also the most energy consuming. A microwave application system needs to be carefully designed with respect to the high power and not least geometry optimization. The same is true for the last heating process step, where clinker is formed while simultaneously heating and stirring the material, with the additional challenge of a more complex microwave containment arrangement due to the size and variability of clinker lumps. Use of the lower ISM band around 915 MHz has very interesting potential in that higher power microwave sources are available than for the more common 2,45 GHz band. The lower frequency band is not generally allowed in Europe (would need special permission), and the experience with it is limited even if the theoretical base is the same.

A study within CemZero done by Combitech and Radarbolaget has given some interesting results and pointed at both opportunities and challenges, a lot more application knowledge needs to be gathered:

- Designing and building a pilot unit(s). So far, all studies are theoretical or performed in small scale laboratory circumstances. A still relatively small, but closer-to-reality scale application where material is actually being processed, will validate the conclusions and give valuable experience and learnings applicable for a later scaled-up implementation. In the design of such unit(s), SBD (Simulation Based Design) will be used to optimize the heating chamber dimensions for best uniformity and efficiency as well as minimize cross-talk between microwave feeding points.

Refinement of measurements of dielectric properties at elevated temperatures. This would serve as enhanced input to the optimization mentioned above.

- Combining microwave heating with another electrically powered heat source. This can bring the best value from two or more heat sources, one volumetric (the microwaves) and one surface heating. Number of microwave sources can be reduced. Infrared heat or hot air (convective) heat is interesting alternatives and there are various ways to create those heating mechanisms, which may be combined in the mentioned pilot unit. A resistive heater integrated in a material feeder is another idea with potential to address clogging issues.

- Microwave driven plasma is a special case involving a combination of methods. Microwaves can be used to activate plasma remotely and without the need of electrodes. Apart from the plasma generation, the microwaves can and will heat in their own way. Control and stability of plasma location may be the main challenge.

- Microwave containment: The suggested approach with microwave absorbing zones is based on material properties and computer simulation. Yet it is key for a successful implementation. A validation experiment in reasonably full scale (tube diameter > 2 wave lengths) would give valuable knowledge on sensitivity for dimensions and other variable parameters such as material mix and density.

EMC: Electromagnetic Compatibility aspects have not been within the scope of the studies so far, but will have to be addressed in a real application. There are authority regulations on both conducted and radiated emissions potentially causing disturbances in mains cable network and for electronics and wireless communication respectively. In particular, mixing products of microwave sources with similar, but not identical frequencies may become a

challenge. A mapping of applicable EMC regulations and measurements on pilot unit(s) is recommended.

-Sensing: In order to utilize the controllability and thereby energy efficiency of microwave heating, the heating should be monitored and closed loop controlled. Temperature measurement by Infra-red sensing has an interesting potential provided an adequate protection for the harsh environment can be created. Also, the measurements of dielectric properties reveal a potential of monitoring the calcination progress.

-915 MHz microwave frequency. Its longer wavelength as well as material property differences we have seen from the investigations from Radarbolaget influences the optimization of a microwave applicator. Also the microwave containment design needs to be different. The availability of microwave energy sources contributes to the interest in building a deeper understanding of its implementation aspects.

-Microwave absorption enhancement by recipe/mix manipulation. This is most interesting in the first process step of pre-heating. The possibility of using magnetite has been shown. Optimization with respect to mix proportion and final product quality influence as well as how the mixing influences the following process steps.

5.1.4. Resistive electrical heating

Another electro-thermal heating processes is the use of electric resistance heating. Heating with resistance in an electric circuit is well-known and is effective providing high theoretically efficiency. Electric resistive heaters could be applied for calcining with no demand on extra gas for energy transfer. Indirect heating is normally applied with heating elements and the heat transfer to the material will be through radiation, conduction and convection. These type of kilns and furnaces are used for both batch and continuously production.

To achieve enough heat, large areas are needed and there are challenges with material managing the high temperatures needed. There are on the market metallic heating elements that can stand temperatures up to 1425°C, and non-metallic molybdenum disilicide (MoSi₂) heating elements for temperatures up to 1850°C. (<https://www.kanthal.com>).

Advantages with resistance heating are:

- Well known technology with products on the market
- No need for CO₂ recycling as heat transfer medium
- Energy losses are low in the power supply and heat generating system

Disadvantages with resistance heating are:

- Due to the temperature limitations and the high temperature when calcination takes place, very large heat transfer areas will be required.
- The high required temperatures for clinker formation set limits for this technology, to be used only for calcination.
- There could be risk for material build ups on the system that insulate and reduce efficiency.

5.1.5. Induction heating

To investigate the possibility to use induction as heating technology for raw material a test was performed together with Nycast. The test equipment is found at Swerea MEFOS and is an 90 kW high frequency induction furnace.

The furnace was filled with about 25 kg raw material. The energy supply was 19.8 kWh during 3 hours which resulted in a temperature rise of 100°C. In fact this means that induction have no effect on the raw material.

To evaluate if indirect heating could be an alternative way to use induction a second trial was conducted with the same sample as the first one but with a graphite element in the center of the meal. The result was little better but far from good. The temperature rise was 550°C close to the graphite element and 350°C in the middle between the wall and the graphite element.

The conclusion was that induction has very little effect on raw meal. The heating efficiency was around 18 % with indirect induction and less with direct induction. Consequently, direct induction it is not a technology to be used in this project.

5.1.6. Hydrogen combustion

Providing the heat for the cement production process through combustion of hydrogen generated through electrolysis of water may be considered as an electrification of the production process. Hydrogen as a fuel is characterized by very wide flammability limits, high burning velocity and a quite high adiabatic flame temperature (Goodger 1982). Combustion of gaseous fuel mixtures with very high hydrogen content, e.g. refinery gases, for heat (and power) generation is well-known, but the application of hydrogen as a fuel in a cement plant would require extensive testing and, most probably, modifications of kilns and the clinker burning process. The challenges related to the use of hydrogen as a main fuel in the kiln are quite thoroughly described in (ECRA 2007). Foremost of these are handling problems (e.g. risk of explosion), effects on heat transfer (temperature profile inside kiln, radiative characteristics) and possible impact on product quality.

5.2. Process layouts

5.2.1. Conventional preheater, pre-calciner and a rotary kiln

Cement plants have during the last 100 years evolved from a wet process for raw material feed, to semi-wet, semi-dry and now most plants are complete dry process. Kiln systems with five stage preheater cyclones and pre-calciner are considered standard technology for today's modern plants. Typical clinker capacities start from around 3000t/d and the largest installations are up to 12000t/d.

Before the raw material enters the system it is ground and dried with exhaust gas from the kiln in a combined drying and grinding plant to reduce the moisture content to below 1%. The blended and homogenized raw mix is then fed (see Figure 9) to a gas-suspension preheater ahead of a pre-calciner and a short rotary kiln. These preheater cyclones are arranged above one-another in series in a tower. During the 40-60 seconds the raw meal transfer in the 5 stages the temperature increase from around 60°C to 820-860°C. The large specific surface of the meal is enough to reduce flow gas temperature from 1100°C to around 350°C after the cyclones. Partial calcination of the raw meal takes place prior to the mix entering the pre-calciner where a (secondary) firing unit is placed. In the pre-calciner the aim is to calcine most of the raw mix (normally 92-95%) before it enters the rotary kiln. Pre-calciners increase total kiln capacity with 2-2,5 times compared to 4-5 stage preheater kiln.

The calcined material enters the rotary kiln in the upper cooler end of the rotating kiln tube which has an inclination of 2-4%. The primary burner is placed in the lower, hot end of the kiln. The inclination and rotation causes the material to move down the kiln from inlet to outlet in counter-current with the combustion gases generated in the primary kiln burner. The kiln is normally divided in inlet zone where final calcination takes place, upper and lower transition zones, burning zone and cooling zone. In the burning zone where the flame is located, the material temperature reaches 1450°C, before it cools down in the cooling zone and enters the clinker cooler, where the material is preferably cooled to around 100°C.

The energy needed for clinker production is distributed between:

- Preheating which takes place in the preheater cyclones
- Calcination which takes place (to 92-95%) in the pre-calciner
- Sintering which takes place in the kiln tube

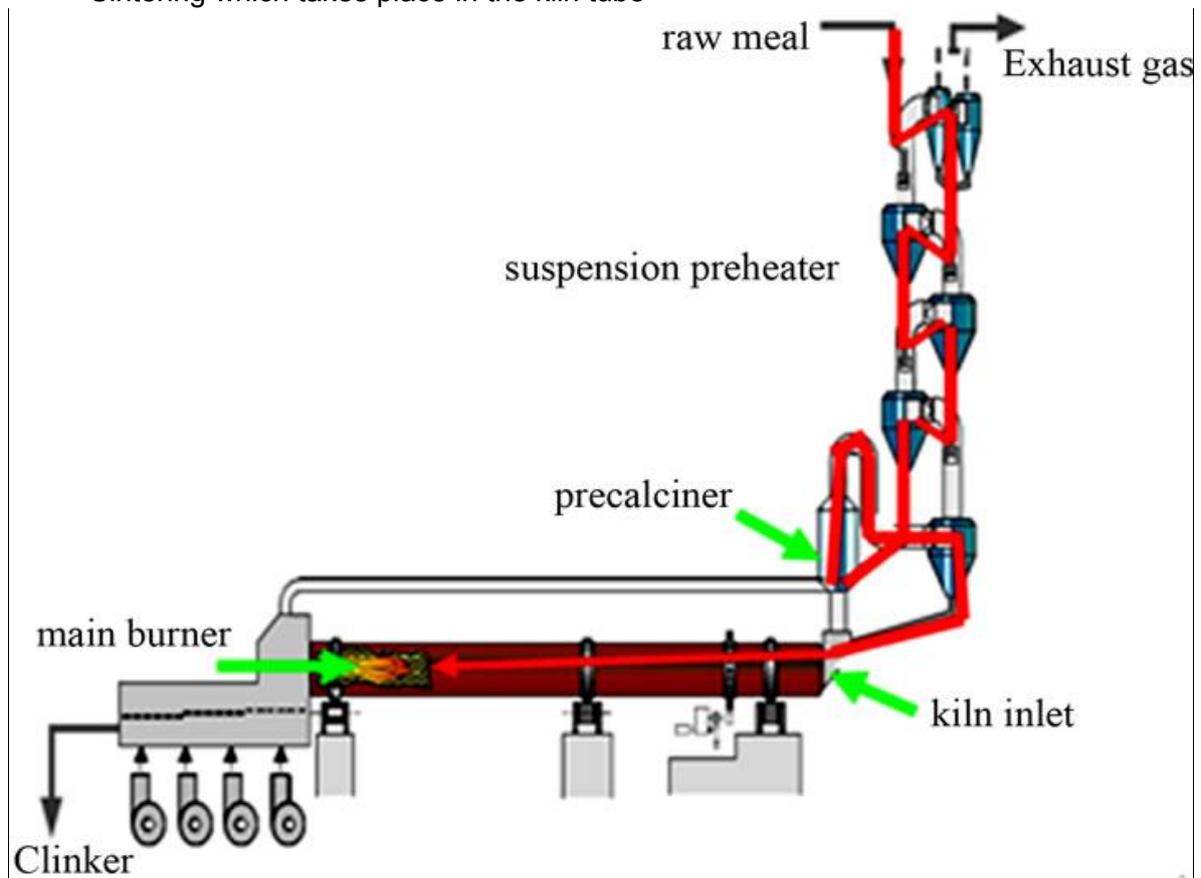


Figure 9: Five stage suspension preheater with pre-calciner (Li et al. 2012).

The pre-calciner and main burner are today combustion burners using ambient air. To use plasma technology for these locations changes the heat transfer situation significantly. The heat transfer medium will be CO_2 and the system must then be gas tight including material inlet and outlet feeding system. The very high temperature ($3000\text{-}5000^\circ\text{C}$) of the CO_2 gas leaving the plasma generator will be necessary to dilute with colder recycled CO_2 in the pre-calciner. If the rotary kiln will be operated in CO_2 condition, the first hot section of the clinker cooler must be operated with CO_2 gas to use secondary hot gas from the cooler.

These kiln systems are conventional technology and have been evaluated for gas tight oxy-fuel operation in various investigations. To minimize investment costs, retrofit of the worlds existing kiln systems is of very high importance. This is why this design and configuration is of high priority in CemZero.

5.2.2. Direct Separation Reactor

During heating of limestone (mainly CaCO_3), solid CaO and gaseous CO_2 is formed. The reaction takes place at approximately 900°C depending on partial pressure of CO_2 in surrounding atmosphere. A direct separation reactor (DSR) uses gravitational forces to separate solid phases from gas phase whilst heating and promoting the chemical reaction as mentioned above.

Within the Leilac project (Low Emissions Intensity Lime & Cement) a reactor for CO_2 separation from limestone or cement raw meal is under construction. The construction will be finalized in April 2019. The pilot plant will handle 8 tonnes/hour of limestone feed or 10

tonnes/hour of cement raw meal. A principal layout of the reactor in the Leilac project consists mainly of a high vertical steel tube, see Figure 10 (Leilac 2017).

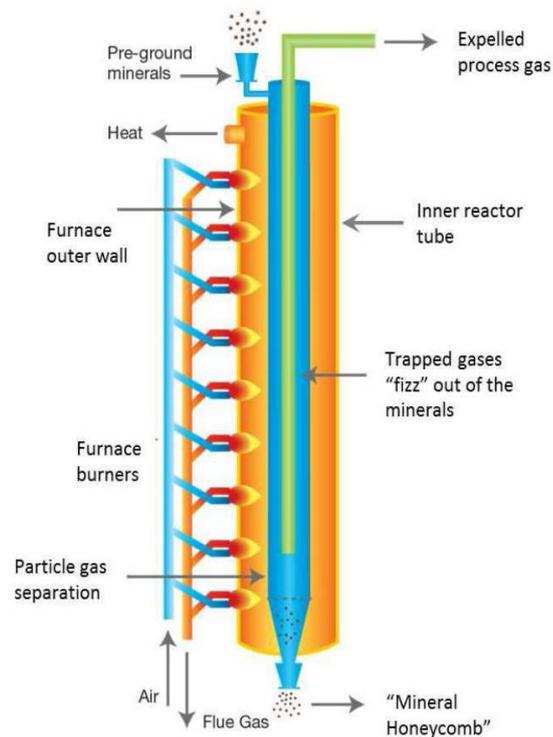


Figure 10. Principal layout of a direct separation reactor used in the Leilac project.

The technical ideas derive and are thus proven from production of magnesium oxide out of magnesium carbonate done by Calix Ltd in Australia. The purpose of the plant is to produce magnesium oxide with nano-active properties. Heating is done with natural gas on the outer wall of the furnace shell. The plant shows that it is technical possible to separate CO₂ from calcination of magnesium carbonate.

Applying this technology to cement production with the aim of using electricity would be possible with using electrical resistive elements for heating the cement raw material instead of combustion of natural gas. The final heating above calcination temperature would need an additional step though. The calcination temperature for magnesium carbonate is approximately 400°C lower than for calcium carbonate, see Figure 11. This will be a challenge to handle as well as the high feed rate of raw meal for cement clinker compared to magnesium oxide production. With high steel tubes and large number of tubes the capacity can be increased.

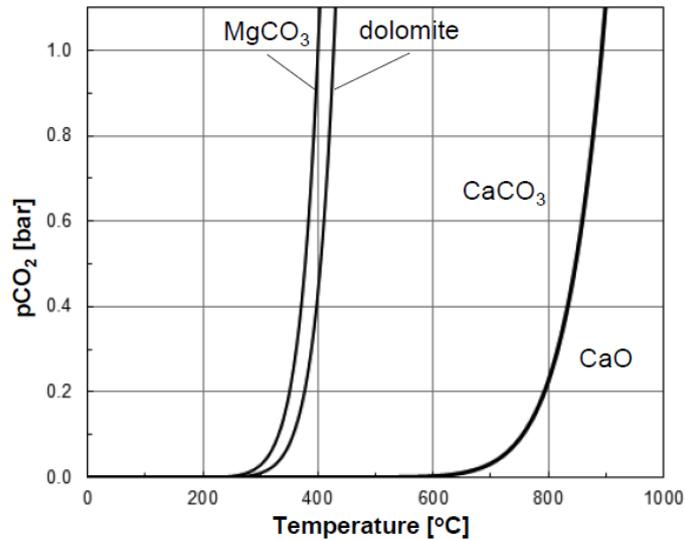


Figure 11. Dependence on the partial pressure of CO₂ on calcination temperature for carbonates (Bale et al. 2016).

5.2.3. Shaft kilns

Reactor technologies widely used for lime production are shaft kilns. The main objective of the kiln is to calcine the limestone to produce lime. A shaft kiln is compared to a rotary kiln more energy efficient. For typical lime production in a shaft kiln the thermal energy consumption is 3,2-4,2 GJ/tonne (parallel flow regenerative kilns) to 5,1-7,8 GJ/tonne for rotary kilns with preheater. A typical shaft kiln is shown in Figure 12.

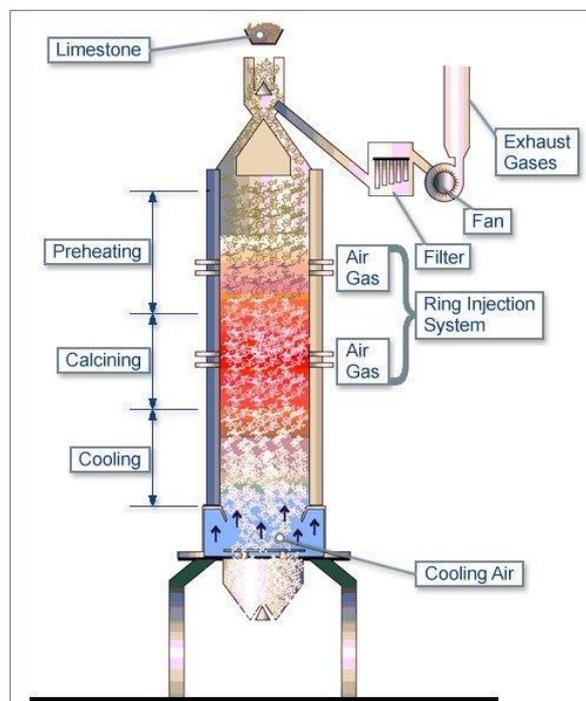


Figure 12. Typical lay-out of a lime shaft kiln (Schorcht et al. 2013).

For applying a shaft kiln to cement production the cooling part of the shaft is possibly excluded. Shaft kilns can burn stone from a minimum of 20 mm diameter up to 175 mm. Shaft kilns, due to their energy efficient production could be used in cement production for calcination if;

- gas tight shaft kilns are possible
- heating with plasma, microwaves, electrical resistive heating, etc is possible
- possible include CO₂-recirculation

Additional shaft kilns could be used for production of cement clinker if;

- feeding of kiln is raw material nodules
- raw meal nodules withstand the physical attrition
- re-carbonation of clinker minerals is minimized

Although today shaft kilns are used for cement production with traditional fuels in for example India and China with low capacity and lower quality cement (GHG 2008).

5.2.4. Fluidized beds

A fluidized bed is a special case of a solid bed/gas system with where the gas is blown through the bed from below with a flow rate enough to cause the bed to fluidize, i.e. the bulk volume of the particle bed increases from the volume of the packed bed. At high enough gas velocities the solid particles are entirely transported out in the upper part of the reactor, see Figure 13.

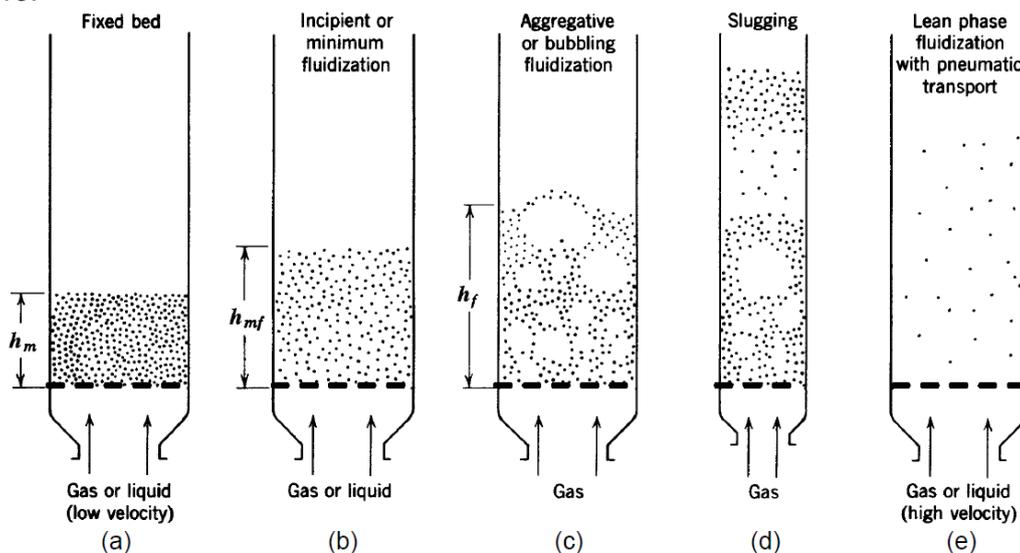


Figure 13. Modes of fluidization.

For combustion purposes, two types of fluidized bed (FB) are used, bubbling and circulating. The gas velocity is lower in a bubbling bed (BFB) and only the smallest particles are transported out of the bed. In a circulating bed (CFB) the gas velocity is higher and most solids are transported out with the gas and are returned to the bed via a cyclone system.

The bed can contain inert bed material in addition to fuel particles and ash, or it can constitute only fuel particles and ash. Coal combustion in FBs usually is done with no inert bed while biomass combustion is done with a bed of sand or other inert or nearly inert materials. Ash has to be removed from the system. Part is removed from the bed and part from filters after the bed. Usually part of the bed material has been removed and is replaced with new material due to risk of agglomeration and de-fluidization.

Usually all combustion air is entered through nozzles in the bottom plate, and the fuel particles is entered just above the dense part of the bed. Several variations of design are used to manage the steam production. Super heaters and other heat exchangers are usually located after the cyclone in CFB, but solutions with heat exchangers in the bed or in the free-board in the upper part are also used.

Fluidized beds are used in several technical applications in a broad range of temperatures and purposes. Aluminum hydroxide calcination is made industrially by fluidized beds and there are applications also for limestone calcination. In addition, concepts for clinker production involving fluidized beds have been suggested. One application is described below any but kind of system analysis is excluded. Merely, the critical parameters from a particle and chemical point of view are discussed.

Today, calcining of CaCO_3 is a part of the Calcium Looping concept to enrich flue gases with CO_2 . It is a two-reactor system with a calciner and a carbonator where free CaO and highly concentrated CO_2 are produced in the calciner. The CaO is used to absorb CO_2 in the carbonator, see Figure 14. The calciner could preferably be a fluidized bed.

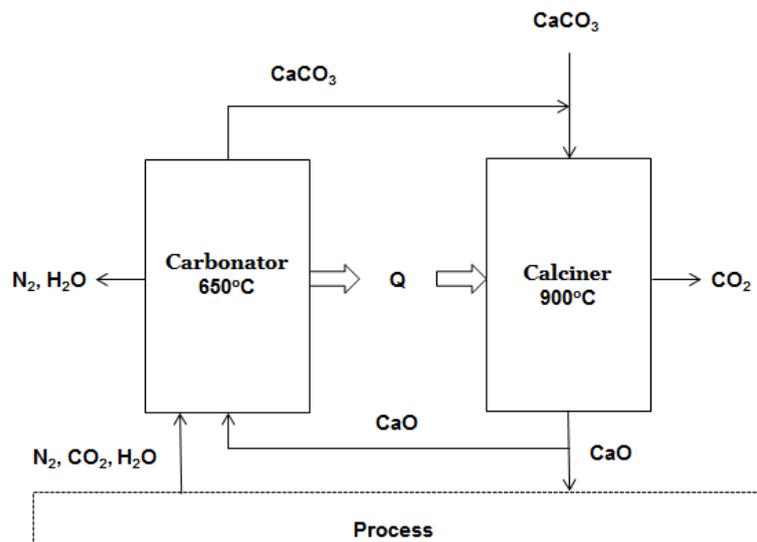


Figure 14. Schematic Ca-looping process

The dynamics and chemistry of the calciner has been extensively studied both in laboratory and in pilot scale. Much useful knowledge is produced in these studies which can be useful for design of a big-scale FB-calciner. A special issue for the Ca-looping concept is that a full carbonization is not needed. Only the outer part of the oxide particle is converted to carbonate, giving a fairly rapid calcination in the calciner. A gradual inactivation of the oxide occurs, mainly due to sintering effects. A dual-bed calcination has been suggested for cement production, see Figure 15. The mass balance for CO_2 and CaO is not fully elaborated in this concept and must be further investigated.

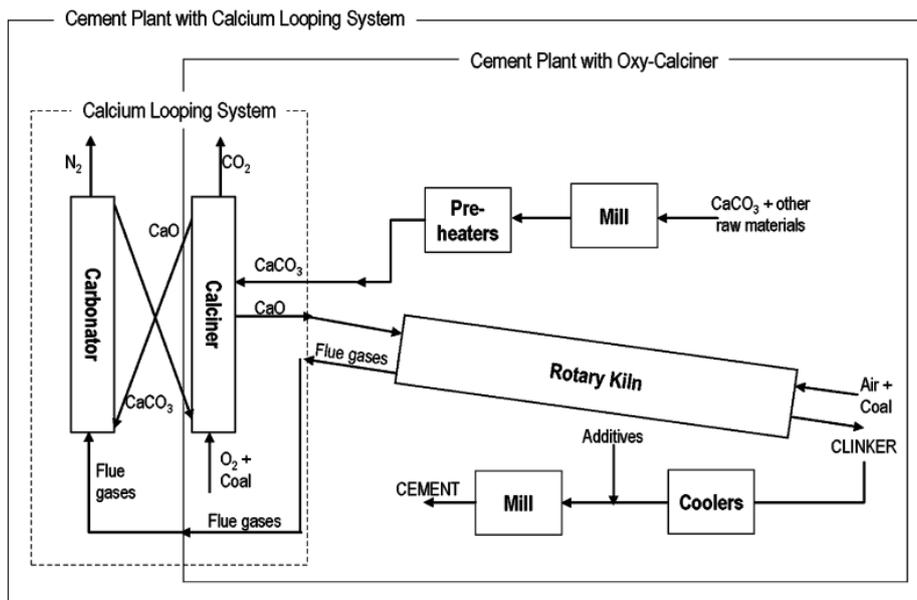


Figure 15. Suggested clinker production with Ca-looping (Rodriguez, Murillo and Abanades 2012).

The key question for FB-calcination for cement production is whether one aims for a partial or full calcination. Particle size is essential for at which calcination level one ends up. The particle size of input limestone must be fairly uniform and not smaller than 10-50 μm . Depending on particle size distribution and calcination rate, a mixture of particles at very different calcination levels will prevail in the bed, at least at a continuous limestone feeding. Thus, it is essential if one should try to separate small particles, which are further calcined than bigger particles. To optimize bed/cyclone/filter performance in this respect is important.

Attrition (particle size reduction) will happen in every bed and it has been shown that different limestone qualities react very different to the mechanical forces in a bed, see Figure 16. Probably there is possibility to find optimal conditions for each limestone. The combined effect of attrition and density changes due to calcination may open ways to develop optimal separation measures.

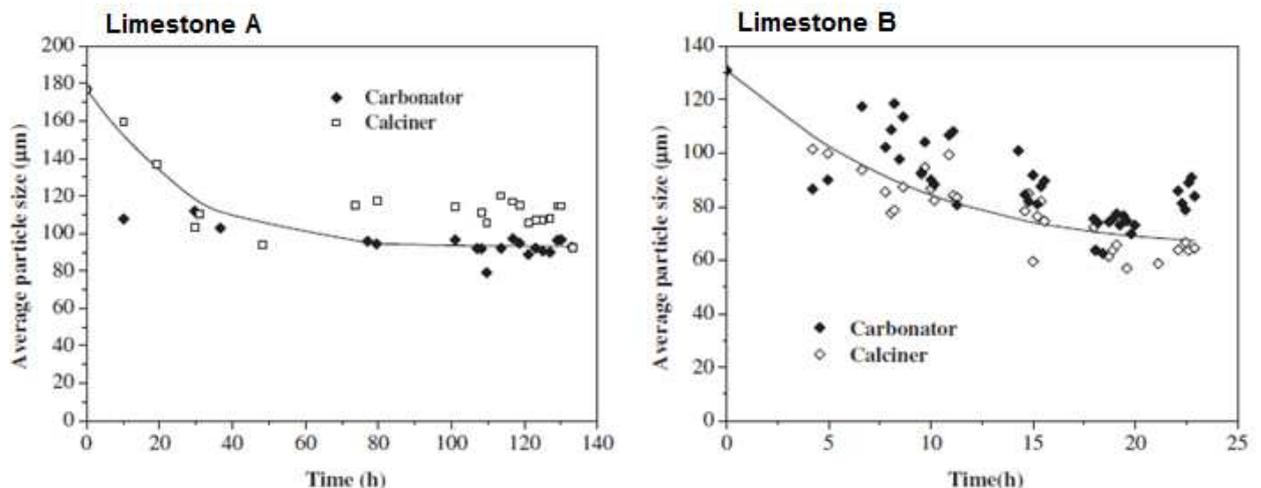


Figure 16. Particle size changes for two limestones in Ca-looping (González, Alonso and Abanades 2010).

There is no final consensus about the rate of calcination of limestone particles. The huge number of rate equations presented differs considerably and it is obvious that limestone quality and impurities affect the rate, as do heating rate and gaseous environment.

Calcination rates measured in laboratory do not always describe the course of events in a relevant way. There are measurements available from fixed beds and particle aggregates where the effect of gas transport has been eliminated. Some trends can be seen from such measurements. Probably the reaction times are shorter in a fluidized bed.

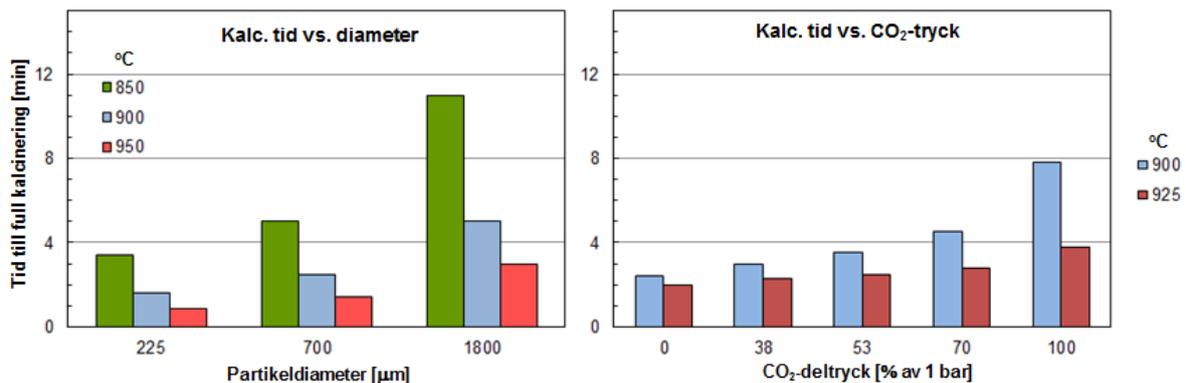


Figure 17. Calcination time vs. particle diameter and CO₂-pressure (Escardino et al. 2012).

It can be seen in Figure 17 that the calcination time is in minutes. The effect of temperature is big, in the order of two times faster at 50°C higher temperature. The effect of particle size is considerable, bigger particles needing more time. This indicates that heat transfer to the particle is important. The CO₂-partial pressure is observable, but not very big, indicating that the CO₂-transport out from the particle is not negligible for the calcination rate.

For a full or pre-calcining in big scale probably both BFB and CFB are good alternatives. BFB has a simpler construction and lower costs than a CFB. On the other hand CFB has more flexibility regarding separation of particles. The gas should be recirculated CO₂ which will give high stability of the operation at 1 bar although a temperature of minimum 950°C is required. Energy demand is minimum 1.4 MWh for 1 ton CaO produced.

Both indirect electrical heating of the wall and heating elements in the bed are possible. Due to good heat transfer and possibilities to adjust both solid/gas ratios as well as total residence time it should be possible to transfer enough heat to the particles for desired conversion. Another alternative is to preheat the CO₂ with plasma or heating elements, or construct a combination of several heating options.

The feature of a fluidized bed with good contact and long residence time between particles opens for a process alternative where quartz sand is added to the bed. It may be possible to produce a layer of belite on the sand particles even at temperatures around 950°C, with no risk for melt formation. Thus a “pre-clinkerisation” could be performed, which would give a precursor to a subsequent alite formation at higher temperature and presence of melt.

The application of using a fluidized bed kiln for cement manufacturing has been evaluated in Japan (Schorcht et al. 2013). The cement sintering technique by means of the fluidised bed cement kiln system has been a project in Japan since 1986. A pilot plant with the capacity of 20 tonnes clinker/day was operational for six years, between 1989 and 1995. A 200 tonnes clinker/day large scale pilot plant was constructed at the end of 1995.

The configuration of the 20 tonnes clinker/day fluidised bed cement kiln system is shown in Figure 18. The system consists of a suspension preheater (SP), a spouted bed granulating kiln (SBK), a fluidised bed sintering kiln (FBK), a fluidised bed quenching cooler (FBK) and a packed bed cooler.

The suspension preheater is a conventional four stage cyclone preheater which preheats and calcines the raw meal. The granulating kiln granulates the raw meal into granules of about 1.5 – 2.5 mm diameter at a temperature of 1300 °C. In the sintering kiln, the sintering of the granules is completed at a temperature of 1400 °C. The fluidised bed quenching cooler quickly cools the cement clinker from 1400 to 1000 °C. Finally, the cement clinker is cooled down to about 100 °C in the packed bed cooler.

The cement clinker produced in the fluidised bed kiln is of the same or better quality as the clinker from a commercial plant. The NO_x emissions are 115 –190 mg/Nm³ when heavy oil is used and 440 –515 mg/Nm³ when pulverised coal is used as fuel (converted to 10 % O₂). According to a feasibility study of a 3 000 tonne clinker/day plant, the heat use can be reduced by 10 –12% compared with a suspension preheater rotary kiln with grate cooler, it is therefore expected that the CO₂ emissions can be reduced by 10 –12%.

The final targets of the technical development of the fluidised bed cement kiln system are (in accordance with the feasibility study on a 3 000 tonne clinker/day plant and based on the results from the 20 tonnes/day pilot plant):

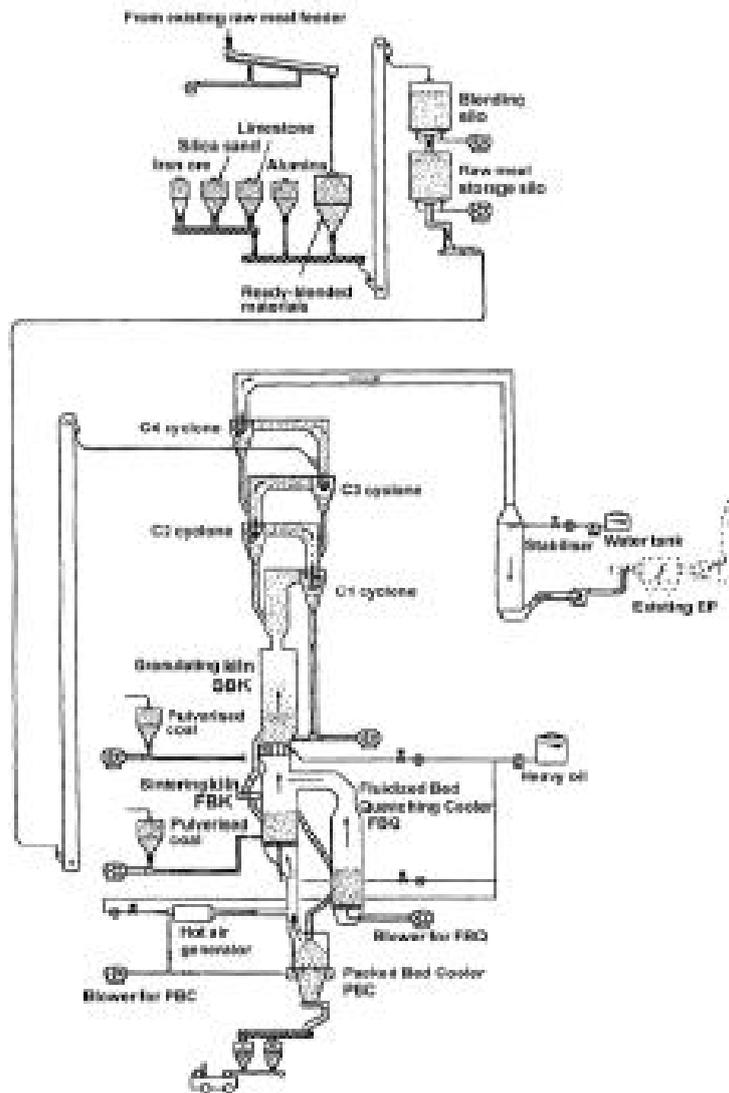


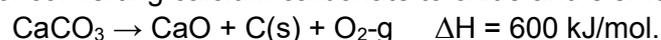
Figure 18. Fluidised bed cement kiln.

5.2.5. Electrolysis via molten salt

Use of electrolysis of a carbonate melt to perform calcination of limestone (STEP CEMENT) has been suggested (Licht et al. 2012) and (Ren et al. 2015). It was found that the carbon precipitated on the cathode was nano-structured (Wu et al. 2016) and (Johnson et al. 2017) and effort has been done to design an industrial scale process for production of nanotubes.

Some process ideas have been presented with the use of electrolysis to produce lime from limestone and simultaneously convert the carbon in carbonate to elemental carbon. It is suggested to use solar based electricity in the system. A system analysis was performed of a complete combined cycle gas plant with integrated molten carbonate electrolysis with nanostructured carbon and electricity as ultimate products and no CO₂-emissions (Lau, Dey and Licht 2016).

The overall reaction of converting calcium carbonate to oxide and elemental carbon is



The energy demand for thermal decomposition of CaCO₃ to CaO and CO₂ is 200 kJ/mol, i.e. two times the energy for calcining must be added to produce elemental carbon.

It is suggested that the electrolysis is made on a carbonate melts with a fairly low melting point. Such mixtures are carbonates of lithium, potassium and sodium which have first melting points between 400 and 700°C, i.e. considerably lower than 900°C needed for thermal decomposition.

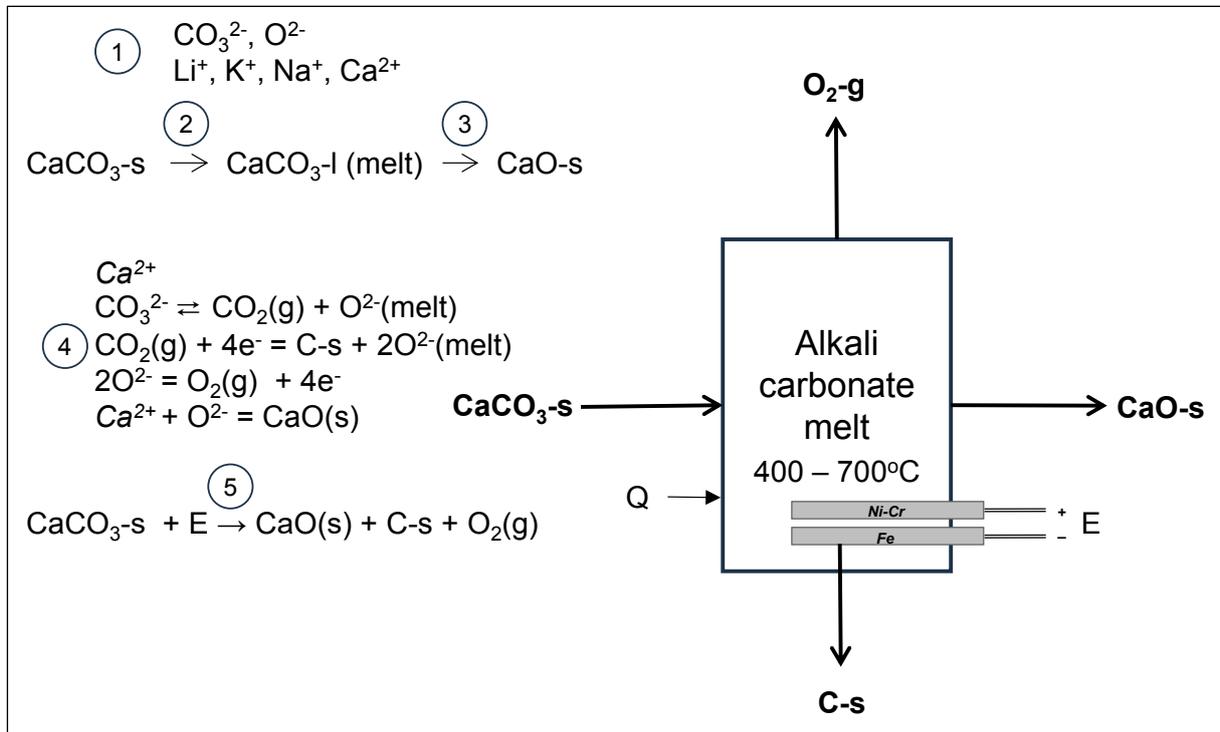


Figure 19. Schematic process of molten carbonate electrolysis.

The overall reaction consists of several steps (Figure 19). It is not clear which steps are kinetically limited.

1. An alkali melt is prepared with low melting point.
2. Solid CaCO_3 is dissolved into the melt.
3. By means of electrolysis, solid CaO is formed and precipitated.
4. The reactions involve (a) equilibrating of carbonate ion and CO_2 (b) splitting of CO_2 to elemental carbon and oxygen (c) precipitation of CaO from melt.
5. The overall reaction needs both electricity (E) and thermal energy to heat melt (Q).

This concept is novel and still far from a realistic process. So far, only laboratory experiments have been made to demonstrate the possible reactions. Chemically this concept is attractive because it makes the calcination reaction possible at lower temperatures which as such are beneficial. On the other hand, the electricity demand is very high and it is thus necessary to find additional values, such as high-price nanostructured materials. However, from a process development point of view, multi-purpose processes are challenging to realize, i.e. to combine efficient CO_2 -mitigation, high and continuous lime production, and production of a novel nano-based product. Integrated into the cement clinker process, the main unsolved problem is how to separate the CaO formed from the carbonate melt. Particle size and density difference between CaO particles and melt are parameter that must be determined before due separation equipment can be designed. In addition, to find a suitable carbonate melt with optimized physical properties, preferably without lithium, still demands a considerable amount of research.

6. Conceptual design of selected concepts

Detailed studies have been conducted for the complete cement clinker production process; a conventional pre-heater, pre-calciner kiln system with air and CO₂ as well as a system with electrical direct separation reactor for calcination with a rotary kiln heated with plasma gas.

6.1. Pre-heater, pre-calciner kiln system heated by electricity

The preheater/precalciner (PH/PC) kiln system is currently the most modern cement manufacturing technology and has greater fuel efficiency than other kiln types. Essentially all new kiln systems are of this type and it accounts for the majority of all clinker production worldwide. It is therefore an obvious candidate for electrification, both from a greenfield and a brownfield perspective.

Plasma generators (pg:s) are capable of generating gas streams with very high specific enthalpy, and thereby also the (very) high temperatures necessary for certain steps in the cement production process. They are also available at useful output power ranges and proven to be industrially robust. Taken together, this makes them, at least for the time being, the primary candidate for heat source for the currently discussed system.

Several conceptual designs for PH/PC kiln systems heated by pg:s have been investigated. The one presented and discussed here is a Separate-Line Calciner (SLC) design, suggested by Heidelberg Technology Center, to best enable the recuperation of heat from the rotary kiln.

Furthermore, two versions of the selected SLC design are presented. Both utilize CO₂ as the heat carrier gas for the calciner. The advantage of this is that it results in an almost pure stream of CO₂ from the calciner, something which greatly facilitates the subsequent CO₂-capture. They differ, however, in that air is used as plasma gas for the rotary kiln in one version and CO₂ is used in the other version. These versions have their respective advantages and disadvantages. Gas-tight operation will be critical for both, but that should be less difficult to achieve for the CO₂/air-version. The CO₂/CO₂-version, on the other hand, can potentially achieve 100% capture whereas for the CO₂/air-version, CO₂ released in the kiln (remaining calcination) and in the kiln string-PHT (possible partial calcination) will not be captured.

Mass and energy (M&E) balances have been performed for a 1 million ton clinker per year unit, with a yearly operational time of 8000 hours. The assumed raw meal composition is that used by the CemZero project (see Table 4). A number of simplifying assumptions were applied:

- raw meal is completely dried before entering the preheater tower (PHT)
- all calcination occurs at a solids temperature of 900 °C (i.e. no partial calcination in the PHT)
- no false air at any position/for any component
- no transport of dust from the clinker cooler
- no raw gas dust
- typical, experience-based temperature levels at various parts of the system are assumed (no computations of actual heat transfer rates).

6.1.1. Plasma heating with a CO₂-atmosphere in the calciner and air in the rotary kiln

Figures 20 and 21 show the conceptual design, in the form of process flow diagrams, together with selected results. The raw meal split between the two strings is chosen to obtain the same gas exit temperature for both PHT:s. 95% of the calcination is assumed to take place in the calciner, remaining calcination occurs in the kiln. CO₂ is recirculated for use as plasma gas and for possible temperature control. Pg efficiencies are taken from previously performed experimental investigations. The clinker is discharged from the kiln at a temperature of 1400 °C. The hot air from the clinker cooler is split into three streams; one high-temperature stream used to control the temperature at the discharge end of the kiln, one medium temperature stream used for raw meal drying and a low-temperature stream (“excess air”) which provides the primary control of the air flow through the cooler.

The MW-numbers specified for each component are the energies per unit time required for, in turn, heating the solids to the specified PHT exit temperature (PHT), further heating to calcination temperature and subsequent calcination (calciner), and the heat requirement for the rotary kiln, the latter being made up by the heat for remaining calcination plus the rise in sensible heat of the solids plus the heat loss (radiative and convective) minus the heat from the clinker forming reactions. The number for the clinker cooler is the change in sensible heat of the clinker, per unit time, related to the cooling of the clinker from 1400 °C to 100 °C. This energy, minus the heat loss, is transferred to the cooler air.

The energy supplied to the rotary kiln is only a fraction of the total energy supply, less than 15%, something which simply reflects the fact that heating and (especially) calcination are the steps that by far requires the most energy.

The specific results in Figures 20 and 21 represent different assumptions for the kiln discharge end gas temperature ($T_{\text{gas, exit}}$), 2500°C vs. 2000°C, and kiln inlet gas temperature ($T_{\text{gas, inlet}}$), 1100°C vs. 1200°C. The lower assumed kiln discharge end gas temperature enables a larger flow of hot gas from the clinker cooler and thereby also a better utilization of the heat from the cooler, the consequence of which is an improved overall energy efficiency. The larger gas mass flow and the higher gas temperature at the kiln inlet means that there is more heat in the kiln exhaust and consequently that a larger proportion of raw meal is fed to the PHT connected to the kiln. Nevertheless, most of the raw meal will still be fed to the calciner-PHT.

Overall energy efficiency is relatively poor for the presented conceptual designs, with a specific energy consumption of ~ 4.6 MJ/kg clinker (energy consumption is defined as the electrical power consumed by the plasma generators divided by the clinker production rate). Certain characteristics are hard to influence, e.g. pg. efficiency, but it is important to keep in mind that the designs are not yet optimized in terms of energy efficiency, there are heat streams not utilized in the process. There is also a potential for improvement of energy efficiency through component development. If e.g. the allowed maximum temperature of the gas going into the pg:s could be raised from 100 °C to 350 °C, the PHT exit temperature, the specific energy consumption would decrease from 4.6 to 4.4 MJ/kg cl (given that the pg efficiency is not affected).

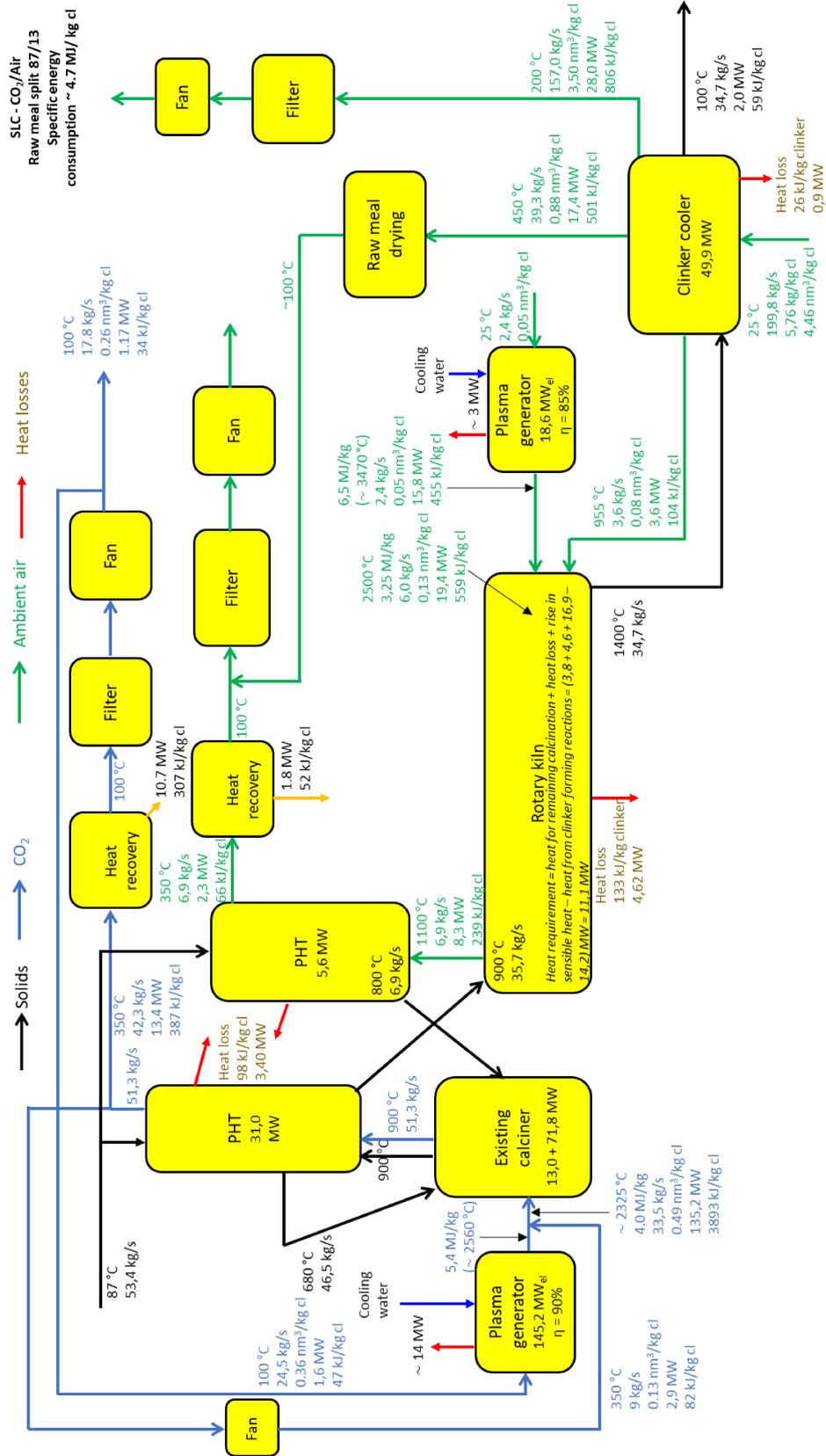


Figure 20. Process flow diagram and selected results for a PH/PC kiln system heated by plasma generators. Heat carrier gas is CO₂ for the calciner and air for the kiln. T_{gas, exit}=2500°C, T_{gas, inlet}=1100°C.

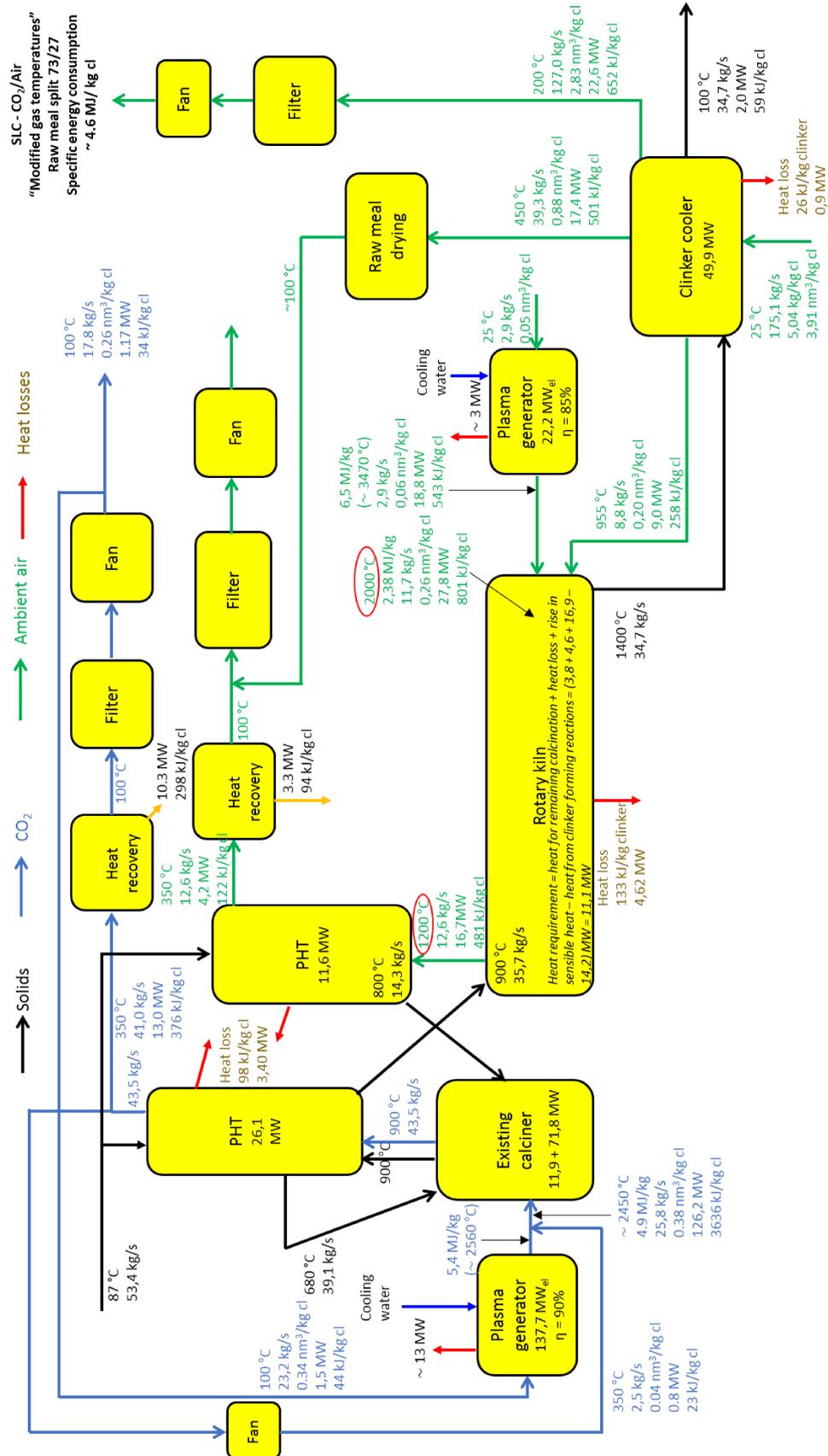


Figure 21. Process flow diagram and selected results for a PH/PC kiln system heated by plasma generators. Heat carrier gas is CO₂ for the calciner and air for the kiln. T_{gas, exit}=2000 °C, T_{gas, inlet}=1200 °C.

Figure 22 shows a process flow diagram for a concept with CO₂-atmosphere in both calciner and kiln. The clinker cooler is now presumed to be partitioned, with CO₂ used as the cooling media for the hot end while air-cooling is retained for the rest of the cooler. CO₂ for clinker cooling is recycled from a position after the preheater towers. CO₂ for plasma gas is taken after cooling and filtering.

It is obvious that this concept presents a challenge in terms of not allowing the cooler air to “contaminate” the CO₂ going to the kiln but as pointed out earlier, it potentially allows the capture of all CO₂ released.

The specific results given in Figure 22 correspond to the same assumptions on kiln inlet and discharge end gas temperatures as for Figure 21. In terms of overall energy efficiency, there is no marked difference compared to having air in the rotary kiln. The estimated specific energy consumption is similar, ~ 4.6 MJ/kg cl. There is also a similar potential for energy efficiency improvement, both through the integration of heat recovery equipment and through component development. E.g. the argument made in the previous section, decreasing the specific energy consumption to ~ 4.4 MJ/kg cl by increasing the temperature of the gas going into the pg:s, is valid here as well. The resulting raw meal split is quite similar to the previous concept, as is the fraction of energy supplied to the rotary kiln.

6.1.3. Heating with electrical flow heater for calcination

The electrical flow heaters described in section 4.3 were evaluated to use as heat source for calcination. The gas heater has a stated efficiency of 0.98. According to evaluations on different process scenarios made by NyCast following were found:

- To achieve calcination, electrical flow heaters will not give enough heat solely without rendering high gas volumes,
- Hydrogen combustion is added to achieve higher temperatures, hence rendering decreased gas volumes in the calcination step,
- Steam is added to decrease the partial pressure of CO₂, hence rendering decreased calcination temperature.

A process flow diagram calculated for the production of 1 Mton clinker annually needs a total effect of 151.2 MW divided on 101.4 MW for the electrical flow heaters and 49.8 MW for the electrolysis to produce hydrogen. Preliminary capex and opex costs together with process flow diagrams are estimated.

6.2. Electrical direct separation reactor for calcination in a complete cement clinker production process

A mass and energy balance was calculated for a theoretical process layout. The main heating sources were an electrical direct separation reactor (E-DSR) for the calcination part and a rotary kiln heated with plasma gas (air) for the clinkering process, see Figure 23. Calculation basis was production of 1 Mton of clinker per year. The preliminary results from a non-energy optimized flow sheet, gave an energy consumption of 3,3 GJ_e/ton clinker. A energy consumption to compare with BAT for cement production of 3,0 -3,3 GJ_{th}/ton clinker.

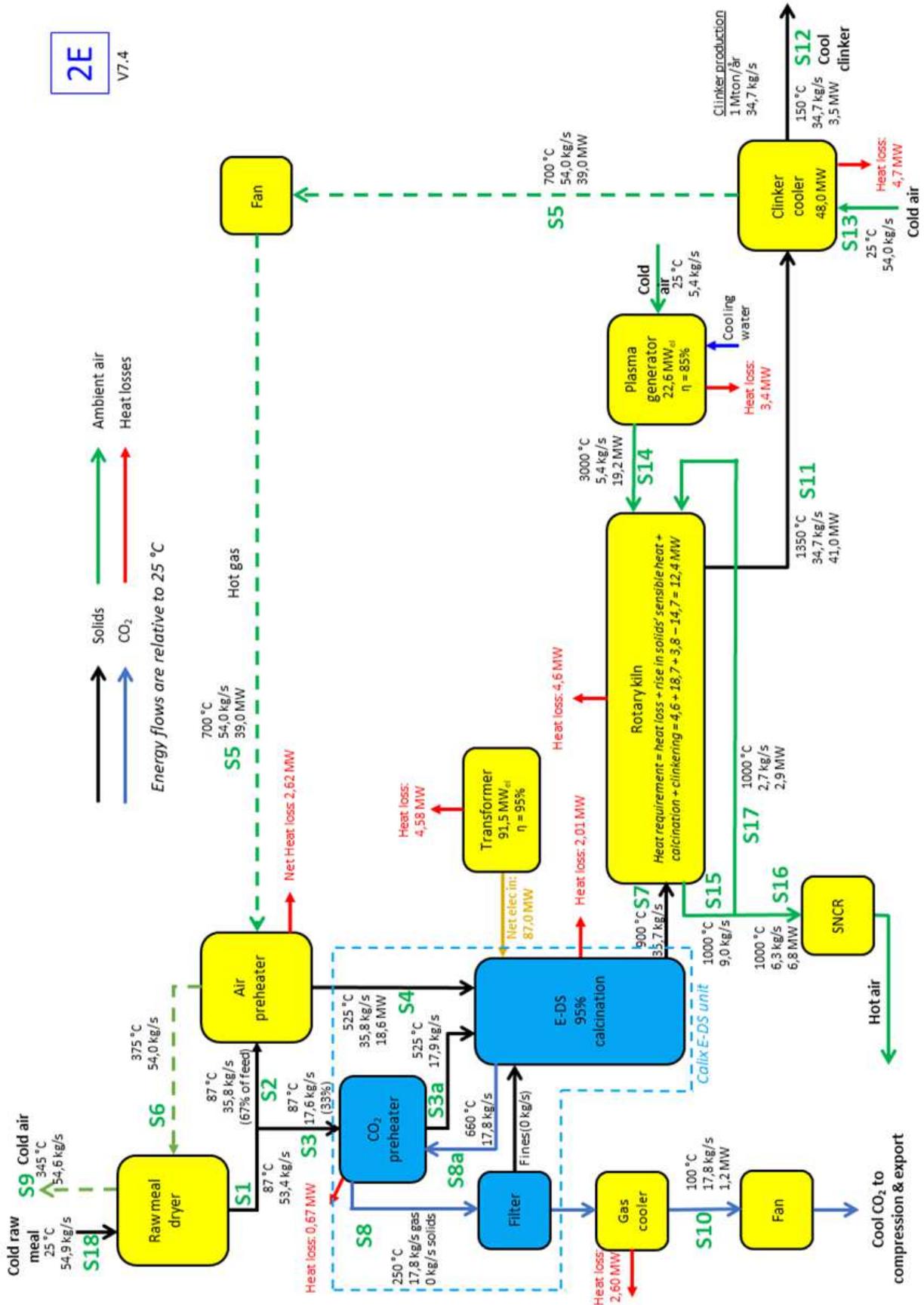


Figure 23. Possible flow sheet with an electrical heated direct separation reactor for calcination and plasma generation for clinkering reactions.

Test results from the pilot plant of Leilac will be evaluated when the construction is finalized and production starts. Pilot plant results will be available in April 2019 according to time schedule (Leilac 2017).

6.2.1. Microwaves in a complete cement production process

In the concept with E-DSR and plasma the heating in the E-DSR could be replaced by microwave heating. Microwave heating as well as electrical elements have the similar properties of not needing a medium to transport the heat with.

7. Electricity supply and the power system; electrification of Slite plant

This chapter will analyze the future power production and consumption when electrifying Cementa at full scale. It is assumed that Cementa will electrify the plant in Slite, Gotland, and approximately with the same production capacity as today. The electrification is approximated to increase the power consumption in Cementa by 260 MW, referred to the thermal power demand. Furthermore, the energy consumption is expected to increase by 2 TWh. This chapter will focus on the required transmission capacity between Gotland and the mainland of Sweden during present and future power production and consumption scenarios.

7.1. Power production and consumption on Gotland

The power generation on Gotland mainly comes from 180 MW wind power capacity. Also, 3 MW of solar power capacity and a negligible part of hydro power is installed on the island. Solar power capacity is currently increasing about 1 MW per year, which almost exclusively consists of micro power generation located at existing end customers. The highest power consumption is approximately 180 MW (Energimyndigheten 2018), also see Figure 25.

In order to analyse the future demand for power import and export to Gotland hourly values for power generation and consumption on Gotland for the period of 2014-2017 have been collected. In Figure 24 the wind power generation during the three years is shown. The wind power generation is often higher during the winter and lower during the summer but there is no clear characteristic for the wind power generation curve on Gotland according to the collected data. Additionally, in Figure 25 the power consumption is shown. As can be seen, the power consumption characteristic is typically a wave form with the lowest demand during the summer while the maximum demand occurs during the winter.

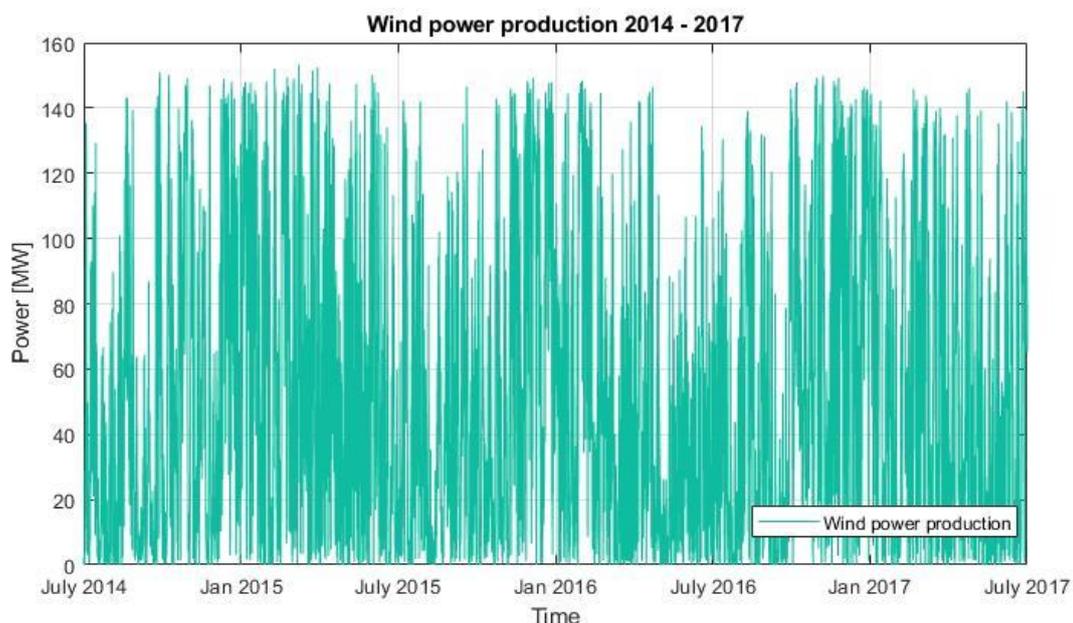


Figure 24 Wind power production on Gotland 2014-2017.

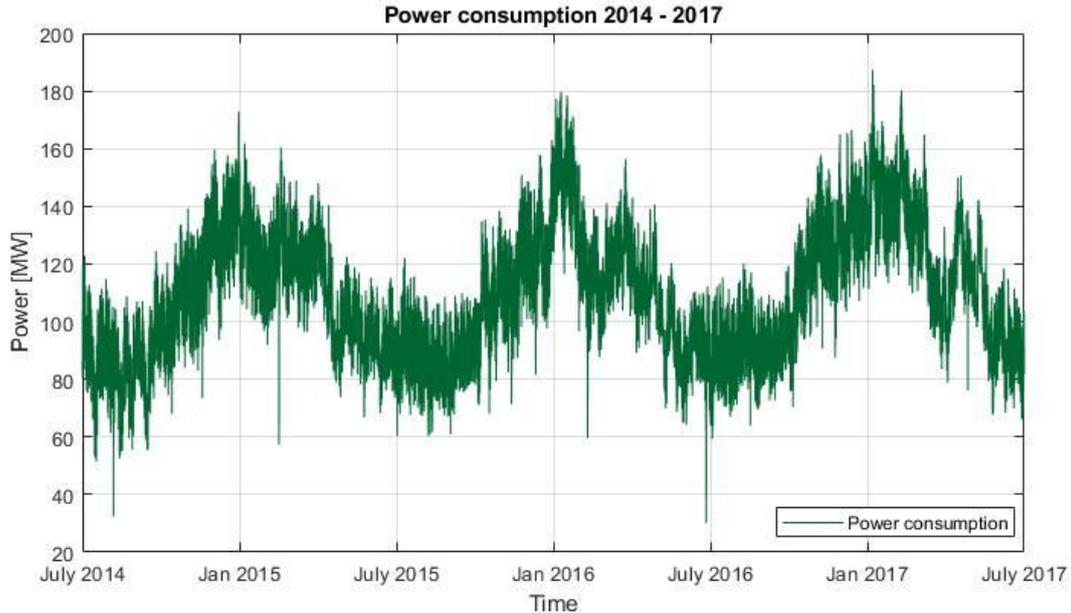


Figure 25. Power consumption on Gotland 2014-2017.

7.2. Scenarios for future power production and consumption

Based on the present values for wind power production and power consumption from 2014 – 2017, future scenarios for power generation and consumption on Gotland have been developed in order to analyze the expected future power transmission from mainland to Gotland. The future scenarios can be seen in Table 8. The scenarios have been developed in cooperation with Vattenfall Eldistribution and the Distribution System Operator (DSO) on Gotland with forecasted future power generation and consumption. The scenarios for wind- and solar power generation are based on the plans for the region of Gotland (Region Gotland 2014), assumptions about future wind power expansions and requests about building new wind farms currently on pause (Johansson 2018). However, the long-term target for the use of wind power on Gotland is an annual energy production of about 2.5 TWh, which corresponds to approximately 600 MW of new wind power (Region Gotland 2017).

The wind speed and solar radiation for the future scenarios are estimated to follow the same characteristics as for the data from 2014-2017. Since the implementation of the transformation proposed in CemZero is estimated to be realized in approximately 2030, the studies in this report focus on the scenario for 2030. However, the additional power consumption addressed to the electrification of Cementa is not included in the overall future scenarios given in Table 8 since the size of the load is uncertain when making general scenarios. Therefore, 260 MW of additional constant load is added in each case analyzed in this report.

Table 8. Future scenarios for wind- and solar power generation and power consumption on Gotland given in MW.

	Year			
	2020	2025	2030	2035
Solar power	5	20	25	30
Wind power	185	285	335	380
Power consumption	185	188	205	205

7.3. Expected power demand on Gotland

In this chapter results from the data analysis are shown. Three different situations are studied consisting of the different penetration levels of wind power into the power system of Gotland, i.e., present, medium and high wind scenario. The present scenario represents the present installation of wind and solar power in the island. The medium scenario represents the wind and solar power generation given for year 2030, listed in Table 8.

The green curve in Figure 26, Figure 27 and Figure 28 represents the reference power transmission between the mainland of Sweden and the island of Gotland with 185 MW of wind power, 3 MW of solar power and 185 MW of maximum power consumption on Gotland. The red dashed line represents the maximum and minimum transmission capacity of the HVDC-connection. In all scenarios, an additional constant load of 260 MW has been added to the present load profile in order to represent the additional load introduced by CemZero.

7.3.1. Present wind power scenario

In the blue curve in Figure 26 the power transmission of the HVDC-connection with the present wind and solar power generation together with 260 MW of additional constant power consumption is shown. It can be seen that the maximum power import to Gotland is about 400 MW, which is remarkably higher compared to the reference case shown in the green curve. Thus, the maximum current transmission capacity for the HVDC-connection of 260 MW is exceeded for the majority of the time. In this case Gotland is always importing power from the mainland and in the reference case there is a mixture of both import and export of power.

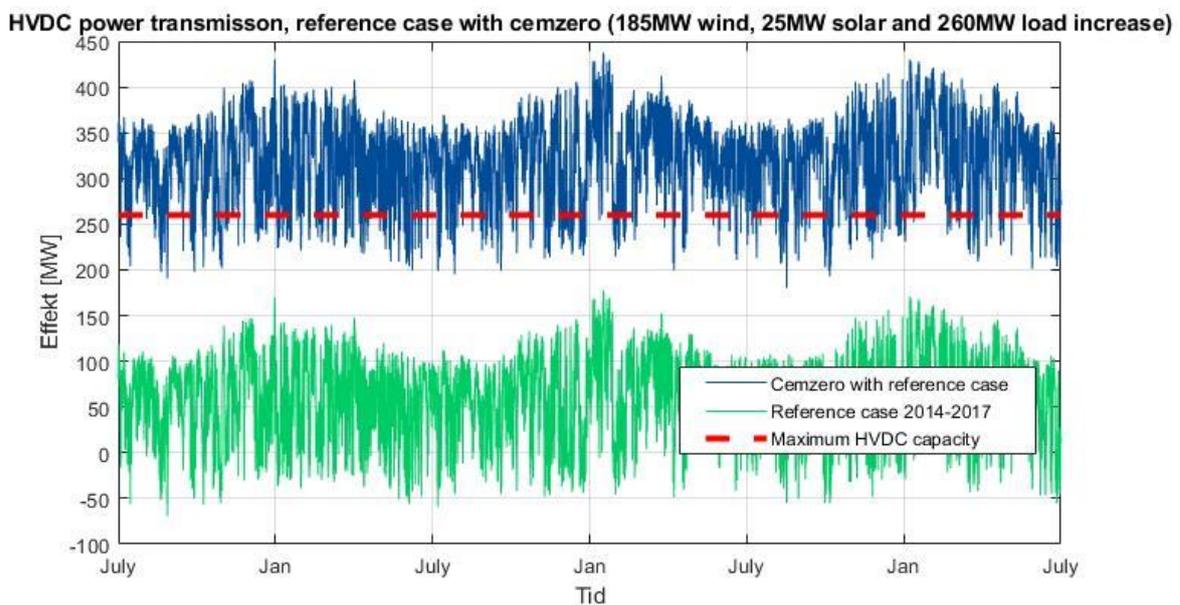


Figure 26. Present scenario, 185 MW wind power, 3 MW solar power and 260 MW additional load.

7.3.2. Medium wind power scenario

In the blue curve in Figure 27 the power transmission of the HVDC-connection for scenario 2030 is shown. The 2030 scenario represents a medium wind power penetration level on Gotland with 150 MW of additional wind power, giving the total capacity of 335 MW wind power. There are no clear changes regarding the maximum power import in this medium scenario compared to the present scenario shown in Figure 26. The reason for this is due to the fact that when the wind is not blowing it does not matter how large the wind power capacity is, it will still not contribute to balance the power consumption on the island.

Furthermore, as also could be seen in the present scenario, Gotland is still always importing power from the mainland.

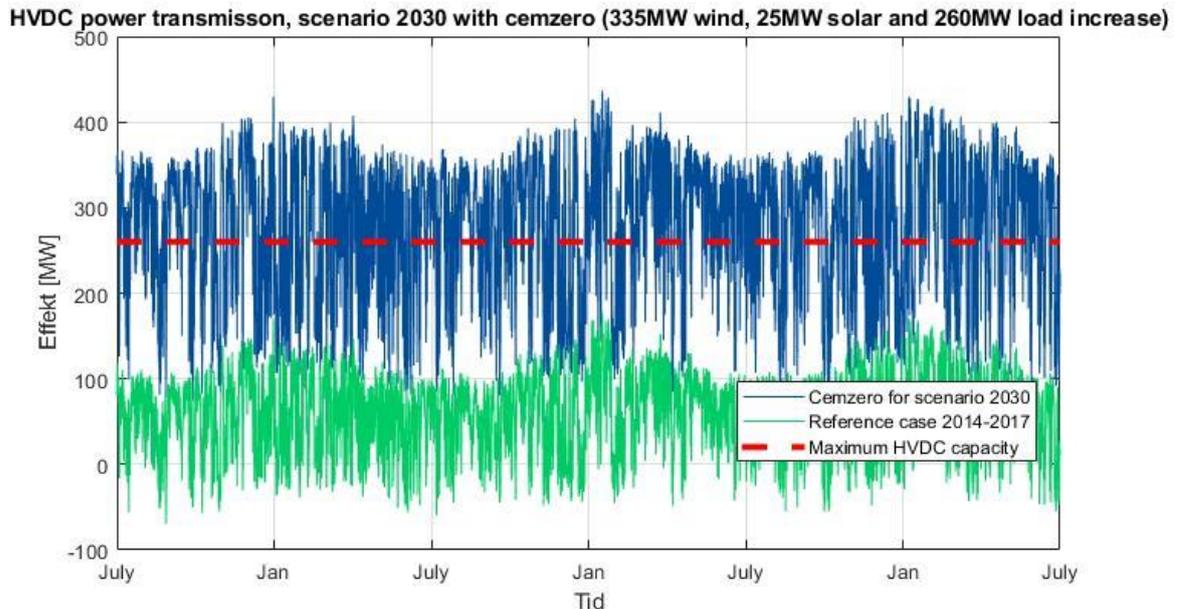


Figure 27 Medium scenario, 150 MW additional wind power, 25 MW solar power and 260 MW additional load.

7.3.3. High wind power scenario

In the blue curve in Figure 28, the power transmission of the HVDC-connection for the high wind scenario is shown. In this scenario 600 MW of additional wind power is added, giving the total capacity of 785 MW wind power. The high wind scenario refers to the long-term goal for the use of wind power on Gotland. With this amount of wind power generation on Gotland there will be a need for both import and export of power from the mainland. The import requirements are still about 400 MW and the export requirements is over 250 MW. The capacity of the present HVDC-connection is approximately 260 MW, which will almost handle the power export requirement but not the power import requirement in the high scenario.

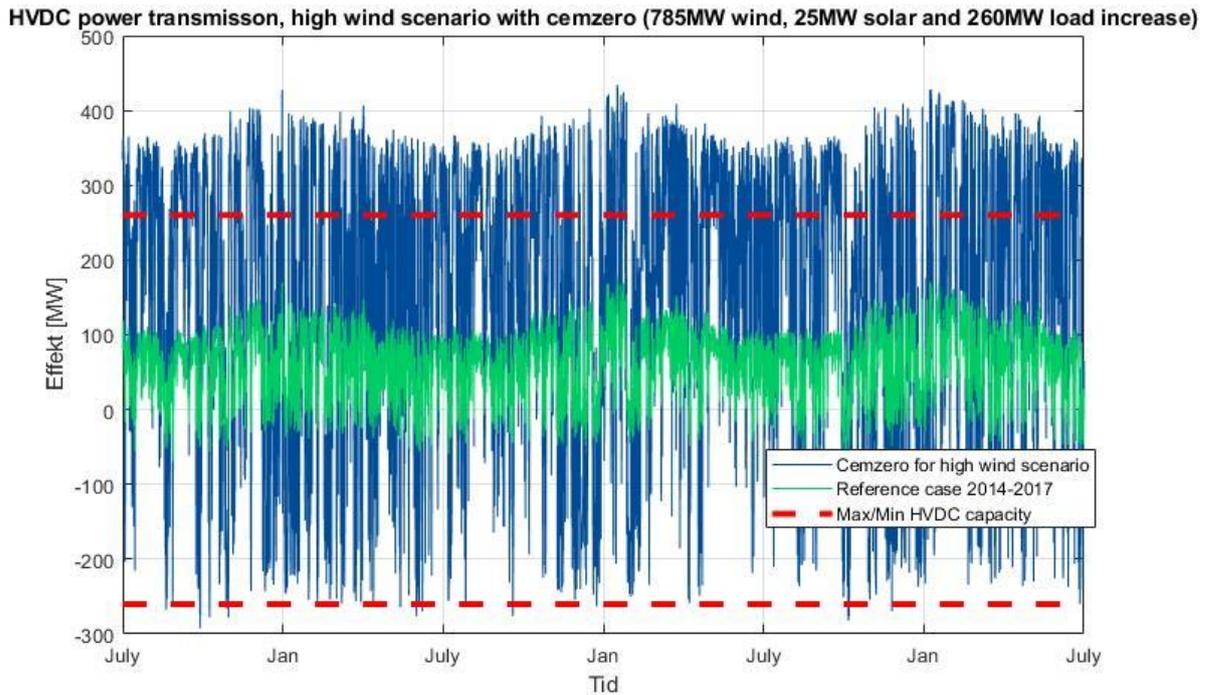


Figure 28 High scenario, 600 MW additional wind power, 25 MW solar power and 260 MW additional load.

In Figure 29 the power transmission of the HVDC-connection for the high wind scenario without any load increase on Gotland is shown. As in Figure 28, 600 MW of additional wind power is added, giving the total capacity of 785 MW wind power. The difference compared to the previous figure is the non-increased power consumption on Gotland. As can be seen in Figure 29 the export power demand (blue curve) is increased compared to the export power demand (blue curve) in Figure 28. This shows how a load increase on Gotland due to the electrification of Cementa reduces the requirement for power export transmission capacity from approximately 500 MW to about 240 MW. Hence, when increasing the load in Cementa by 260 MW the power import demand is the dimensioning criteria for the transmission capacity between Gotland and the mainland, which is about 400 MW. Power import demand is higher than power export demand in Figure 26.

HVDC power transmission, high wind scenario without cemzero (785MW wind and 25MW solar, no load increase)

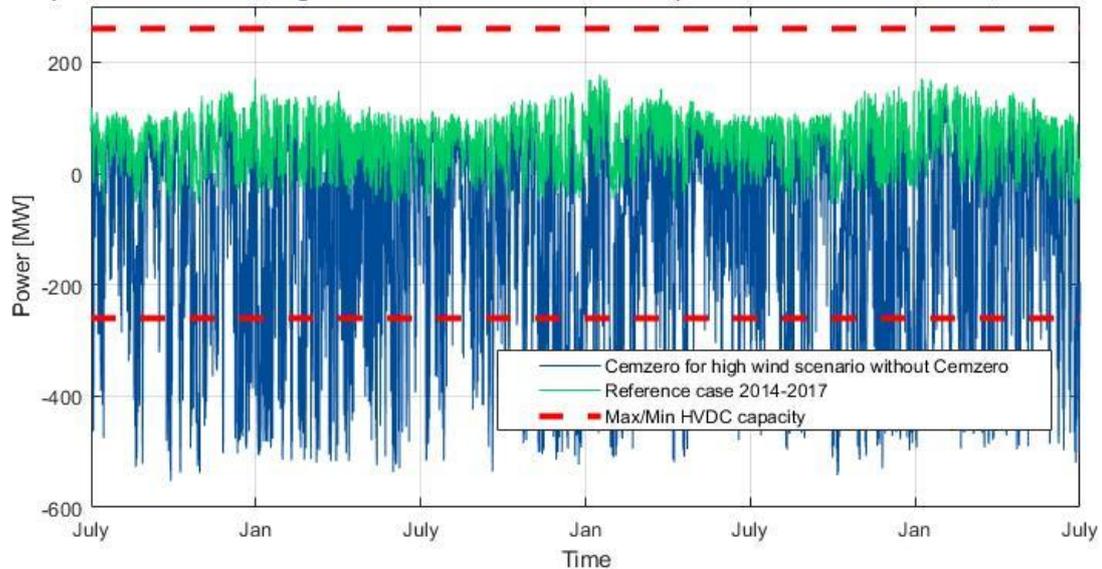


Figure 29 High wind scenario, 600 MW additional wind power, 25 MW solar power but no load increase.

7.3.4. Analysis for storage capacity in Cementa

As can be seen in the figures in section 7.3, the maximum power import requirement is approximately 400 MW. Therefore, in this report 400 MW is set as a capacity requirement for any new transmission connection to the mainland of Sweden when introducing CemZero to the power system of Gotland. However, with maximum transmission capacity of 400 MW the limit will be exceeded during some import hours. One option to handle those exceeding hours can be by introducing storage capacity to the process related to CemZero.

In Figure 30 the high wind scenario is illustrated. The red dashed line shows the limit where 400 MW of power import is reached. Maximum power import in this scenario is 434 MW. Thus, there is a maximum surplus power demand of 34 MW. The situation with power demand above the limit could hypothetically be solved by reducing flexible power consumption in Cementa, reducing other power consumption units in the grid and/or by using energy storage. Further information of an investigation of an energy storage on Gotland for other power consumption units than CemZero and a local market for ancillary services can be seen in (Lidström et al. 2018). During the studied period of three years the power import limit is exceeded during 200 hours, which corresponds to 0.8 % of the total time.

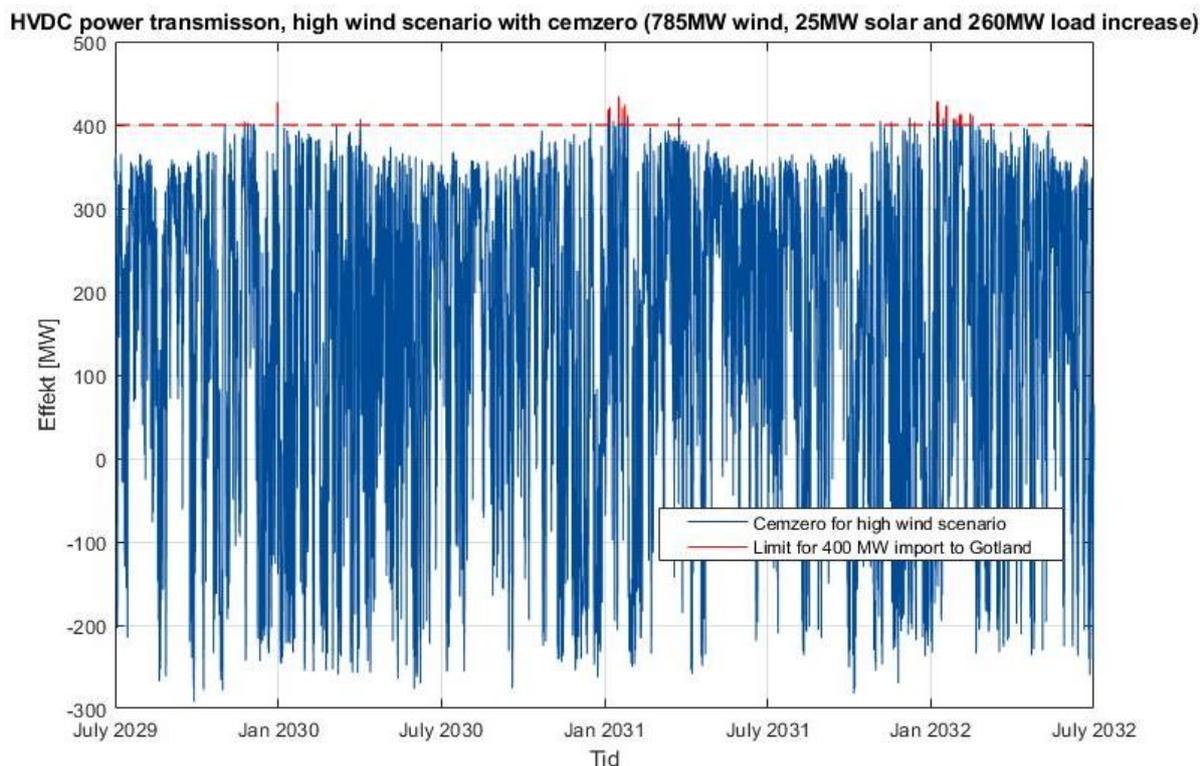


Figure 30 High scenario showing the periods exceeding 400 MW of power import.

7.4. Summary of the case study

By introducing the assumed 260 MW of additional power consumption to the power system of Gotland, this will result in a large increase of power imported from the mainland of Sweden. The maximum power import to Gotland when adding 260 MW power consumption is about 400 MW, regardless of the installed wind power capacity. The reason is due to the absence of wind power generation when the wind is not blowing on Gotland, and during periods of low wind power generation combined with high power consumption the power import is at its highest level. Thus, the capacity of the present HVDC-connection between the mainland and Gotland is not enough in order to supply an increasing power demand for the electrification in Cementa. Therefore, the CemZero transformation, which will increase the power demand at Cementa, is not possible with the current mainland connection which would require about 400 MW of transmission capacity.

On the other hand, by transforming the processes in Cementa towards electrification the export power demand will be reduced if the future goal with 600 MW of additional wind power capacity is installed i.e. adding additional power consumption on Gotland could counteract some of the requirement for power export to the mainland. Hence, with CemZero the requirements on the power transmission capacity to the mainland could be reduced when increasing wind power capacity on Gotland. The behavior is especially notable during the high wind scenario when the power export is high. If only the wind power capacity on Gotland is increased by 600 MW without any load increase on the island, the export transmission capacity demand would be even higher. The maximum power export would then be approximately 500 MW, since the domestic power generation could not be consumed on the island.

A new connection to the mainland with power transmission capacity of 400 MW will still result in some peak demand period when the maximum transmission limit will be exceeded. During those hours energy storage adapted to CemZero, flexible power consumption or a combination of the both could hypothetically be the solution to the transmission limitations.

8. Economic analysis and comparison

This chapter describes the capital and operating costs of an electrified cement plant. To be able to benchmark these costs with similar carbon capture technologies, the project has decided to use post combustion amine method for carbon capture as a comparison. Both the electrified with plasma cement plant (scenario Plasma) and the post combustion amine method for carbon capture with electrical boiler (scenario Amine) technologies are based on a modern dry feed 5 stage pre-heater and pre-calciner reference cement plant (reference plant). The cost of the reference plant with no carbon capture is therefore also a part of this section.

Costs for scenario Plasma are based on the electrification concept described in chapter 6.1. However, we see that some of the other technical concepts, for example the DSR, have potential to be being more energy and cost efficient than the one presented in scenario Plasma. This is further discussed in the sensitivity analysis below.

The capital cost for the reference plant was estimated by the HeidelbergCement Group based on the assumptions above with input from IEA reports and standardized installations executed by HC group recent years.

The estimated accuracy of the costs is $\pm 25\%$.

8.1. Assumptions

The main financial assumptions used for this study were based on the IEA GHG reports (Barker et al. 2009) and (IEAGHG 2013) and on input from HeidelbergCement Group. The key assumptions are summarized below:

Plant size

- A newbuilt 1 million ton clinker per year plant with 5 stage pre-heater and pre-calciner dry feed technology and at a clinker/cement ratio of 73.7%.

Location

- A greenfield site in Sweden with no special civil works implications was assumed.

Currency

- The results of the studies are expressed in Euro € applicable to 2018.

Allocation of investment

- The expenditure during construction of the cement plant was as follows:
 - Year 1: 50% investment
 - Year 2: 50% investment

Depreciation time

- Depreciation time of twenty-five years is assumed.

Capital charges

- Rate of interest assumed to be 8%.
- Inflation assumptions have not been made. No allowance is made for escalation of fuel, labor or other costs relative to each other.

CO₂ capture rate

- The capture rate of the reference plant with post combustion carbon capture is assumed to be 90%.
- The capture rate of the reference plant with electrification carbon capture is assumed to be 100%.

CO₂ transport and storage

- Assumed transport cost for shipping CO₂ is €21.3/t CO₂. Assuming the scenario of shipping 2.5 Mt/y CO₂ at least 1.500 km incl. liquefaction (ZEP 2011). Euro consumer price index 2011 – 2018 7.82% is used.
- Assumed storage cost of CO₂ is €6.5/t CO₂. Assuming the scenario of an offshore depleted oil and gas fields (DOGF) with legacy wells and medium risk level (ZEP 2011). Euro consumer price index 2011 - 2018 7.82% is used.

Thermal efficiency

- The thermal efficiency of the reference plant with 70% alternative fuels and with no carbon capture is assumed to be 3.5 MJ/kg clinker.
- The thermal efficiency of the reference plant with 70% alternative fuels and with post combustion carbon capture is assumed to be 3.5 MJ/kg clinker.
- The thermal efficiency of the reference plant with electrification carbon capture is assumed to be 4.4 MJ/kg clinker (not optimized).

8.2. Reference plant

A reference cement plant operating as of today, i.e. with no carbon capture technology installed, with minor changes made. This was used as a base for both the post combustion amine method and the electrified cement plant. Therefore, cost estimations were made for the reference plant and used to calculate the additional costs for scenario Amine and Plasma.

The reference plant used for this study is defined as a conventional, complete greenfield cement factory with a capacity of 1 Mton clinker per year (1.35Mton cement) including; raw material preparation and handling, raw milling and homogenization, preheater, pre-calciner, rotary kiln, cooler, silos, coal preparation, alternative fuel preparation, cement milling and cement packing and loading. The construction cost is harmonized with the context in northern Europe. The production costs are the sum of,

- Capital costs
- Variable operating costs
- Fixed operating costs

8.2.1. Capital Costs

Table 9. Capital cost of reference plant

Total equipment cost	145	M€
Design & engineering	10	M€
Construction	45	M€
Other costs	5	M€
EPC services	5	M€
Total installed cost	210	M€
Owners cost	5	%
Contingencies	5	%
Total capital required	231	M€

8.2.2. Production Costs

Table 10. Production cost of reference plant

Fuel	4.2	€/ton cement
Power	3.9	€/ton cement
Capital	24.3	€/ton cement
Other variable O&M	5.3	€/ton cement
Fixed O&M	14.9	€/ton cement
Total production cost	52.6	€/ton cement

8.3. Scenario Amine

For the purposes of evaluating costs for scenario Plasma, the project decided to use scenario Amine as a comparison. This technology is assumed by the project to be the most mature carbon capture technology and consequently has the best cost estimate accuracy. An electrical boiler is assumed to be used for the post combustion amine scrubber method. The costs are based on the reference plant in chapter 8.2, and costs for carbon capture are taken from IEA reports from 2008 and 2013 and input from scientific articles (Leeson et al. 2017), (Barker et al. 2009) and suppliers.

8.3.1. Capital Costs

Table 11. Capital cost of scenario Amine

Total equipment cost	145	M€
Design & engineering	10	M€
Construction	45	M€
Other costs	5	M€
EPC services	5	M€
Total installed cost	210	M€
CPU (CO₂ processing unit)	28.5	M€
Other CC related (EPC etc.)	16.7	M€
Electrical boiler	32.3	M€
Post combustion	52.5	M€
Total installed incl. cost carbon capture	340	M€
Owners cost	5%	%
Contingencies	5%	%
Total capital required	374	M€

8.3.2. Production Costs

Table 12. Production cost of scenario Amine

Fuel	4.2	€/ton cement
Power	29.4	€/ton cement
Capital	39.4	€/ton cement
Other variable O&M	8.9	€/ton cement
Fixed O&M	19.6	€/ton cement
Total production cost	101.5	€/ton cement

8.4. Scenario Plasma

Scenario Plasma is based on the costs for the reference plant with minor changes assumed and with the additional costs of electrifying the process. The design of the technology and the process of scenario Plasma is described in chapter 6.1.

One assumption made to scenario Plasma is that the thermal efficiency of the process is higher compared to scenario Amine and the reference plant, 4.4 MJ/kg clinker versus 3.5 MJ/kg clinker. The reason for this is further described in chapter 6.1. Another assumption is the price €40/MWh for electricity. For scenario Plasma, the investment and operation costs for alternative fuels and coal grinding and handling are excluded.

8.4.1. Capital Costs

Table 13. Capital cost of scenario Plasma

Total equipment cost	143.9	M€
Design & engineering	10	M€
Construction	40.5	M€
Other costs	5	M€
EPC services	5	M€
Total installed cost	204.4	M€
CPU (CO₂ processing unit)	19.2	M€
Plasma system	47.5	M€
Other CC related (EPC etc.)	5.0	M€
Total installed cost incl. carbon capture	276.2	M€
Owners cost	5%	%
Contingencies	5%	%
Total capital required	303.8	M€

8.4.2. Production Costs

Table 14. Production cost of scenario Plasma		
Fuel	0	€/ton cement
Power	41.7	€/ton cement
Capital	32.0	€/ton cement
Other variable O&M	7.3	€/ton cement
Fixed O&M	19.1	€/ton cement
Total production cost	100.0	€/ton cement

8.5. Cost comparison

The cost comparisons between the scenarios are reliant on a large number of assumptions shown in chapter 8.1.

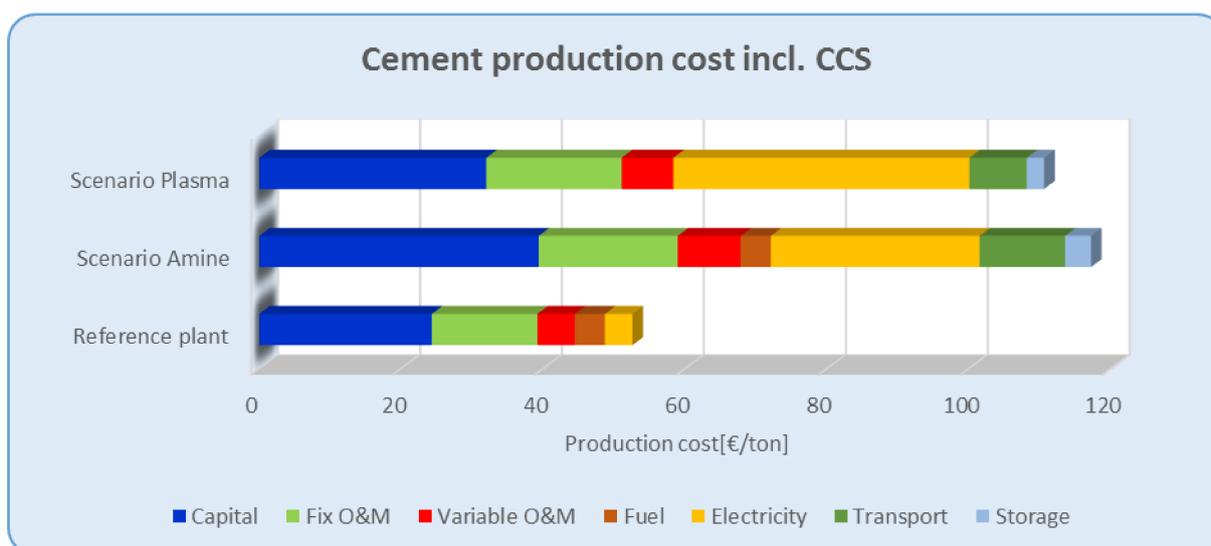


Figure 31: Cost comparison including transport and storage (27.8€/ton CO₂) for CCS plants

In Figure 31, the reference plant has a production cost of 52.6€/ton cement without any CCS solution, whilst the two CCS plants, including transport and storage, have a total production cost of 110.6€/ton cement for scenario plasma and 117.2€/ton cement for scenario amine. However, in Figure 32 a few scenarios representing different levels of cost for CO₂, €/ton, is introduced in the comparison. The cost scenarios of CO₂ are between 20€/ton and 100€/ton.

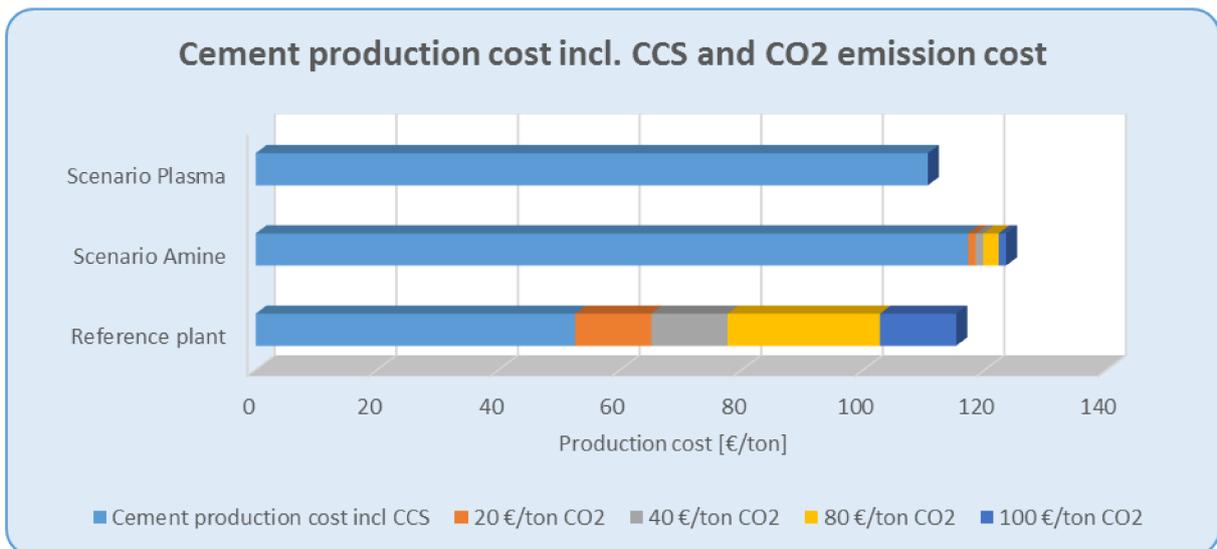


Figure 32: Cost comparison including transport and storage for CCS plants and different scenarios of cost for CO₂.

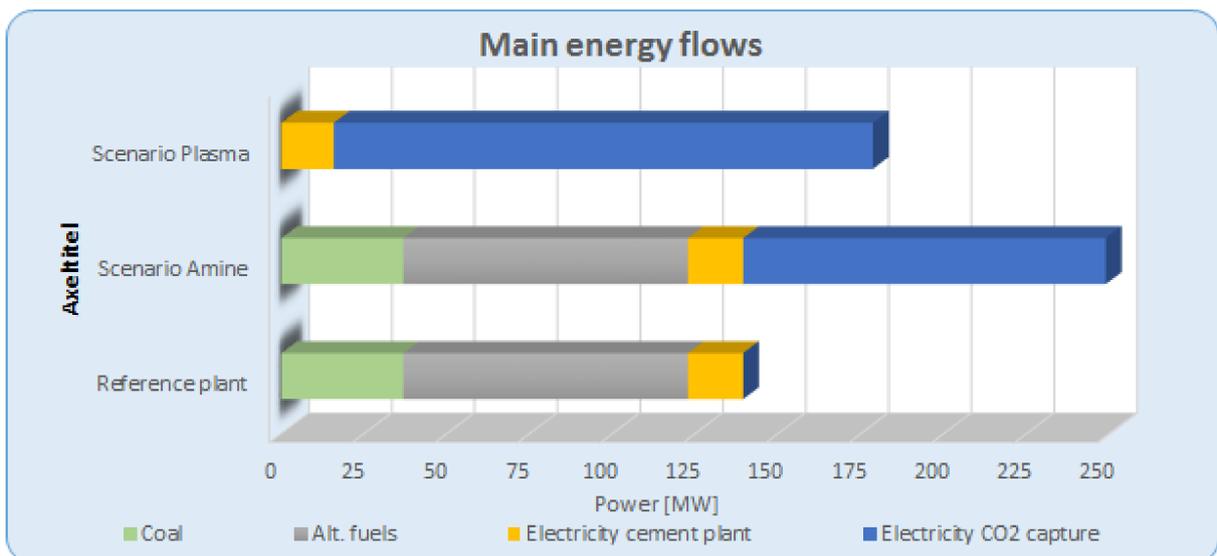


Figure 33: Main energy flows in the three scenarios

In Figure 33, it is shown that both CSS technologies require more energy than the reference. However, electrification has significantly lower total energy consumption than Scenario Amine. For the amine scrubber, an electrical boiler is assumed for CO₂ capture energy. Energy requirements for amine carbon capture (3GJ/t) are close to the thermal energy required for clinker production in the reference plant.

Table 15. Emissions and specific costs related to carbon capture excluding transport and storage.

	Reference	Amine	Plasma
Total cement production cost excl. transport and storage (€/ton cement)	52.6	101.5	100.0
CO ₂ emitted (ton CO ₂ /year)	850 417	85 042	-
CO ₂ captured (ton CO ₂ /year)		765 375	515 000
CO ₂ avoided (ton CO ₂ /year)		765 375	850 417
Spec. CO ₂ emissions (kg CO ₂ /ton cement)	626.8	62.7	-
CO ₂ capture cost excl. transport and storage(€/ton CO ₂)		86.7	125.1
CO ₂ avoidance cost excl. transport and storage(€/ton CO ₂)		86.7	75.7

In Table 15, some KPI:s used in the scientific literature for comparison of different carbon capture technologies are shown. Due to the lower amount of generated CO₂ with plasma technology, the capture cost rate is higher than amine scrubber technology. But when calculating avoidance costs, the cost advantages with electrified plasma and its lower amount of generated CO₂ is shown. Transport and storage are here excluded since most scientific papers present these KPIs this way.

8.6. Sensitivity analysis

Sensitivities to the different scenarios are shown in Figures 34 to 36.

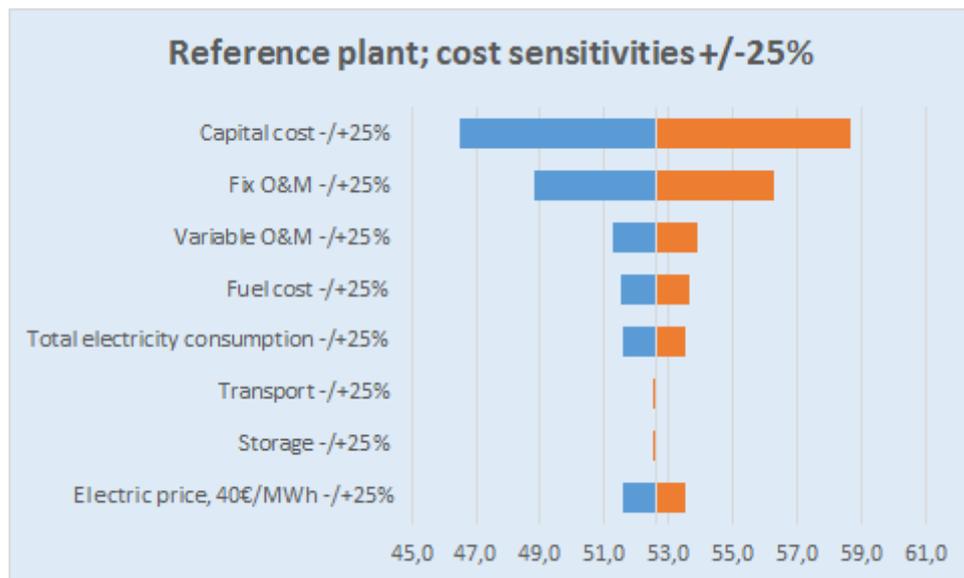


Figure 34: Sensitivity specific cost analysis (€/ton cement) Reference plant at 52.6 €/ton cement.

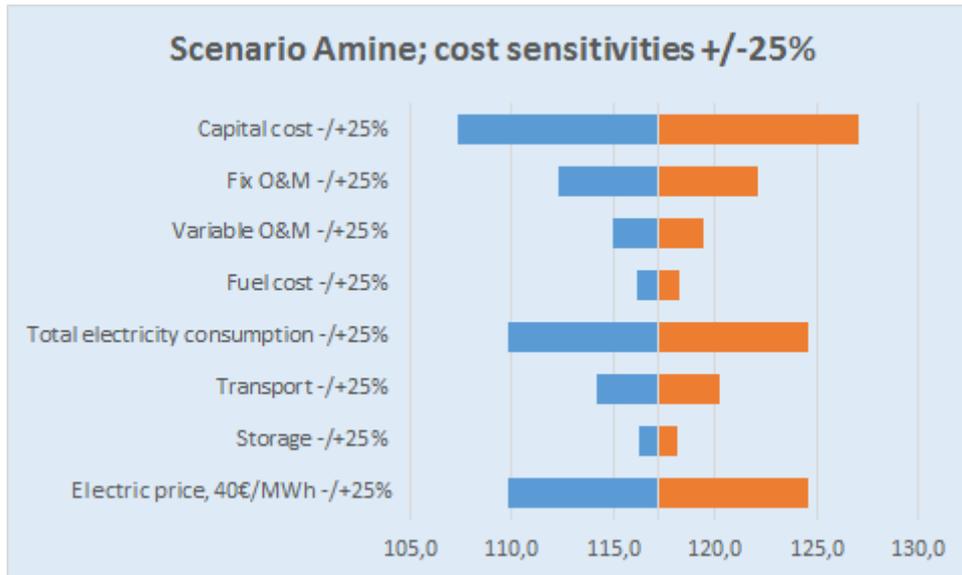


Figure 35: Sensitivity specific cost analysis (€/ton cement) Scenario Amine at 117.2 €/ton cement.

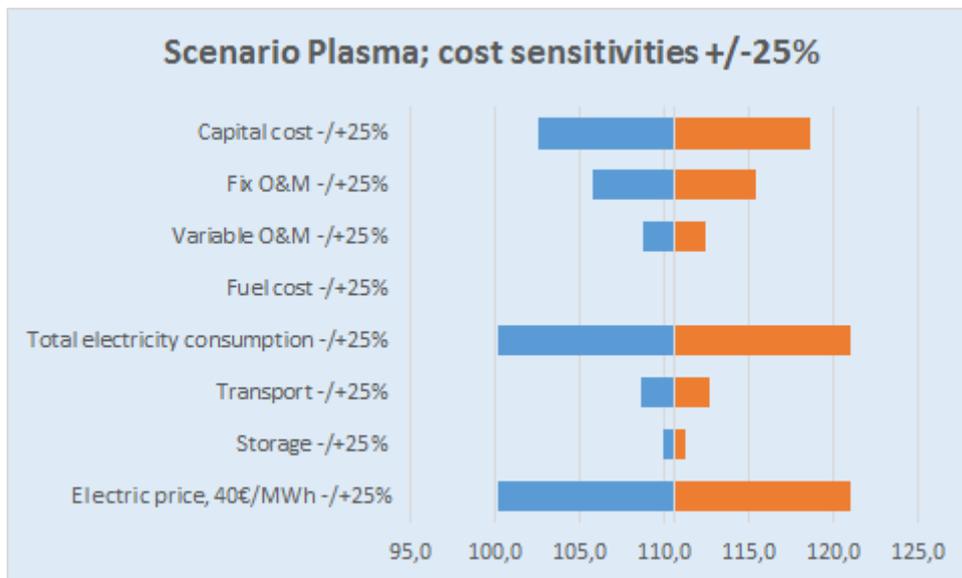


Figure 36. Sensitivity specific cost analysis (€/ton cement) Scenario Plasma at 110.6 €/ton cement.

Capital cost is a major parameter in all cases that influence the total specific cost €/ton cement. However, this parameter affects all scenarios for the general CAPEX. Capital cost is at its lowest for the reference plant since no CCS equipment is included.

For the two CCS scenarios, electrical energy consumption and price are the two major parameters that influence the total cost. As indicated earlier, the thermal efficiency 4.4GJ/t clinker for scenario plasma has been used in the calculations. If an electrified installation is achieved corresponding to the potentials in the sensitivity analysis (3.3 GJ/ton clinker) above and with the lower electricity price (30 €/MWh), the cost will be more favorable for the electrified scenario, see Figure 37. The DSR design, as described in chapter 6.2, corresponds approximately to this lower energy consumption and indications showing potentials for even higher thermal efficiency when fully optimized. In Figure 32, a few scenarios representing different levels of cost for CO₂, €/ton CO₂ are introduced in the comparison.

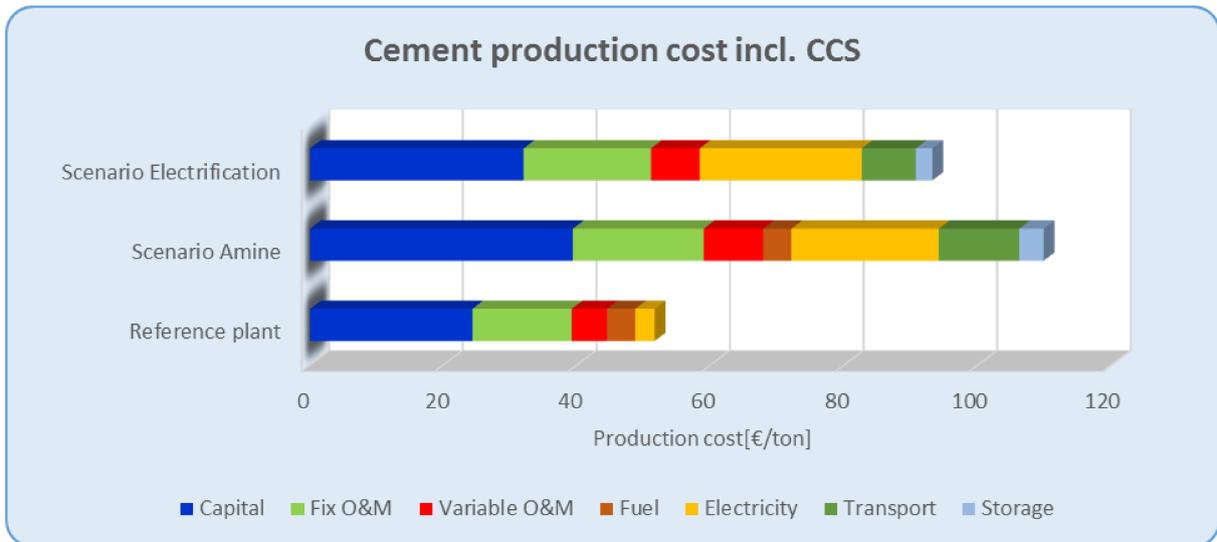


Figure 37: Cement production cost incl. CCS of an electrified cement production based on the lower range of thermal efficiency and electricity price as described in the sensitivity analysis above.

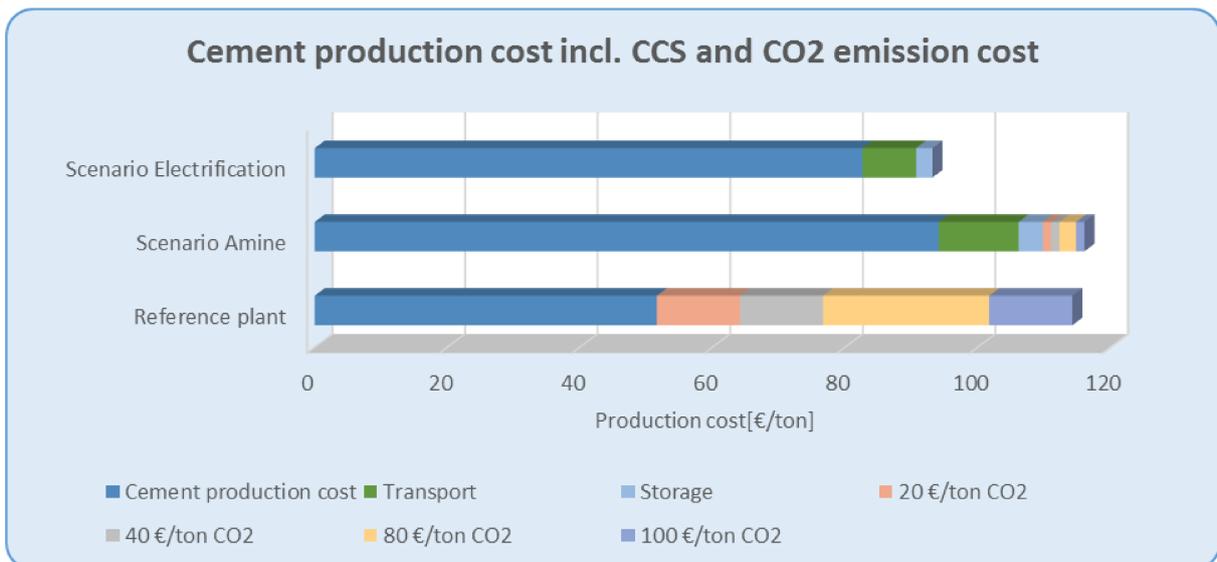


Figure 38: Cost, represented by -25% figures according to sensitivity analysis above, comparison including transport and storage for CCS plants and different scenarios of cost for CO₂.

In Table 16, the CO₂ capture and avoidance KPI:s are presented to the optimized electrified installation. Transport and storage are here excluded since most scientific papers present these KPIs this way.

Table 16. KPI:s related to CO₂ capture and avoidance excl. transport and storage of an electrified cement production based on the lower range of thermal efficiency and electricity price in the sensitivity analysis as described above.

	Reference	Amine	Plasma
Total cement production cost excl. transport and storage (€/ton cement)	51.6	94.1	82.6
CO ₂ emitted (ton CO ₂ /year)	850 417	85 042	-
CO ₂ captured (ton CO ₂ /year)		765 375	515 000
CO ₂ avoided (ton CO ₂ /year)		765 375	850 417
Spec. CO ₂ emissions (kg CO ₂ /ton cement)	626.8	62.7	-
CO ₂ capture cost excl. transport and storage(€/ton CO ₂)		75.4	81.7
CO ₂ avoidance cost excl. transport and storage(€/ton CO ₂)		75.4	49.5

8.7. Summary of the economic analysis

The outcome from this economic analysis indicates that the production cost for an electrified cement process is approximately twice the cost of a reference cement plant operating as of today, the latter meaning a fossil-based combustion process with no carbon capture technology installed.

However, the study also shows that electrification as a carbon capture technology compares economically well to other carbon capture technologies of today. A detailed comparison indicates higher production cost for a post combustion amine method. Also, the electrification scenario has significantly lower total energy consumption than the post combustion amine method. All of these factors together with the forecasted prices for raw material, energy and CO₂ emissions mean that a fossil-free electricity-based cement process appears to be economically viable.

9. Conclusions and discussions

The main conclusions of the study are:

- Electrification of the cement production process, for example by means of plasma technology, appears to be technically possible but needs to be verified in larger scale tests,
- The production cost of cement in an electrified process appears to be doubled compared to today's technology, but is competitive compared to other technology options for radical emission reductions,
- Simulations have indicated that possible future electrification of Cementa's plant in Slite would work well together with planned expansion of wind power on Gotland, partly through improved energy balances, but also by reducing the maximum power surplus that wind power would otherwise give rise to,
- The cross-sectoral approach with cooperation between industry and universities supported by the Swedish Energy Agency has been important for the success of the project,
- Cementa and Vattenfall are continuing the collaboration into the next phase where pilot tests of technology will be made to reduce technical risks and provide important information for future upscaling and implementation.

Literature studies, tests in laboratories and at a small scale and extensive calculations have concluded that the results from this study are essentially positive and indicate potential for CemZero and a fossil free value chain through an electrified cement making process. There is still quite a significant need to develop the concept together with large challenges coming with the conversion.

The evaluated technologies have different degrees of maturity with stated disadvantages and unclear issues needing to be further examined.

The concept of using plasma generators in a pre-heater, pre-calciner kiln system is at present the main technology path for future development. The technology of using plasma is mature. However, there are challenges of the technology related to the possible use of carbon dioxide as carrier gas as well as requirements on gas tight systems. The goal is to investigate the technology with this concept in a pilot scale plant.

The direct separation reactor concept for calcination may achieve high energy efficiency. This technology will be assessed for production of cement in continuous mode. The non-electrified version of the reactor is to be experimentally evaluated in the Leilac project within 2019. If these pilot-scale tests are successful, the combination of electrical direct separation reactors for calcination and a kiln heated by plasma generators for clinkering must be considered a very relevant alternative.

Tests in pilot scale are of utmost importance in reaching the goal of zero carbon footprint for cement production.

Chemical issues emerging with electrical heating source and high carbon dioxide atmosphere needs to be examined carefully.

Compared to combustion heating, electrical heating indicates that the concentration of carbon dioxide becomes very high in the exhaust gases. The amount of carbon dioxide also reduces significantly when combustion of fuel is excluded. If heating occurs otherwise

without hot gases, a further reduction of flue gas volumes is expected. This leads to a much easier capture and purification of carbon dioxide from the flue gases.

According to economic analysis a non-optimized plasma in a pre-heater/a pre-calciner kiln system including CCS has approximately the double production cost compared with a reference plant with no CCS. It is also shown that electrification of cement production is more economically efficient than CCS amine scrubber technology.

A possible future electrification of Cementa's plant in Slite would work well together with planned expansion of wind power on Gotland, partly through improved energy balances, but also by reducing the maximum power surplus that wind power would otherwise give rise to.

An electrified cement production would still require the handling of process related carbon dioxide with CCS or CCU solutions.

10. Suggestions for future work

Many parallel actions in a broad sense are needed to reach a zero carbon footprint for cement production. Starting from Cementa's vision of zero carbon dioxide emissions in 2030, the following time schedule is proposed:

	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	
Research and Development	Heating with plasma generators in 'preheating tower, calcination and rotary kiln' with related chemical aspects.												
Pilot plant		Detailed engineering study	Building	Tests									
Demo plant					Demonstration plant trials								
Full scale plant									Full scale engineering	Construction			Electrification applied
Supporting activities													

Research and development activities will give invaluable results and input to pilot plant engineering studies. Continuous evaluation of selected concepts will be done.

Tests with a plasma (air and CO₂) generator need to be conducted to evaluate heat transfer and plasma torch mechanisms and the formation of SO_x and NO_x. Related to electrical heating, several chemical questions need to be investigated such as high CO₂- atmosphere effect on process, product and exhaust gas quality. The possible design of a plasma heated calcinator also needs to be analysed further.

Identified technologies for electrification need to be developed to function in full scale. The common steps are through pilot and demonstration plant tests before full scale engineering and construction is possible.

An activity related to implementation of electrification technologies in full industrial scale needs to start. The formation of collaborative parties and business models are some of the activities needed.

The direct separation reactor needs to be followed and evaluated in the on-going Leilac project as well as in an electrified version. Progress in the use of microwaves and the development of magnetrons needs to be followed closely.

Other activities that are prerequisites for a successful implementation of CemZero such as power system integration and the development of CCS/CCU, including legal issues and storage capacity of carbon dioxide need to be addressed.

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