PBL Netherlands Environmental Assessment Agency

DECARBONISATION OPTIONS FOR THE DUTCH CEMENT INDUSTRY

C. Xavier, C. Oliveira

25 March 2021

MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation Options for the Dutch Cement Industry

The Hague, 2021
PBL publication number: 4339
TNO project no. 060.47868 / TNO 2021 P10108

Authors
C. Xavier and C. Oliveira

Acknowledgements
We would like to thank Rob Huydts (ENCI HeidelbergCement), Mark van Halderen (ENCI HeidelbergCement), Kira West (TNO), Dick van Dam (PBL), and Ton van Dril (TNO) for their help and valuable input.

MIDDEN project coordination and responsibility
The MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network) was initiated and is also coordinated and funded by PBL and TNO Energie Transitie. The project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. Correspondence regarding the project may be addressed to:
D. van Dam (PBL), Dick.vanDam@pbl.nl or S. Gamboa Palacios (TNO), silvana.gamboa@tno.nl

Erratum
In this version a reference has been corrected to: Kudra, T., 2012. Energy Performance of Convective Dryers. *Drying Technology*, 30(11-12), pp.1190-1198.

PBL Netherlands Environmental Assessment Agency is the national institute for strategic policy analysis in the fields of the environment, nature and spatial planning. PBL contributes to improving the quality of political and administrative decision-making by conducting outlook studies, analyses and evaluations in which an integrated approach is considered paramount. Policy relevance is the prime concern in all of PBL’s studies. PBL conducts solicited and unsolicited research that is both independent and scientifically sound.

TNO Energie Transitie has a twofold mission: to accelerate the energy transition and to strengthen the competitive position of the Netherlands. TNO conducts independent and internationally leading research and we stand for an agenda-setting, initiating and supporting role for government, industry and NGOs.

This report has received contributions from ENCI HeidelbergCement. PBL and TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the company.

Contents

FINDINGS

Summary

The Dutch cement production takes place at the Eerste Nederlandse Cement Industrie (ENCI), the first and only cement industry active in the Netherlands (since 1926). The company is nowadays owned by the German multinational HeidelbergCement and has two producing industrial plants, one located in Rotterdam and one based in IJmuiden. The Rotterdam and IJmuiden industrial sites have a production capacity of 600 kilotonnes (kt) and 1,400 kt of cement per year, respectively. They produce two main different types of cement for the Dutch market, Portland cement (CEM I) and blast furnace slag cement (CEM III). The main feedstock for cement production is clinker, which is not produced in the Netherlands anymore. For this reason, the Dutch market is depending on imports of clinker from other EU countries.

The production process of ENCI Netherlands consists of drying, dosing, and grinding. The drying process serves to prepare the portion of the (wet) blast furnace slag coming from the steel industry before dosing it and mixing it with the other components. The drying step is the main one responsible for direct carbon emissions in the industrial sites because the dryer's thermal energy is generated by burning natural gas. The dosing and grinding processes are done sequentially, with the grinding installations being responsible for most of the electricity demand of the sites. The raw materials (clinker, blast furnace slag (BFS), limestone, and calcium sulphate) are dosed, mixed, and ground according to the desired cement type. There are differences within the grinding facilities in the IJmuiden and Rotterdam industrial sites; in IJmuiden, a roller press and two ball mills are used in the process, while Rotterdam uses only two ball mills. After the raw materials go through the grinding processes, the cement is ready for use.

This study identified the following as the main decarbonisation options for the Dutch cement industry:

- Fuel substitution to reduce the use of natural gas. The literature's alternatives mentioned are: heat pump dryer (using renewable electricity), solar dryer, hydrogen and biogas use as fuel substitute, and waste heat use from other industrial sites.
- Process design change to further improve the energy efficiency in the grinding process. The literature's alternatives mentioned are: roller press (both as pre-grinding and as grinding equipment), vertical roller press, or high-pressure grinding rolls instead of the ball mills and high-efficiency classifiers.
- Alternative feedstock to reduce the use of the carbon-intensive clinker even more. The literature's alternatives mentioned are: blast furnace slag, fly ash, natural pozzolanas, natural calcined pozzolanas, limestone and belite cement.

Cement is an important sector towards the decarbonisation of industry, for having high carbon-intensive processes and being the most extensive manufactured product in volume on earth. For that reason, this report also mentions some of the most relevant decarbonisation alternatives presented in the literature for the cement manufacturing chain as a whole, beyond the partial production processes sited in the Netherlands (including, then, clinker production). The main topics of this subject from literature are: more sustainable clinker production, re-carbonation, CO_2 uptake, efficient use of cement in concrete and increased circularity of cement and concrete circularity.

FULL RESULTS

Introduction

This report describes the current situation for cement production in the Netherlands and the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, analysts, and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Scope

In the Netherlands, cement producers include ENCI Rotterdam and ENCI IJmuiden. Production processes include drying, dosing and grinding; products include: Portland Cement (CEM I) and Blast Furnace Slag Cement (CEM III).
The main options for decarbonisation for the Dutch cement production are alternative feedstock, alternative fuel, electrification, and process design changes. This report also briefly discusses the decarbonisation options for feedstock (clinker) production which takes place outside Netherlands' borders.

Reading guide

Section 1 introduces the Dutch cement industry. Section 2 describes the current situation for cement production processes in the Netherlands, and Section 3 describes the relevant products of these processes, while options for decarbonisation are systematically quantified and evaluated in Section 4. The feasibility of and requirements for those decarbonisation options are discussed in Section 5.

1 Cement production in the Netherlands

Cement is the largest manufactured product on Earth by mass. It is a hydraulic binder that can be produced by grinding and mixing different components like cement clinker, granulated blast furnace slag (GBFS), pozzolana (siliceous or silico-aluminous material with cementitious properties in the presence of moisture), limestone, and fly ash. Those various components go through distinct processes and treatments and are dosed in different quantities to form different types of cement (ECRA, 2015). When mixed with water and other minerals, it creates other cement-based binding materials, such as the concrete, the second most utilized material in the world after water (Scrivener, John, & Gartner, 2016). The high demand for this material in our civilization is directly linked to the economic development of societies. The common goal of achieving a more just, sustainable society requires substantial progress in the built environment, which drives the growth of this industry.

The Dutch production takes place at the Eerste Nederlandse Cement Industrie (ENCI), the first and only cement industry active in the Netherlands since 1926. Currently, the company is owned by the German multinational cement giant HeidelbergCement and has two producing industrial plants, one located in Rotterdam and the other based in IJmuiden (Figure 1 and Figure 2). They also owned another plant in Maastricht that was recently closed (Figure 3). ENCI has a central office located 's-Hertogenbosch, where the sales, planning, and marketing activities occur. Within the two active industrial sites, the company has a production capacity of around 2 million tonnes (Mt) of cement per year and produces mainly cements type CEM III (Blast Furnace Slag Cement) and CEM I (Portland Cement). ENCI's principal clients are concrete plants and building companies that use cement for concrete. The Rotterdam site provides a specific research center with laboratories that conduct studies to assist clients produce cheaper and more efficient concrete, also serving to HeidelbergCement's Belgian interests. That connection between product and services provided allows clear interaction between cement making, research, and buyer interest (Global Cement, 2012).

Figure 1- ENCI Rotterdam industrial site.

Figure 2 - ENCI IJmuiden industrial site

Figure 3 - ENCI Maastricht closed industrial site.

The Netherlands is one of the countries that do not produce all the demanded cement. The country's natural and geographical characteristics have strongly influenced the consumption and production of cement in the country. The predominance of open water environments in the Netherlands' landscape creates some disadvantages for the concrete industry. The moist and saltiness are characteristics that can directly affect the concrete durability, especially in areas where the water table is elevated. The Dutch low stocks of limestone make the industry dependent on imported clinker from across the border in Germany and Belgium. For this reason, ENCI benefits from the limestone area of the CBR's Lixhe plant in Belgium, which is only 12km to the south of the Dutch border. Those characteristics drove the cement industry to be ruled by cement type CEM III, rich in blast furnace slag which contributes to enhanced durability to concrete structures with less use of clinker (Global Cement, 2012). Still on the influence of geographic conditions on cement production, the Netherlands' coastal and inland waterways narrow the distances over which cement is transported by road or rail. Thus, large amounts of material are carried by boat to inland areas, a delivery configuration that would be more difficult for other nations.

The cement production in the Netherlands is remarkably different from most of the cement sites worldwide due to the aforementioned distinct characteristics and the environmental standards. When analysing only the Dutch scope of production, Dutch cement's ecological situation is in a relative advantage compared to the production of other countries. The most carbon-intensive process in the cement industry is the limestone's treatment to turn into clinker. Thus, the extensive use of Blast Furnace Slag (BFS) to substitute the Portland clinker cement in the Netherlands represents an advantage. These two materials are by-products of other industrial processes and require low or no emissions in order to be used in the cement production chain. The Portland cement is extensively used in other countries and has a clinker content of 95%, while the Dutch cement has an average clinker content of 46% (Cement & Beton Centrum, 2019). On the other hand, the Dutch cement industry still has room to improve, especially towards reducing import of the carbon-intensive clinker from outside the borders.

2 Cement production process

As the most manufactured product in the world, cement production is large in size with many manufacturing sites around the world that share a very similar process (IEA; CSI, 2019). Cement, as a product, can be worldwide understood as the result of processing different types of minerals undergoing continuous grinding, thermo-treatment, and dosing processes; being limestone, clay, and gypsum the main used raw materials (Leetham, 2015). The minerals composition can be slightly distinct among companies due to countries' quality standards or specific uses. The type of cement produced can change with the addition of alternative binding materials. The production chain can be simplified and divided into two main steps: clinker fabrication and cement production. Figure 4 presents more details of both stages. The Dutch manufacturing industry for cement, unlike most other countries, does not include anymore the production of clinker and focuses on the second stage of cement production.

The main element of cement production is clinker. Clinker is produced through energy-intensive kiln process and provides the mineral composition necessary for the binder function of cement in concrete (Cement & Beton, 2018). This production process generally has the following pathway:

a) Raw Material Extraction: Marl (lime-rich mineral), loam, fly ash, and ferrous raw materials are the primary raw material for the manufacture of clinker. Excavations in the soil remove the minerals from nature while the fly ashes come from other industries.
b) Transport: The raw materials are transported to the manufacturing industry. The clinker production facilities are almost always located next to, or very close to, the sources of the main raw materials to facilitate this stage.
c) Crushing: The marl is broken and sieved in the crushing facility, removing a considerable amount of flint stones from the limestone.
d) Milling: The lime with the other raw materials go to the milling zone to be homogenized and pre-mixed in finer grains.
e) Drying and Preheating: The ground components of clinker are dried to obtain a flour-like composition fed to a preheating cyclone tower. As it falls, the flour absorbs rising gas energy and reaches a temperature of 800 °C.
f) Kiln: The flour goes to a rotary oven gradually heated to a temperature of about 1450 °C. This stage is the most carbon-intensive in cement manufacturing, mainly because of the large amount of raw material heated with fossil fuels at such a high temperature. Some companies have been using alternative fuels for this process, decreasing the carbon footprint.
g) Cooling: When leaving the oven, the clinker is led to an air-cooling system, causing its temperature to drop to approximately 100 °C.

The next step is the cement production itself. At this stage, the type of cement produced is defined, mostly by changing its composition and granularity. This process is composed basically by the grinding and dosing of clinker and other binding additives. The primary type of cement produced worldwide is the Portland Cement, which has more than 95% of clinker on its composition (Leetham, 2015). This grinding and dosing of clinker and other binding additives is the only process occurring in the Dutch manufacturing facilities and it will be explored in the following section.

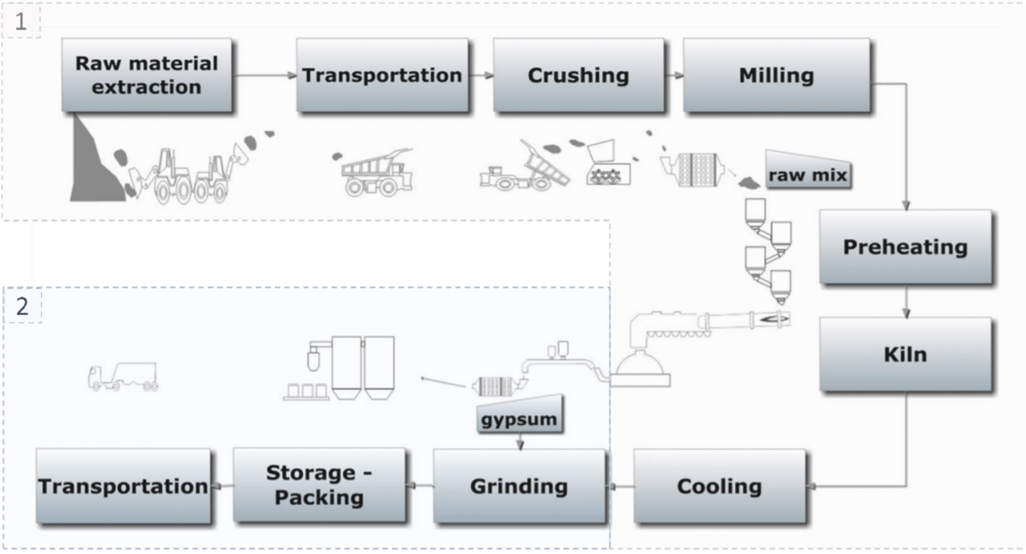

Figure 4 - Cement manufacturing Process. 1 - Clinker Production; 2 - Cement Manufacturing (Chrysostomou, Kylili, Nicolaides, & Fokaides, 2015).

2.1 Dutch Production Process

The Dutch cement manufacturing process no longer includes the production of clinker. The industrial site responsible for producing clinker inside borders was the Maastricht production site of ENCI that completely closed in 2020. Before that, at the beginning of 2019, the clinker production was, due to an agreement on ending extraction from the adjacent limestone quarry, already stopped, making the Dutch cement production sites completely dependent on imports of clinker. The main importation sources of clinker to the Dutch cement production sites are the Belgian Heidelberg Cement facilities, part of the Benelux production organization. One of these plants is located in Lixhe 12 km to the south from the former Maastricht site, the other is located in Antoing. They support the cement production of Rotterdam and IJmuiden. The increase in the maintenance and operation costs led the ENCI to declare that this site was unable for this industrial site to remain competitive, which led to its closure (Horrichs, 2019).

Thus, the Dutch production process is only related to the grinding and dosing facilities, running in the Rotterdam and IJmuiden industrial ENCI sites. Both produce the same types of cement and have a similar manufacturing configuration regarding the raw materials use and the process chain. The main differences, however, rely on the production capacity, on the mix composition of raw materials, on the amount of each type of cement produced, energy use, and emissions. Figure 5 and Figure 6 show the production scheme for both IJmuiden and Rotterdam industrial sites, respectively, and indicate the estimated differences between the amount of raw material used (grey), energy demand (yellow), production capacity (blue) and emissions (red) in tons per year. The values presented are estimations based on the full-capacity production of each production site, according to the mixture mass balance proportions.

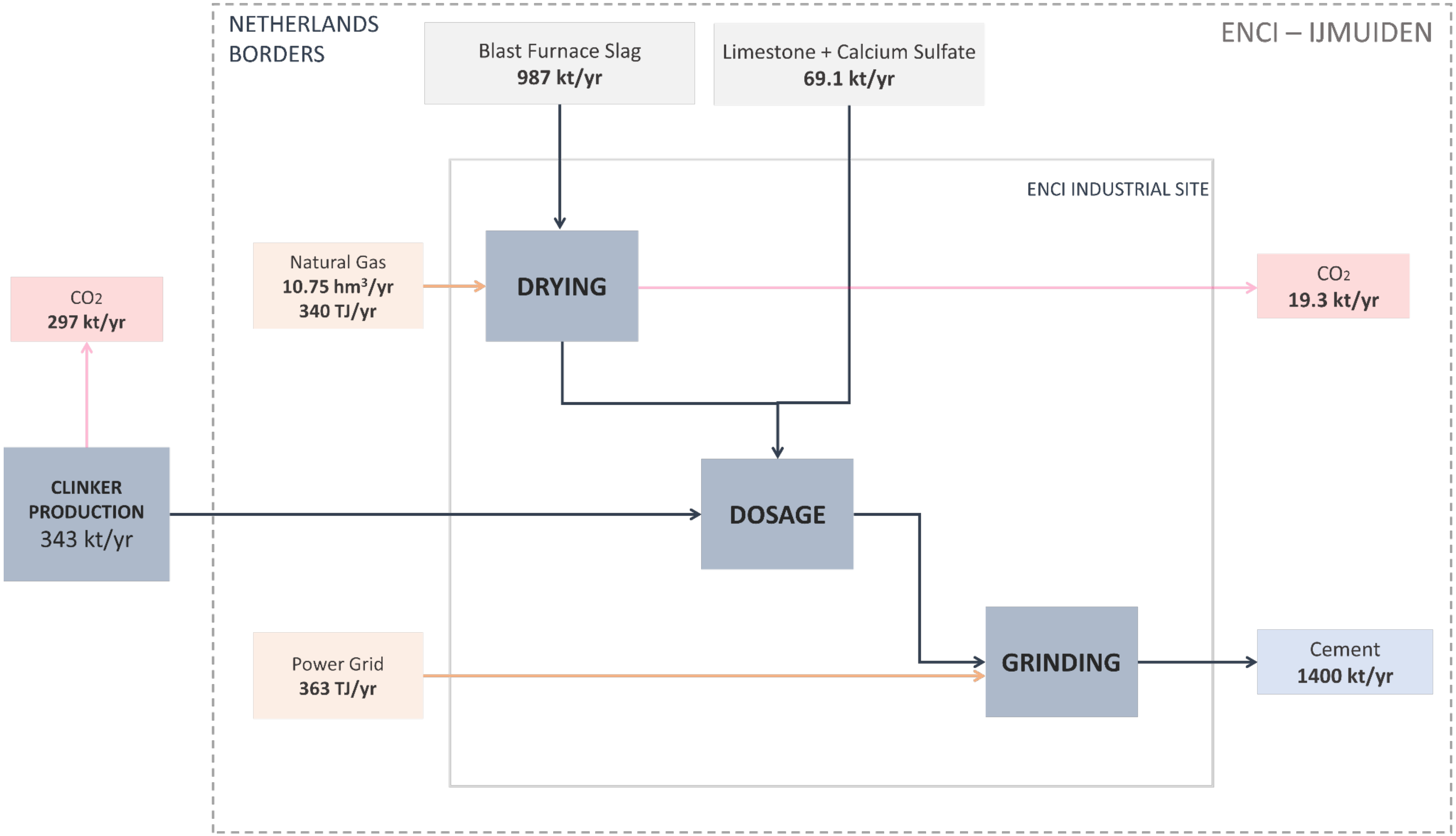

Figure 5 - Production process scheme for ENCI IJmuiden in full production capacity.

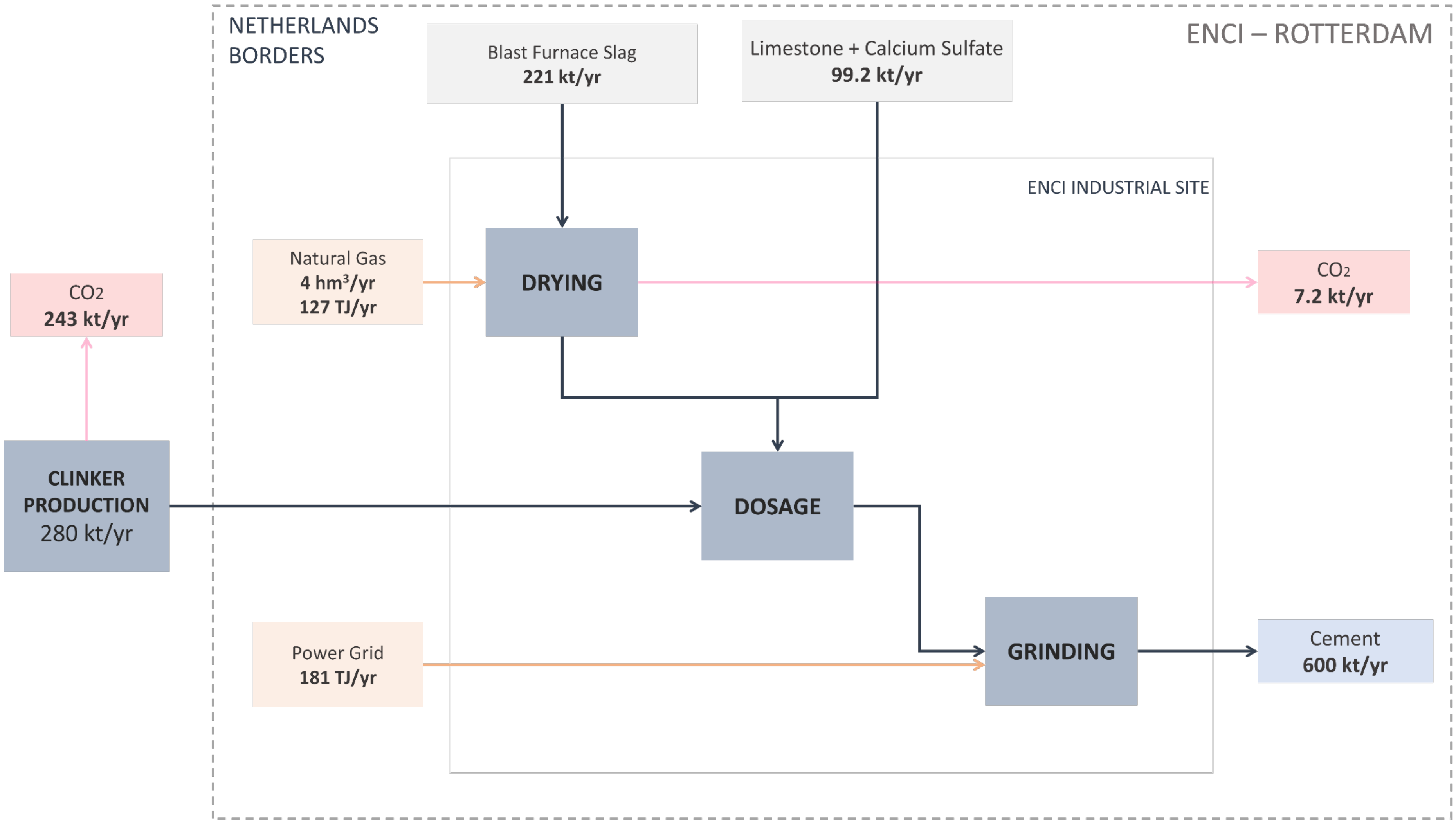

Figure 6 - Production process scheme for ENCI Rotterdam in full production capacity.

To draft the Dutch cement production process in Figure 5 and Figure 6, the material and energy flows were estimated according to public data on the ENCI production capacity for each industrial site (ENCI , 2017). The clinker and blast furnace slag consumption were retrieved from ENCI (2017), the CO_2 emissions are based on NEA (2020) and Emissieregistratie (2005), and the process scheme is according to interviews with the company. The portion of the other binders (calcium sulphate and limestone) were calculated considering the composition and shares of the different types of Dutch cement (ENCI, 2020a; 2020b; 2020c). The volume of natural gas consumed and, consequently, the energy demand for drying, were obtained by considering its emission factor (Zijlema, 2018) and the carbon emissions of this process. Also, the electricity use was calculated according to the grinding equipment used on each industrial site, its capacity and consumption (ECRA, 2015). Finally, the CO_2 emissions of the imported clinker were estimated according to the emission factor for this process (Betonhuis, 2014).

2.1.1 Raw materials for the Dutch cement production

The production process schemes for both industries highlight the variety of materials used to manufacture ENCI's cement. As mentioned previously, the Dutch production has a distinguished cement manufacturing which consists mostly of CEM III (Blast Furnace Slag cement) and CEM I (Portland Clinker cement). Blast furnace slag (BFS) plays an important role in the production. It is supplied by the nearby steel manufacturer Tata Steel based in IJmuiden, produced during the quenching of molten iron slag with water (Krese, Strmčnik, Dodig, & Lagle, 2019). CEM III has a composition of 36 to 95%wt of BFS, which explains the large amount demanded (around 1,200 Mt BFS for both industrial sites) (ENCI, 2020a). Also, the production of BFS cement is growing in the past years, especially in the IJmuiden production site which is close to the Tata Steel factory, the primary producer of this material (ENCI , 2017; Keys, Van Hout, & Daniels, 2019). Figure 7 shows the growth of its consumption in the past years.

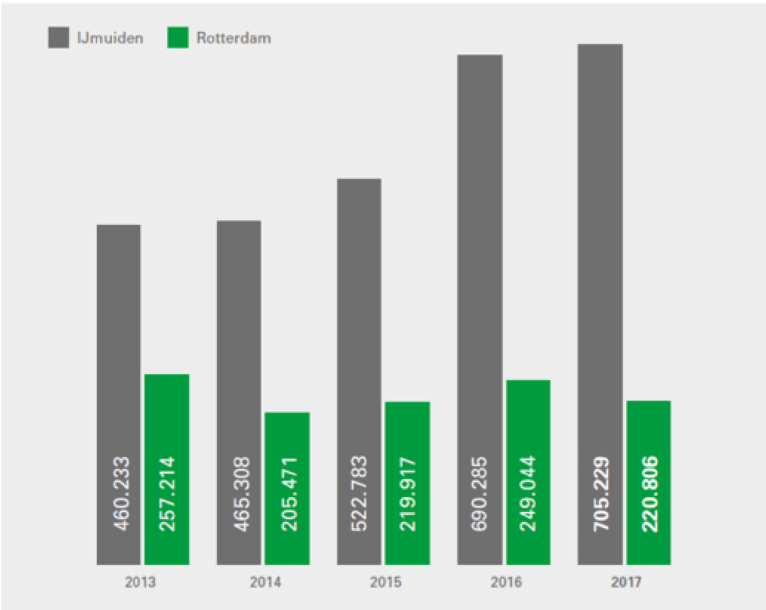

Figure 7 - Amount of blast furnace slag consumed in ENCI in tonnes (ENCI , 2017)

Another essential raw material for the Dutch cement sector is clinker. All types of cement produced in IJmuiden and Rotterdam use clinker as one of the main components, but especially in the Portland cement CEM I, composed of 95-100%wt of clinker. The other main type of cement produced, BSF cement CEM III, contains around 20-64%wt of clinker, respectively **(ENCI, 2020b) (ENCI, 2020c)**. The industrial sites are becoming relatively more dependent on clinker since the cement production is continuously increasing, as shown in Figure 8. From 2017 onwards it is expected that the clinker consumption has increased even more. This, alongside with the Maastricht site's closure tends to increased import dependence of this good.

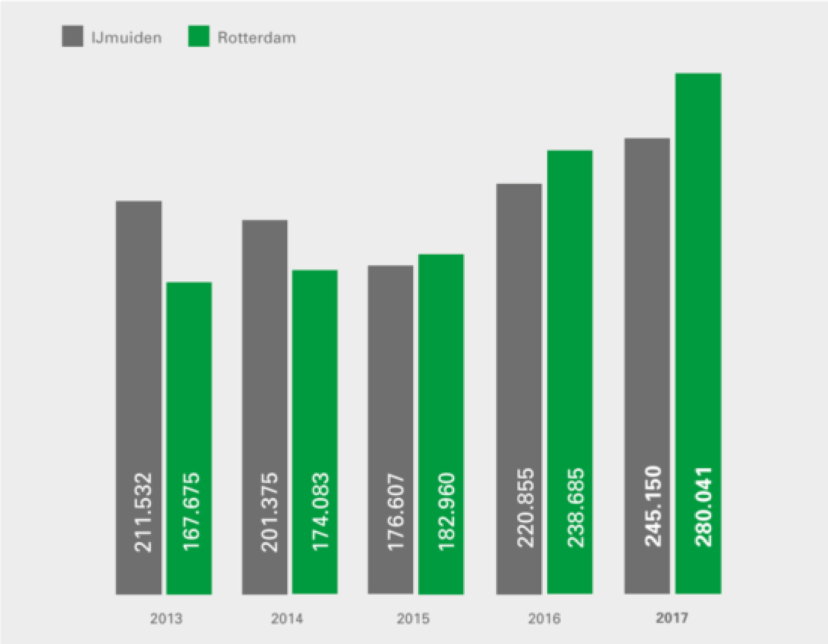

Figure 8 - Amount of clinker consumed in ENCI in tonnes (ENCI , 2017)

Calcium sulphate and limestone are the other raw materials used in ENCI's cement manufacturing. After the recent closure of the Maastricht factory, it is expected that the IJmuiden and Rotterdam sites will work in almost full capacity running continuously. For that reason, the values presented in Figure 5 and Figure 6 are estimates of the raw materials consumption for the total capacity of both plants. Table 1 also displays the original values shared by the company and the drafted estimates.

Table 1 - Estimation for raw materials input in Rotterdam and IJmuiden (ENCI , 2017), (internal communication with the company, 2020)

FULL PRODUCTION CAPACITY ESTIMATE		
	IJmuiden	**Rotterdam**
Production Capacity kt/yr)	1,400	600
Clinker (kt/yr)	343	280
Blast Furnace Slag (kt/yr)	987	221
Calcium Sulphate (kt/yr)	17	25
Limestone (kt/yr)	52	74

2.1.2 Drying Process

The BFS that is supplied for the Dutch cement production is still wet and needs to be dried before being dosed and incorporated into ENCI's final product. For this reason, the Rotterdam industrial site uses an individual dryer before the grinding facilities. The IJmuiden site uses a drying process coupled with a roller press, step that occurs previously to the ball mill grinding. Both drying methods use natural gas as fuel, and they are the only significant source of scope 1 emissions (direct CO_2 emissions on-site) in this process (internal communication with the company, 2020). It was considered that all emissions registered at the industrial site come from this process step with the burning of fuel in order to estimate the amount of natural gas used for the drying process (Zijlema, 2018). Then, each industrial site's most recent emission records and literature values for the CO_2 emission per m^3 of the fuel were used, generating the results presented in Table 2. The values and the estimations for full load capacity are also presented. Also, it is important to highlight that there is relevant energy losses in industrial gas dryers. For indirect dryers, there are around 30% losses already in the heat exchange of the drying gas to the substrate. For direct dryers, even almost all of the heat carried by the natural gas is passed into drying air, thermal energy losses to the environment and released with exhaust gases reduce the overall energy efficiency to 60% or less (Kudra, 2012).

Table 2 - Estimation of natural gas consumption for the ENCI Rotterdam and IJmuiden (Zijlema, 2018).

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	Rotterdam
Production Capacity (kt/yr)	1,400	600
CO_2 Emission (kt/yr)	19.3	7.2
Natural Gas Consumption (million m^3/yr)	10.7	4.0
Natural Gas Consumption (TJ/yr)	340.3	127.4

2.1.3 Dosage Process

The dosing process carried out in the production of cement serves mainly to control the quantity of each type of cement produced. According to ENCI (2020a, 2020b, 2020c), there are two different types of cement produced within the Dutch production chain:

- CEM I Portland cement (95-100%wt clinker)
- CEM III Blast Furnace Slag cement (20-64%wt clinker; 36-80%wt BFS).

2.1.4 Grinding Process

The process of grinding raw materials is also essential to allow differentiating quality and applications to the cement produced. Grinding is the most electricity-intensive process in cement manufacturing, being responsible for 60 to 70% of the electrical energy used in the whole European cement production chain (ECRA, 2015). In the Dutch industry, this number increases from 90 to almost 100%, since it does not have the early stages of processing the marl for clinker formation. The grinding configuration for both industrial sites is different from each other. In the Rotterdam site, two ball mills are used in the grinding process. This method is reported in the literature as the least energy-efficient way to grind the cement, consuming around 30 to 42 kWh per tonne of ground mix. For IJmuiden, the configuration uses a combination of a roller press for pre-grinding and two ball mills for grinding. The roller press as a pre-grinding installation helps to improve the energy efficiency of the process, being reported to have a potential decrease in electricity consumption of up to 30%, or 8-12 kWh per tonne of ground mix (IFC, 2017). Also, it is important to notice that the grinding process is intrinsically a low efficiency process, where up to 80% of the energy is dissipated as heat (Napier-Munn, 2013). Considering those values, Table 3 presents an estimation for the energy consumption of this process on each industrial site. After the grinding process, the cement is ready to be packed and stored/transported.

Table 3 - Electricity consumption for the grinding process - ENCI

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	Rotterdam
Production Capacity (kt/yr)	1,400	600
Pre-Grinding Configuration	ROLLER PRESS	-
Grinding Configuration	BALL MILL + BALL MILL	BALL MILL + BALL MILL
Electricity Consumption (TJ/yr)	241 – 381	155 – 180

2.2 Greenhouse gases emissions for the Dutch cement production

Clinker production is the main source of CO_2 emissions in the cement sector, but The Netherlands does not produce this material inside its borders. Hence, the reduction of the carbon emissions related to the production of clinker outside the country is not the primary focus of this study. Since the Dutch cement industry's current configuration is composed by only grinding and dosing, the scope 1 emissions are remarkably lower compared to other cement industrial sites with coupled production. For that reason, emissions related to clinker production will be mentioned in this chapter to provide a complete view of cement production and also be further discussed in Section 4. Nevertheless, the accompanying MIDDEN dataset includes only scope 1 emissions and addresses the energy consumption per process unit.

For the CO_2 emissions related to ENCI's industrial process, the information for the IJmuiden production sites was retrieved from the NEA database with a value of 13.7 kilotonnes of CO_2 in 2019 (NEA, 2020). Since all the electricity consumption related to the grinding process is purchased and its emissions fall into the scope 2 (indirect emissions related to imported energy which is consumed by the process), all that CO_2 comes from the drying process. The Rotterdam site emissions are not in the ETS database, for that reason the information regarding its emissions was retrieved from the Emissieregistratie database (Emissieregistratie, 2020), showing an emission of 7.2 kilotonnes of CO_2 in 2005, which is the most recent data available (Emissieregistratie, 2020).

Taking into account that in 2018 around 0.56 kg of CO_2 was produced per kWh of electricity in the Netherlands (PBL, 2020) and that it is estimated that 0.9 tonnes of CO_2 are produced per tonne of clinker manufactured (Betonhuis, 2014), it is possible to estimate the number of emissions on scope 2 and 3 related to the cement production. Scope 3 emissions include the direct emissions related to the feedstock production; for the Dutch cement sites, the clinker production emissions are scope 3 because this material is produced elsewhere. Thus, Table 4 and Figure 9 present an overview of the estimated scope 1 emissions form the ENCI industrial sites and the emissions related to the scope 2 and 3, regarding electricity generation and the production of the clinker outside the Dutch borders, respectively. It is interesting to notice that the scope 1 emissions are assessed to represent only 2 to 5% of the sum of emissions of the whole production chain.

Table 4 - CO_2 emissions estimation for the ENCI Rotterdam and IJmuiden industrial sites

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	**Rotterdam**
Production Capacity (kt/yr)	1,400	600
SCOPE 1: ENCI direct emissions (kt CO_2/yr)	19.3	7.2
SCOPE 2: Electricity generation emissions estimation – outside the fence (kt CO_2/yr)	46.1	28.2
SCOPE 3: Clinker production emissions estimation – outside the fence (kt CO_2/yr)	309	252

NOTE: Emission factor of 0.56 kg of CO_2 per kWh of electricity in the Netherlands (PBL, 2020). Emission factor of 0.9 tonnes of CO_2 per tonne of clinker manufactured (Betonhuis, 2014).

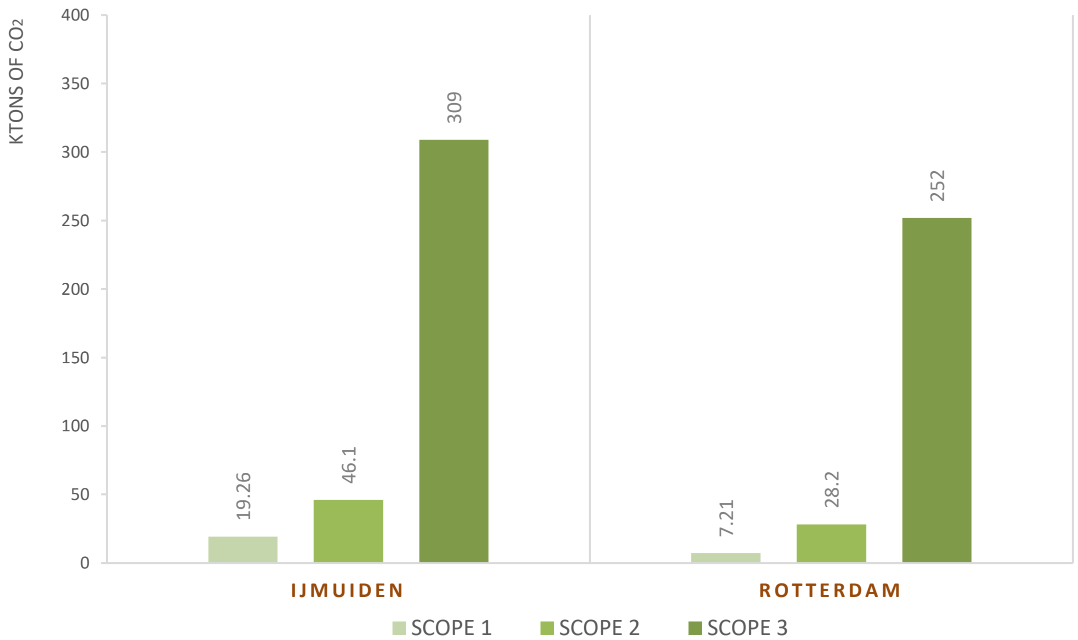

Figure 9 - Scope 1 emissions for cement production compared with the scope 2 and 3 emissions estimated for electricity consumption and clinker production (PBL, 2020) (Zijlema, 2018).

2.3 Overview of inputs and outputs of energy and materials

Considering the discussion, estimations and considerations above mentioned, it is possible to draft the input and output flows for energy and materials on the Dutch cement production, presented in the Table 5:

Table 5 - Overview of inputs and outputs of energy and materials for the Dutch cement industrial sites

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	Rotterdam
Energy Inputs (TJ/yr)	**703.2**	**308.8**
Electricity (TJ/yr)	362.9	181.4
Heat - Natural Gas (TJ/yr)	340.3	127.4
Energy Outputs (TJ/yr)	**630.6**	**272.5**
Water Vapour (TJ/yr)	238.2	89.2
Heat loss (TJ/yr)	102.1	38.2
Losses - Grinding Process (TJ/yr)	290.3	145.1
Material Inputs (kt/yr)	**1,399**	**600**
Clinker (kt/yr)	343	280
Blast Furnace Slag (kt/yr)	987	221
Calcium Sulfate (kt/yr)	17	25
Limestone (kt/yr)	52	74
Material Outputs (kt/yr)	**1,419.3**	**607.2**
CEM I (kt/yr)	131.3	308.8
CEM III (kt/yr)	1,268.8	291.3
CO_2 (kt/yr)	19.26	7.21

3 Cement products and application

Cement represents an essential value in our society and it is deeply integrated into our daily life. Its primary use is as a binder in concrete, a versatile and robust building material with a wide variety of utilization. It is used in practically every type of building, including houses, highways, skyscrapers, hospitals, industrial sites and ornaments like patios, floors, staircases, driveways, pool decks, and sculptures. Because of its extensive use, cement is the largest manufactured product in the world in volume.

3.1 Cement Products

There are different types of cement in the market, but they can be divided according to their composition. The European cement standard EN 197-1 specifies 27 types of cement and their components, which are classified into the subsequent classes (CEN, 2011):

- CEM I Portland cement (>95%wt clinker)
- CEM II Portland-composite cement (65-94%wt clinker)
- CEM III Blast furnace slag cement (5-64%wt clinker)
- CEM IV Pozzolanic cement (45-89%wt clinker)
- CEM V Composite cement (20-64%wt clinker).

The recent trends of environmental awareness on the carbon emissions related to clinker manufacturing are changing the production and consumption of these cement types. In Europe, the Portland cement, which was the most consumed type in the past, lost market share for the Portland Composite (CEM II) and Blast Furnace Slag Cement (CEM III). The most sold cement type in Europe is currently the CEM II-A, as shown in Figure 10, where clinker is replaced with limestone up to a full replacement of 20%wt (Favier, De Wolf, Scrivener, & Habert, 2018).

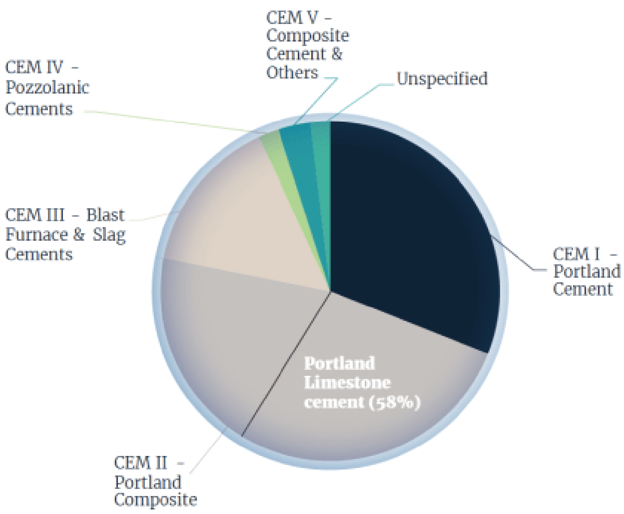

Figure 10 – European cement share by type in 2015 (Favier, et al. 2018).

Worldwide, the cement's primary use is on the building industry as the main material for concrete. According to the European Cement Association (2020), there are two main types of application: ready-mix concrete or prefabricated concrete. The first is manufactured in a batch-mixing industrial plant and distributed by a truck-mixer to the construction facilities. The prefabricated (or precast) is shaped and casted in a reusable mould, and transported to the construction site to be immediately used (Cembureau, 2020). Around 76% of the European cement produced is used within these two categories, where 56% goes for ready-mix concrete and 20% to precast concrete. Retailers, wholesalers, builders creating their own concrete, and mortars for big building sites consume the remaining 24% of the cement produced (Cembureau, 2020).

3.2 Cement global market

The total global cement production is about 4 billion tonnes (Cembureau, 2020). China is by far the biggest producer of cement globally, representing approximately 54.5% of world production, as shown in Figure 11. However, the Chinese market is almost wholly controlled by domestic suppliers, with little impact from multinational players. The second-largest market, India, also is mostly covered by large domestic companies such as UltraTech Cement, Dalmia Bharat, and Chettinad Cement, with not much international share or only locally-branded multinational subsidiaries **(Edwards, 2018)**.

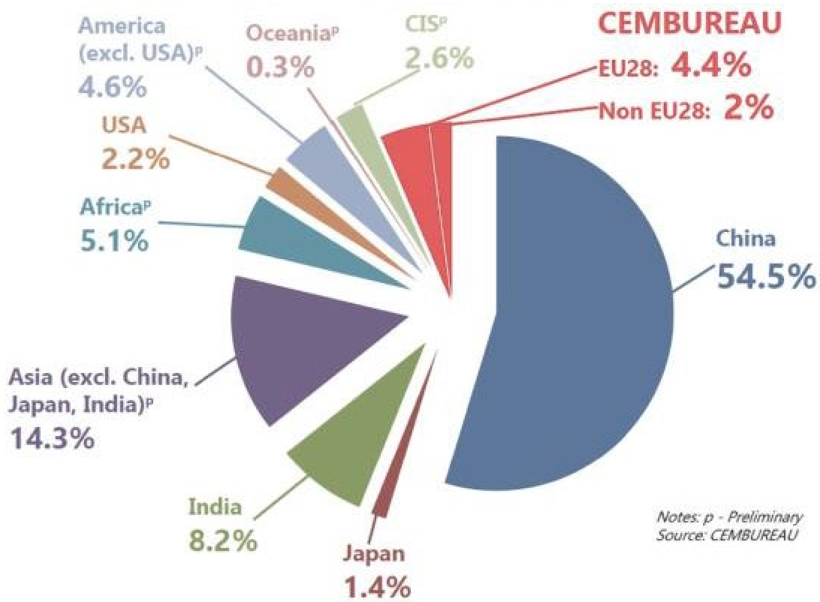

Figure 11 - World cement production share 2018 (Cembureau, 2020)[1]

Table 5 shows the leading players in the cement market, ranked by total cement capacity and excluding those from China, which are disproportionally big, and mostly only locally influenced.

[1] CIS refers to the Commonwealth of Independent States, which is a Eurasian organization with Russia as the largest member state.

Table 6 - Top cement producers worldwide (Edwards, 2018).

PRODUCER (ORIGIN)	CAPACITY (Mt/yr)	NUMBER OF PLANTS
LafargeHolcim (Switzerland)	345.2	220
HeidelbergCement (Germany)	185.4	141
Cemex (Mexico)	91.6	61
UltraTech Cement (India)	91.4	39
Votorantim (Brazil)	70.8	59
InterCement (Brazil)	53.5	42
CRH (Ireland)	50.5	54
Buzzi Unicem (Italy)	49.2	37
Eurocement (Russia)	47.2	19
Dangote Cement (Nigeria)	43.8	12

The cement market has been consistent in the past decades, with global production growth of more than 2.5 times from 2000 to 2013, stabilizing since 2014, as shown in Figure 12. The most significant influence that drove this increase at the beginning of the century was primarily China's domestic construction boom and development. This shows how correlated the urbanization and development processes are to the cement use and production. Also, cement industry operating margins (profit after costs and before taxes) have settled under 12% after the 2008 crises, but it reached the pre-2007 margin of around 14% in 2018, showing a positive financial tendency (Bjacek, 2019).

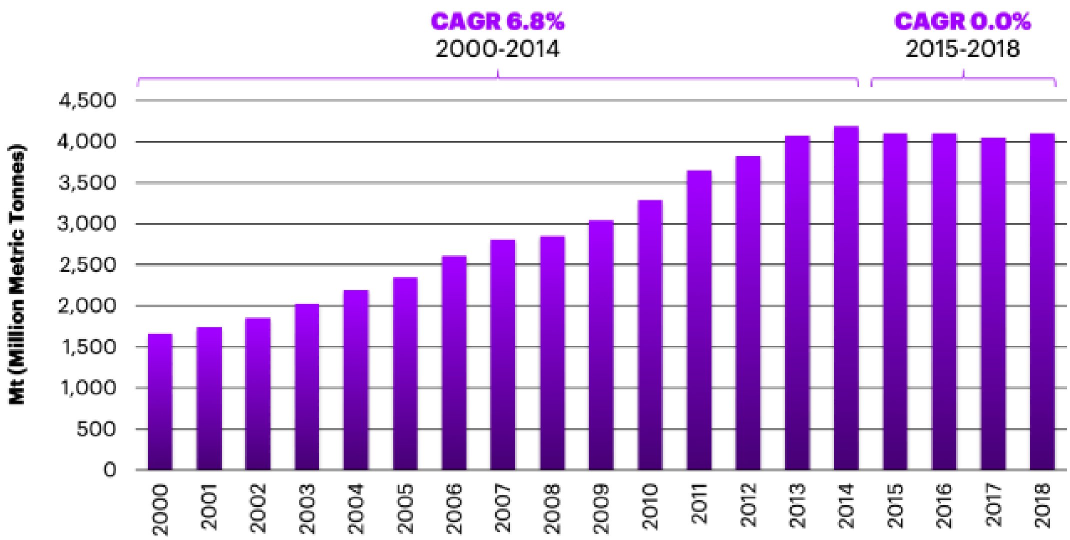

Figure 12- Global cement production (Bjacek, 2019).

Besides that, different factors such as population growth, urbanization in developing countries and infrastructure improvements are expected to increase cement production by 12-23% above the 2014 level by 2050 (IEA; CSI, 2019). Figure 13 shows the projection for the production pattern of cement across the world until 2050, showing how cement production levels vary extensively across regions. According to 2016 measures, the Chinese national cement production peaked in 2014, with a production per capita of 1.8 tonnes, way above the global values that range on 575 kg per capita. Other developing countries, such as India, are expected to extend their production to accomplish their infrastructure progress demands, rising three times the production level by 2050. According to this analysis, the Asia Pacific growth would remain relatively stable and represent almost the double of the current production over this period. This growth rate in India and Asia would be equivalent to more than 90% of Chinese production's expected growth rate reduction. The remaining foreseen global cement production expansion is in Africa, with more than triple, and America with almost double their current cement production level by 2050 (IEA; CSI, 2019).

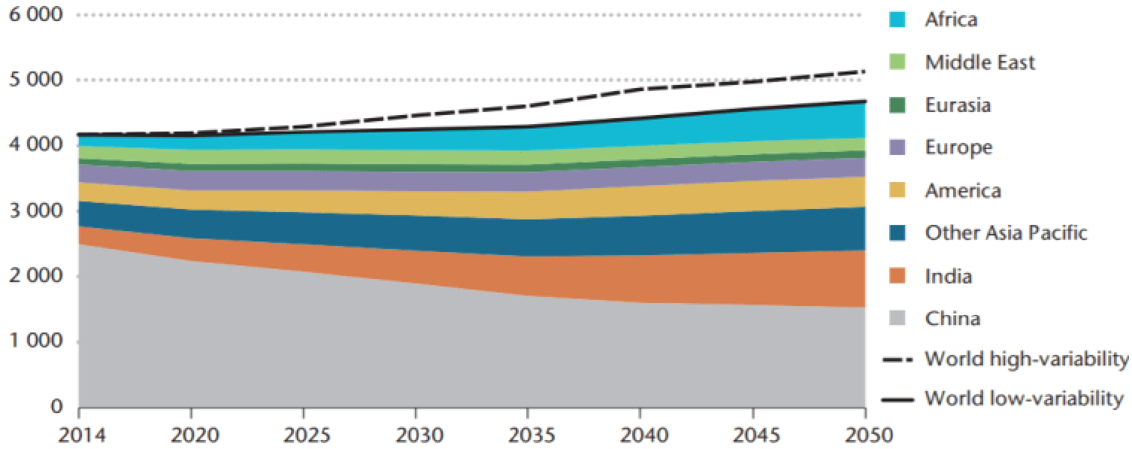

Figure 13 - Cement production by region towards 2050 (IEA; CSI, 2019)

Cement prices can vary across regions due to trade environments, input costs, and demand and supply, among other factors. Despite the recent lower demand from China, the market is today more mature and developed, leading to new market growth with more balanced prices due to the increase of supply-demand in emerging markets.

3.3 Dutch cement market

The cement consumption in the Netherlands, with roughly 5 Mtonnes, is only 0.1% of the worldwide consumption (Cement Online, 2017). Since the national production is responsible for only approximately 2 Mtonnes, a considerable amount of the country's cement consumed is imported, mostly from other EU countries. Besides that, even the cement produced inside the Dutch borders is dependent on imports, since the country has no clinker production anymore. However, as shown in Figure 14, the cement and clinker imports are decreasing in the past years. That can be understood as a direct response to the growing consumption and production of CEM III and CEM II within the Dutch production chain. In 2019, for example, around 54% of the Dutch cement consumption was still imported from outside the borders (CBS, 2020).

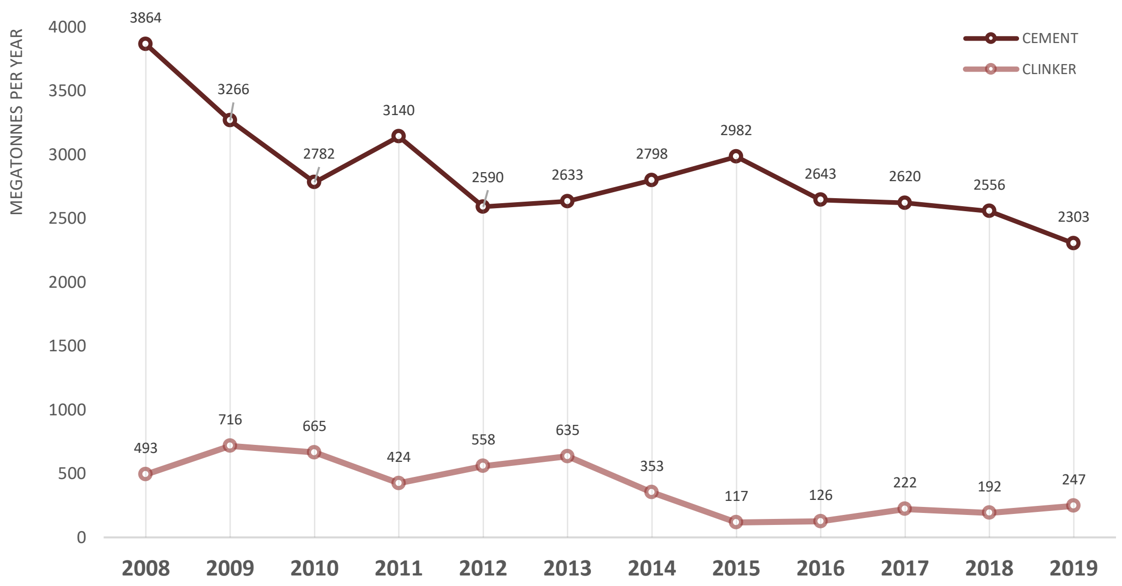

Figure 14 - Cement and clinker imports in the Netherlands. Data: (CBS, 2020)

Regarding cement consumption in the Netherlands, blast furnace cement share is reasonably steady, ranging around 50 to 60%. Also, the percentage is shared between Portland Cement (CEMI) with 35% and mainly Portland flying ashes (CEM II) with shares between 5 and 15%. CEM III leads the Dutch production, making the Netherlands a reference worldwide for production of low CO_2 BFS cement. The mortar industry uses from 50 to 55% from the total produced, while the concrete industry is responsible for about 35 to 40% of the cement consumption. The rest reaches construction projects via contractors, building material dealers, suppliers of floor and masonry mortar (Global Cement, 2012).

Analysing the expressive amount of cement imported by the Netherlands, it is noticed that the main imported types are also Portland Cement (CEM I) and alternative binders cement (CEM II and III). Figure 15 shows that, between 2008 and 2020, around 66% of the imports are of CEM I, while 28% are of CEM II and III. Calcium Aluminate Cement, a high-performance cement resistant to microbial corrosion and adequate for specific use in sewer infrastructures (Scrivener, Cabiron, & Letourneuxb, High-performance concretes from calcium aluminate cements, 2009), has 3% of the share, while other special cement, such as dental, resins and fireproof cement, has the other 3% (CBS, 2020).

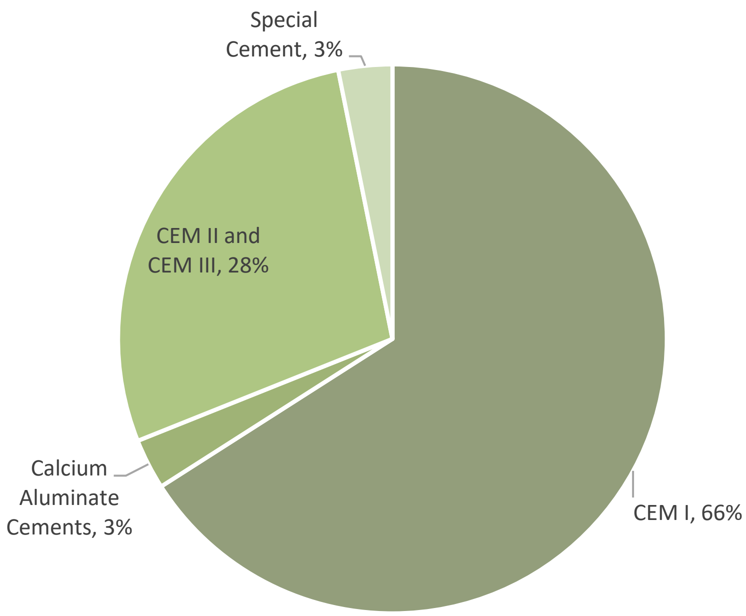

Figure 15 - Netherlands cement imports, 2008-2009 (CBS, 2020)

In the Netherlands, the import prices for Portland cement is relatively constant between 2008 and 2019. According to CBS data (Figure 16), the average price is between 60 and 85 euros/tonnes in that timespan (CBS, 2020).

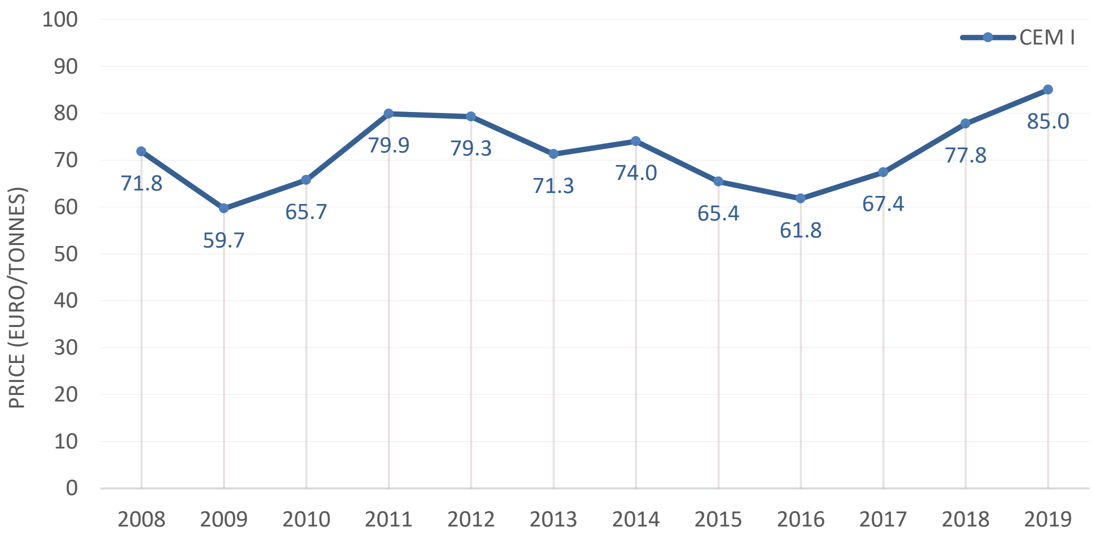

Figure 16 - Import prices for Portland CEM in the Netherlands from 2008 - 2019.

4 Options for cement decarbonisation

Many literature studies mention clinker production as the largest emitter of greenhouse gases in quantity. The carbon-intensive stage of clinker production, coupled with the massive demand for cement in the market, makes this commodity's emissions reduction very essential for the industry in general. As mentioned earlier in Section 2, the Dutch production in Scope 1 does not encompass the clinker production, since this is an imported feedstock, it fits within Scope 3.

Due to the cement industry's particularities, this chapter will be subdivided into "Primary Decarbonisation Alternatives", encompassing the options usually presented by the MIDDEN methodology and under the Dutch cement sites' limits, and "Other Decarbonisation Alternatives", analysing other alternatives outside the Dutch industry scope for a more holistic analysis. Only the primary options will be considered for the MIDDEN database, while the other alternatives will be mentioned in this report with the purpose to broaden the view regarding the whole production chain.

4.1 Primary Decarbonisation Alternatives

This section describes possible decarbonisation options for the cement manufacturing process. Conceptually, there are several different actions that can reduce carbon emissions in an industrial process. The methodology adopted in MIDDEN to explore and evaluate each option is illustrated by Figure 17. Literature review and analysis of each specific technology were key aspects of the investigation. The alternative solutions include the following topics that could play a role in the ENCI process decarbonisation:

- Fuel substitution (1): substitution of the (currently fossil) energy supply: e.g., biogas, hydrogen, recycled heat, or using electric energy.
- Feedstock substitution (2), e.g., with biomass, recycled flows, or other upstream material substitution.
- Energy efficiency improvements (3) that do not fall under incremental 'autonomous' efficiency improvement (which is currently 0.5% annually, but might reduce in the future).
- Use of residual energy (6) (heat), in company or externally.

Of these, only fuel substitution, energy efficiency improvements and in-house residual energy use lead to a reduction in scope 1 emissions, while feedstock substitution and external use of residual energy reduce emissions elsewhere.

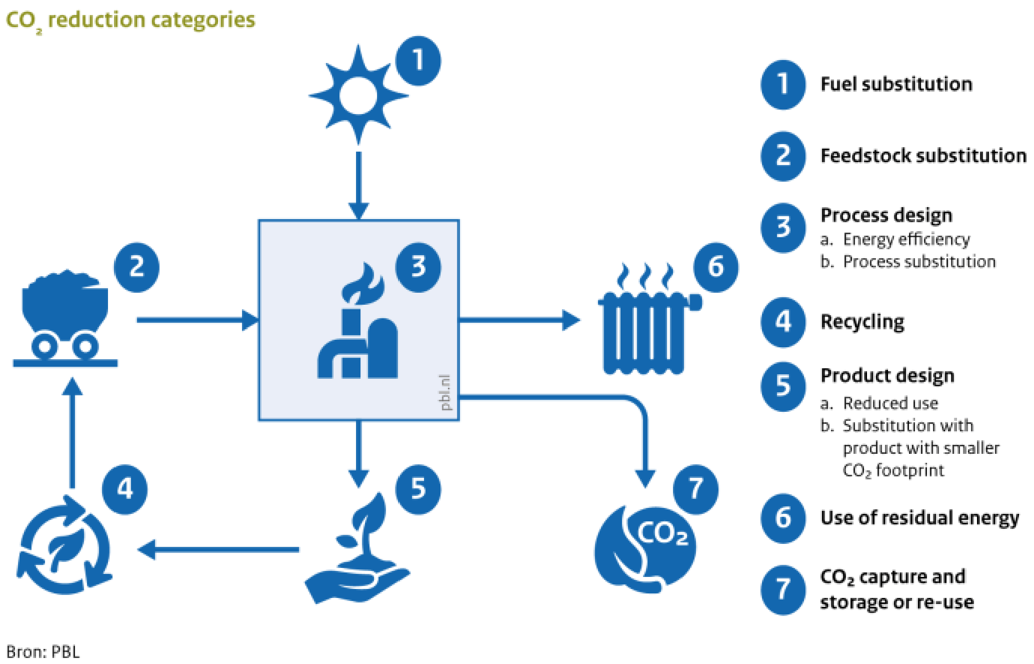

Figure 17 - CO_2 reduction categories investigated in MIDDEN

4.1.1 Fuel Substitution - Drying

The primary (and almost only) source of direct carbon emissions of scope 1 in the Dutch cement industry originates from the process of drying the wet Blast Furnace Slag. As Figure 5 and Figure 6 show, this process uses natural gas as the main fuel in IJmuiden and Rotterdam, the combustion generates the heat needed to remove the water content of the BFS granulates. Replacing this fuel with a lower carbon alternative or changing this process would be essential to reduce industrial site emissions. Among the existing alternatives, the following stand out:

1. Heat Pump Dryer:

Heat pump dryers are a novel technology that has developed from pilot projects to industrial utilisation in Norway. This type of dryer is designed to be thermally efficient, to operate in a closed-system of different fluids and to use electricity to increase and delivery optimal heat exchanges, with no emission to the climate and environment. For a full cycle sustainable drying process, the use of renewable sources of electricity should be used.

A heat pump dryer (HPD) is projected centring on capacity, efficiency, sustainability, and operation with environmentally friendly fluids (Alves-Filho, Walmsley, Varbanov, Su, & Klemeš, 2018). Figure 18 describes a simplified scheme of the several cooling elements integrated with the drying chamber in a general HPD mechanism. The input of drying air goes through the drying chamber at point 1 and removes the moisture from the product to be dried. The water-rich air at point 2 is directed to the evaporator.

There are two different types of evaporator systems that can be used. One is a direct expansion coil, where a refrigerant goes through a double-phase transition from liquid to vapor, cooling, and dehumidifying the air in this process. The other is a cooling water system where heat exchange with lower temperature that cools the air and dehumidify it uses water instead of a refrigerant. Figure 18 represents the schematic model of a refrigerant drying system in a drying chamber. The drying air 1 goes through the drying chamber, removing the humidity of the system. During this dehumidification, from point 2 to 3, the air exchange heat with the refrigerant and its temperature is lowered to its dew point, condensing its water content. The heat removed from the system is absorbed and used to boil the refrigerant (or cooling water) to a vapour state in the evaporator. The high-temperature refrigerant is then pumped to the condenser (3), increasing even more its enthalpy in this process. The dried air from the drying chamber goes to be heated again in the condenser (4), exchanging heat again with the refrigerant in the condenser moving to the starting point 1 when it is used again used in the drying chamber (Chua, Chou, Ho, & Hawlader, 2002). This operation is only possible due to the different temperatures and pressures that allow the heat change between the refrigerant and the drying air, using electricity as an energy source.

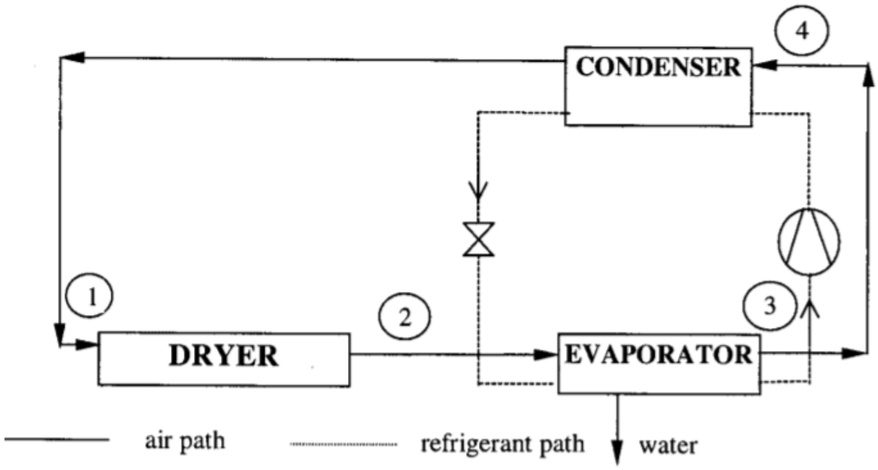

Figure 18 - Schematic representation of heat pump drying system (Chua, Chou, Ho, & Hawlader, 2002).

Among the advantages of this type of drying are improvements in energy efficiency, accurate control of drying conditions, flexibility to a wide range of drying conditions, an increase of throughput and reduced operational costs. The disadvantages are related to maintenance costs, refrigerant leaks, and high capital expenditure when compared to other drying mechanisms (Chua, Chou, Ho, & Hawlader, 2002).

2. Hydrogen Dryer

An alternative to this process would be to replace the fuel with hydrogen. For this option be considered as a decarbonization alternative, the hydrogen used should be either 'blue' (methane reforming while capturing the formed CO_2) or 'green' (electrolysis with renewable electricity). Although the use of hydrogen for drying processes has not yet been applied on a large scale, this is a fuel with relevant potential for replacing natural gas. Hydrogen combustion is a very exothermic process and produces water vapor, following the chemical reaction:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \quad \Delta h = -286kJ/mol$$

The amount of hydrogen needed to produce the same amount of energy for the drying process is described by Table 7. The caloric values are according to RVO (Zijlema, 2018).

Table 7 - Hydrogen demand for drying (own calculations)

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	Rotterdam
Natural Gas Consumption (million m^3/yr)	10.7	4
Natural Gas Consumption (kt/yr)	8.6	3.2
Energy Demand for Drying (TJ/yr)	340	127
Hydrogen Demand (million m^3/yr)	31.5	11.8
Hydrogen Demand (kt/yr)	2.7	1

3. Biogas Dryer

One option of biogas that could be used is Substitute Natural Gas (also called SNG, biomethane, and green gas), the upgraded form of the biogas produced by anaerobic digestion of organic substrates. The upgrade of biogas is done by removing the CO_2 content and cleaning the siloxanes (organic materials, such as chlorine and sulphur), resulting in a gas with the same natural gas characteristics (RVO, 2019). In that way, the production process would remain exactly the same, as well as the mass and energy flows; only the type of fuel would be changed. Instead of upgrading the biogas to SNG, the biogas may also be used directly without upgrading. The current Dutch biogas production is limited to agriculture (manure), sewage sludge treatment (industrial and public) and some house hold waste (GFT) treatment, therefore, which brings constraints for sourcing this fuel to the cement sites.

4. Solar Dryer

Solar thermal energy is used for drying processes for a long time, even before the most evolved societies developed. However, solar drying for industrial-scale operations is still little used since the use of fossil fuels for this purpose began. More recently, environmental concerns and the desire to decarbonise the industry, have led research and some sectors to evaluate new ways to use this source of energy in their processes. The use of these kinds of technologies may contribute to the transition to a low-carbon energy future (Kamfa, Fluch, Bartali, & Baker, 2020). Therefore, new technologies have emerged to increase efficiency and use solar energy for drying processes applications.

Today, the primary forms of solar drying in the industry can be divided in three main categories:

- solar natural dryers using natural energy sources only;
- semi-artificial solar dryers, with a fan connected to an electric motor to keep a continuous airflow in the drying space; and
- solar-assisted artificial dryers, able to operate using conventional energy sources, if needed.

Each of these categories may present different configurations of drying systems, with different designs, sizes, temperature ranges, and objectives. Those different configurations should be considered when analysing the best options for the BFS drying in the Dutch Cement industry. Given the specifications of the cement process, the solar-assisted dryer with heat pump and heat storage could be a good option. For the Netherlands, due to the rate of solar radiation not being as high as in tropical countries, relying only on solar energy for drying can be risky at some times of the year. This type of configuration, however, can work with or without the use of solar energy. It is a combination of a heat pump with thermo-solar panels, that increases energy efficiency and can make it even independent of electricity, providing the same drying effect of a standard heat pump.

Figure 19 shows this configuration with two different paths in this system, one with airflow (stripped line) and the other with the refrigerant (continuous line) (Mohammod & Rahman, 2003). The air system is composed of the solar air collector, air-cooled condenser, auxiliary heater, blower, dryer unit, dehumidifier, temperature controller and dampers. The solar air collector warms the circulating air and then passes over the condenser coil, where it is heated even more by the energy released by the condensing refrigerant. The air is, therefore, used for drying purposes, so depending on the temperature and the meteorological conditions, there is no need to use electric energy or the refrigerant cycle in the process. Then, the airflow that leaves the dryer is cooled and dehumidified, and the heat removed goes to the air-cooled condenser to be used in the next cycle.

For the refrigerant flow path, the different components are dehumidifier, collector evaporator, an open type reciprocating compressor, evaporator pressure regulators, expansion valves, condenser tank and a fan coil unit. Also, in a clear vision, the refrigerant gas that comes out of the air-cooled condenser goes through the coil submerged in a tank, heating the water by releasing the heat and assuring complete condensation (Mohammod & Rahman, 2003).

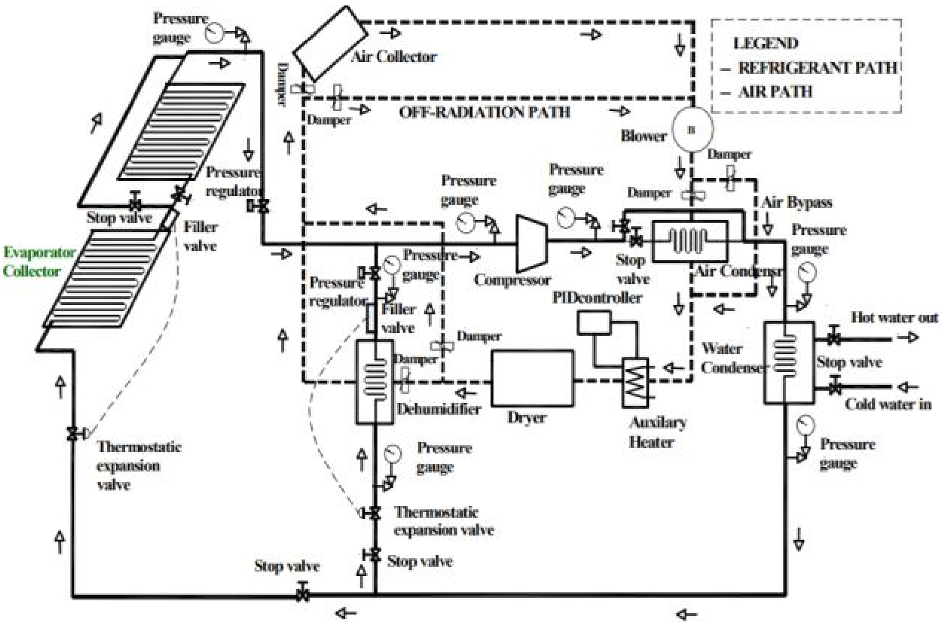

Figure 19- Solar Dryer with heat pump and heat storage (Mohammod & Rahman, 2003).

5. Waste Heat from other industrial sites

The BFS drying is an energy-intensive process that could benefit from the utilization of waste heat from other near industrial sites for drying or even pre-drying. Industrial waste heat is described as heat discarded from industrial processes, which is utilized for other processes within the same industrial site or not. This waste heat comes in the form of different thermal carriers, in which the most common ones are exhaust gas, flaring gas, low-quality steam, cooling air, hot oil, cooling water, or even hot steel. Both ENCI grinding factories are located in an industrial cluster, close to other industrial sites that could provide a source of waste heat for the drying process. Those synergies would need to be evaluated, but Figure 20 shows the synergies that the IJmuiden industrial cluster has correlated with the Tata Steel industrial site and with other industries (Gorazd Krese; Boštjan Strmčnik; Vera Dodig; Boris

Lagler , 2019). Besides sourcing BFS to ENCI IJmuiden, Tata Steel also provides steam to other industries.

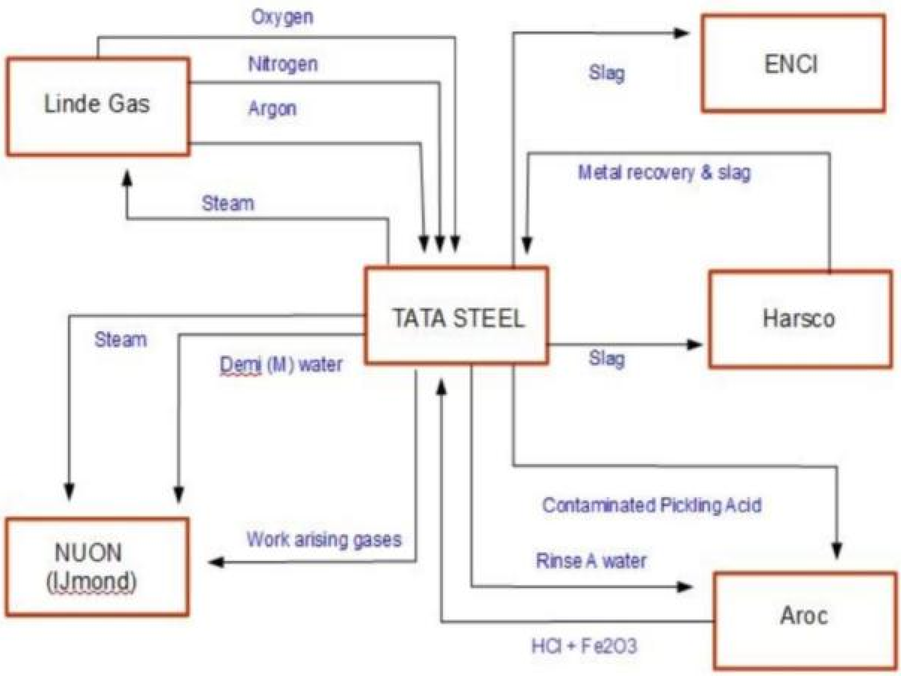

Figure 20 - Current Industry Symbiosis in IJmuiden industrial cluster (Gorazd Krese; Boštjan Strmčnik; Vera Dodig; Boris Lagler , 2019)

Cost Analysis

Table 8 presents the cost analyses for the drying techniques presented in this section. Natural gas is the current technology used. Only its operational costs were considered, adding the fuel cost to the maintenance and operation costs concerning its power capacity, according to Global Petrol Prices (2020). For the industrial closed heat pumps, its variable operation and maintenance (O&M) costs are fully dependent on the electricity price according to Lensink (2020). The heat pump has an expected lifetime of 12 years and its efficiency (expressed as the energy output per electricity consumption, or COP) is for this purpose assumed to be 3.5 as in the SDE subsidy scheme (Lensink, 2020). For the hydrogen and biogas (SNG) alternatives, this study considers that only operational costs would change due to the fuel and O&M changes, according to parameters found in Elzenga & Lensink (2020) and Gorre (2019), respectively. No specific information about costs for solar and waste heat drying were found in the literature for the capacity required for ENCI industrial site. The capital costs consider in its calculation the necessary modifications and new equipment to run the new process. Theoretically, for SNG as biogas, the fuel would be similar enough to the original natural gas to an extent of not needing changes in the infrastructure. For using hydrogen however, modifications or even new equipment would be probably needed, but due to lack of information on hydrogen dryers in the literature, that cost could not be estimated. The operational costs consider workforce, maintenance and operation according to the literature, excluding the costs for utilities (electricity, water, fuel costs).

Table 8 - Costs figures of drying techniques (excluding utilities)

TECHNOLOGY	IJMUIDEN			ROTTERDAM		
	Capacity (TJ/yr)	CAPEX ($MEURO_{2020}$)	OPEX ($MEURO_{2020}$/yr)	Capacity (TJ/yr)	CAPEX ($MEURO_{2020}$)	OPEX ($MEURO_{2020}$/yr)
Heat Pump[1]	340.3	13.47	0.296	127.4	4.93	0.108
Hydrogen Dryer [2]	340.3	Unknown	0.44	127.4	Unknown	0.306
Biogas Dryer (SNG)[3]	340.3	0	0.162	127.4	0	0.097

1 - **(Lensink, 2020)**
2 - **(Elzenga & Lensink, 2020)**
3 - **(Gorre, 2019)**

4.1.2 Process Design Change – Grinding

The process of grinding substrates to form cement is one of the most energy-intensive processes in the production. In the case of ENCI's industrial plants, this process uses the configuration of two ball mills in Rotterdam and one roller press and two ball mills in IJmuiden. The ball mills are reported as one of the least energy-efficient for the cement industry with an energy consumption of between 30-42 kWh per tonne of grounded material. More energy-efficient configuration options for that process would be the following (ECRA, 2015):

- **Roller Press as pre-grinding**, with 8-12 less kWh per tonne of ground material
- **Vertical roller mill**, with 21-33 kWh per tonne of ground material
- **High pressure grinding rolls**, with 23-30 kWh per tonne of ground material

The above alternatives for configurations could represent significant energy savings for the ENCI Rotterdam and IJmuiden industrial sites, as shown in Table 9. By using a configuration with Roller Press and Vertical Roller Mill, for example, it would be possible to save up to 26% of energy in Ijmuiden and up to 42% in Rotterdam.

Table 9 – Energy demand for using roller press as pre-grinding coupled with different grinding configurations (ECRA, 2015).

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	Rotterdam
Production Capacity (kt/yr)	1,400	600
Capacity Utilization	100%	100%
Actual Grinding Configuration ENCI	ROLLER PRESS + 2 BALL MILL	BALL MILL+ BALL MILL
Actual Configuration Energy Consumption (GWh/yr) ENCI	67-106	43-50
Roller Press + 2 Ball Mill Configuration (GWh/yr)	67-106	29-47
Roller Press + 2 Vertical Roller Mill Configuration (GWh/yr)	42-81	18-35
Roller Press + 2 High-Pressure Rolls Configuration (GWh/yr)	48-73	20-31

Additionally, **high-efficiency classifiers** that separate the fine grains from the ones that still need to be grounded, can reduce operation costs. This technology has a range of energy reduction between 0-6 kWh per tonne of material ground (ECRA, 2015). It could represent relevant energy saving for the ENCI Rotterdam and IJmuiden industrial sites, as shown in Table 10 with an estimation of the energy saving that could be reached for this alternative. The use of high classifiers could represent up to 12% electricity saving for the Ijmuiden industrial site and 8.4% for the Rotterdam site.

Table 10 - Energy savings of different grinding technologies (ECRA, 2015).

FULL PRODUCTION CAPACITY ESTIMATION		
	IJmuiden	Rotterdam
Production Capacity (kt/yr)	1,400	600
Capacity Utilization	100%	100%
Using High-efficiency classifiers (GWh/yr)	8.4	3.6

Cost Analysis

Table 11 presents the cost analyses for the grinding alternatives in this section. All the utilized parameters, capital, and operational costs were retrieved from the ECRA (2015) report on "*Future Grinding Technologies for the Cement Industry*", considering installation of new equipment, maintenance and operational costs, excluding utilities costs. The capital cost includes investment in new mechanisms and installations and structural improvements required for applying each technology.

Table 11 - Cost analysis for grinding techniques

TECHNOLOGY	IJMUIDEN			ROTTERDAM		
	Capacity (Mt/yr)	CAPEX (MEURO2020)	OPEX (MEURO2020/yr)	Capacity (Mt/yr)	CAPEX (MEURO2020)	OPEX (MEURO2020/yr)
Actual Configuration	1400	-	1.54	600	-	0.66
Roller Press + 2 Ball Mill	1400	-	1.54	600	10.5	0.66
Roller Press + 2 Vertical Roller Mill	1400	24.5	1.54	600	21	0.66
Roller Press + 2 High-Pressure Rolls	1400	46.2	1.54	600	19,8	0.66
High-efficiency classifiers	1400	2.36	0.56	600	1.14	0.24

4.1.3 Alternative Feedstock – Clinker Substitutes

An alternative that would help reduce the amount of carbon emitted in the cement production process is the substitution of clinker by new feedstock with less embodied carbon. This would reduce emissions of cement suppliers, which currently happens outside The Netherlands. Today, ENCI already uses alternative feedstock (BSF, fly ash, and limestone) in higher amounts than the competitors, but this could be further expanded with other alternative binder materials, especially for clinker replacement (Global Cement, 2012). New alternatives are being researched within the cement industry, such as:

1. Use of Blast Furnace Slag

This method of clinker substitution is already primarily done by the ENCI industrial site, especially in IJmuiden, and it uses granulated blast furnace slag (GBFS) as another main constituent of the manufacturing process. In that way, less clinker is needed per ton of cement, reducing the CO_2 emissions and the embodied carbon content of the final product. The use of GBFS may also require additional fuel for drying and extra electricity for grinding, depending on higher fineness (ECRA, 2017). The European standard EN 197-1 (CEN, 2011) defines nine cement types with up to 95 wt% GBFS or even up to 80 wt% of a mix of GBFS and pozzolana (where the maximum amount of GBFS in the blend is 50 wt%). The mechanical performance and the use of those extremely high GBFS content cement is still being debated in many nations and on a European level. However, in practice, the amount of GBFS technically viable to be used in cement usually ranges from 30 to 70 wt% (ECRA, 2017). The both ENCI industrial sites are in line with these standards, IJmuiden having 70% of BFS as cement raw materials, and Rotterdam with around 40%. This difference in the consumption of GBS relates to the demand and the material availability in each industrial site, but there is still room to grow.

2. Use of Fly Ashes

Fly ash is produced by the precipitation of powdery particles from flue gases of furnaces after burning pulverized coal. The material forms a fine dust-like and chiefly spherical particle with pozzolanic properties (property of reacting with calcium when exposed in order to moisture to form compounds possessing cement properties), which may also have hydraulic characteristics. The incorporation of fly ash in the cement mix demands electricity for grinding and blending, but decreases the cement production's thermal energy requirement almost linearly. The fly ash content in practical matters used in the industry is usually restricted to about 25 to 35 wt% (ECRA, 2017). In the Dutch industrial plant already used Fly ash to produce CEM II, but the manufacturing process of this type of cement ended in 2019 (internal communication with the company, 2021).

3. Use of Natural Pozzolanas

The manufacturing of cement with pozzolanic materials as one of the primary constituents diminishes the quantity of clinker required, directly reducing also the embodied carbon content of the final product. Pozzolanas are materials with a siliceous or silico-aluminous composition. They can react to water or moisture at ambient temperature, dissolving into calcium hydroxide ($Ca(OH)_2$) and producing a cement-like composite of calcium silicate and aluminate hydrates. The cement types include pre-processes of crushing, drying, grinding, and inter-grinding or combining the cement clinker with the pozzolanic substance. The electric energy demand is expected to be lower due to the more favorable grinding properties of pozzolanas compared to clinker. Also, the thermal energy demand reduces approximately in a linear way with an addition of the pozzolana being able to reduce up to 14% when compared with Clinker cement (ECRA, 2017).

4. Use of Natural Calcined Pozzolanas

Natural calcined pozzolanas are regularly thermally treated clays used for cement production. With the heat, the material releases physically and chemically fixed water. Its structure changes, resulting in silica and alumina composites that can react with water to form a cement-like material. Pure kaolin is the most suitable clay to be used as raw material for that process, but clays of lower grade or mixtures of several different clays are the most economically feasible because of their availability. The production process encompasses the pre-treatment of the clay, succeeded by grinding and mixing the regular clinker with the pozzolanic material. Since calcined clays of lower grade do not react as fast as clinker, the properties of compressive strength of cement decrease when growing calcined clay proportions, and according to EN 197-1 (CEN, 2011), the content of reactive silicon dioxide must be at least 25 mass% (ECRA, 2017).

5. Use of Limestone

An easy and effective solution to reduce the clinker content of cement is the use of limestone. The grinding characteristics of limestone are also more fitting to the production than clinker. This drives to an electrical demand reduction coupled with CO_2 emission reduction and thermal energy demand decrease. Limestone-rich cement usually shows reduced water demand for reaction, driving to a more desirable workability of concrete. Nevertheless, these types of cement have to be crushed finer to produce the equivalent strength as Portland cement. The balance between limestone and the cement content is crucial for concrete’s endurance to carbonation and other natural adversities (ECRA, 2017). The EN 197-1 restricts the proportion of limestone in cement to 35 wt% (CEN, 2011). Usually, cement plants are located in limestone-rich regions, which facilitates the extraction process and also its use as a clinker substitute, but this is not the case of ENCI. However, limestone could also be provided by the Belgium industrial site that sources clinker to the company.

6. Belite Cements

Ordinary Portland cement (OPC) clinker comprises 40 to 80 mass% alite (impure tricalcium silicate, C3S). In contrast, belite-rich clinker (belite is impure dicalcium silicate, C2S) can be produced in the same way as OPC clinker, but contains no or only small amounts of alite and up to 90 wt% belite, with less calcium and produced at lower temperatures (around 1350 °C). In principle, fuel energy and CO_2 emissions can be avoided due to the decrease of limestone content in the feedstock and the lower reaction temperature. One disadvantage is the improved resistance of belite, requiring extra energy for the grinding process. Another difficulty of manufacturing belite clinkers is its low hydraulic reactivity compared to alite, that leads to a slower strengthening process, considered unsatisfactory by most customers. For the hydration process, less water is needed, lowering the water/cement proportions. Consequently, the pore formation of hard concrete can be notably enhanced, driving to improved long term strength and durability (ECRA, 2017).

Table 12 presents a comparison between the feedstock alternatives regarding their substitution ratio percentage, impact on the thermal and electric energy demand, impact in the direct and indirect CO_2 emissions and costs according to ECRA (2017).

Table 12 – Alternative binders comparative impact on the cement production (ECRA, 2017)

MATERIAL INPUT	RATIO (%)	THERMAL ENERGY (MJ/t cem)	ELECTRIC ENERGY (kWh/t cem)	DIRECT CO_2 (kg/t cem)	CAPITAL COST (€/t cem)			OPERATIONAL COST (€/t cem)		
					2015	2030	2050	2015	2030	2050
Clinker	100	2,879	514	900	-	-	-	-	-	-
Blast Furnace Slag	30-70	1,289	524	270	5 to 10	5 to 10	5 to 10	-6.4	-8.5	-10.6
Fly Ash	25-35	2,519	499	675	8 to 12	8 to 12	8 to 12	0.7	0	-0.9
Natural Pozzolanas	0-35	2,519	517	675	8 to 12	8 to 12	8 to 12	-2.9	-3.5	-4.1
Calcined Natural Pozzolanas	0-35	2,729	509	202	8 to 12	8 to 12	8 to 12	-7.2	-8.5	-9.9
Calcined Natural Pozzolanas with Limestone	15-50	2,499	507	450	8 to 12	8 to 12	8 to 12	-7.2	-8.5	-9.9
Limestone	10	2,519	509	820	8 to 12	8 to 12	8 to 12	2.7	3.1	3.7
Belite Cement	100	2,679	554	883	0 to 12	0 to 12	0 to 12	3.8	4.5	5.3

The values considered in this table correspond to an estimation of the thermal energy consumption, electricity consumption, CO_2 direct emissions and costs when applying the alternative binders for cement production specified on the maximum ratio proportion equivalent. The estimation costs are in $EURO_{2019}$.

4.2 Other Decarbonisation Alternatives

The cement industry has a critical participation in building a sustainable future for being the most voluminous manufactured product globally and, at the same time, being such a carbon-intensive product. The patterns of carbon consumption show that its demand tends to increase, especially considering the infrastructure improvements in developing regions driven by population and economic growth. For that reason, understanding the entire cycle of cement impacts, from mining to its use, is important to value its impact and consider solutions. Therefore, the goal of this section is to move a bit further and present options on how this product could be a tool for decarbonisation in Scope 3, beyond the industrial production process of the Dutch cement industry and considering its applications and use.

4.2.1 Sustainable clinker production

Making the clinker production sustainable and carbon-free is reasonably the most challenging goal of the current cement industry. Clinker is still the most economically feasible alternative for meeting the cement demands due to its cheap and abundant stock of raw materials and simple production process. However, its current production process depends on the use of a large amount of thermal energy, the majority from fossil fuels (mostly coal). For that reason, searching for alternatives to make the clinker production more sustainable without compromising cement competitiveness is a challenge. Several options to make clinker more sustainable are being studied, from which are highlighted the following:

1. Biomass as alternative fuel

Fuel replacement is one of the most debated CO_2 mitigation proposals for the cement industry. Usually, within the industry, it relates to switching coal for oil or gas, which are more refined forms of fuel that emit relatively less greenhouse gas (GHG) emissions, although they are still fossil fuels. One alternative that is being more considered in this sphere and that could be a better way to control the carbon emissions would be using biomass as the primary fuel. For example, the CO_2 abatement potential of changing from hard coal to heavy fuel oil is about 16%, while switching to natural gas would lead to a 40% reduction, but at the same time, switching to biomass could drive to a 100% emission factor reduction, taking into account its net emissions from fuel use. Several types of biomass could be used in the cement industry, such as biomass wastes, waste wood, rice husk, sawdust, and sewage sludge. It is also possible to use organic substances as biomass fuel, enabling the use of liquid biomass and biomass products, such as oils, corn, woods, and even certain grass types. A different range of factors should also be considered to decide the best fuel to use, such as availability, cost, farming conditions, and land use (ECRA, 2017). Moreover, the use of biomass as a sustainable fuel alternative is still a topic of debate.

2. Kiln electrification

Using electricity as the primary source to provide thermal energy could contribute to decarbonising the clinker production. Several pilot projects are being explored with different technologies to electrify the cement manufacturing; including, for example, creating heat via plasma generators or even using microwave energy. The majority of those technologies are still in the experimental phase waiting to be developed beyond the laboratory (European Commission, 2019). A critical step towards this goal of electrification is the CemZero project, from a partnership between Vattenfall and the Swedish cement manufacturer Cementa, which is currently investigating the best technology toward clinker production electrification (EIR, 2019). This pilot project showed that the electrification of the heating in the cement process is technically possible, being able to produce cement clinker based on electric plasma kiln technology. Also, it showed that the electrified solution is competitive when compared to other radical emission reduction alternatives. One interesting fact is that Cementa is also part of the HeidelbergCement group, just like the Dutch ENCI, which is important considering the possible technical knowledge sharing and potential future common solutions (Vattenfall, 2019).

3. Carbon Capture Storage and Utilization (CCUS)

With Carbon Capture Storage and Utilization (CCUS) technologies, the emission reductions are achieved by capturing the emitted CO_2, which is then compressed and transported through pipelines to be stored deep underground in appropriate reservoirs or to be used as a feedstock for other industrial processes. Although some barriers need to be overcome, the IEA has suggested that CCS is the most impactful new technology to decrease CO_2 emissions in the cement industry, together with lower clinker ratios (IEA, 2018). According to this study, there are expected to be 10 to 15 commercial cement plants working with carbon capture technology and 20 to 35 million tonnes of CO_2 captured and stored per year by 2025 (IEA, 2018).

The cement industry is already engaging in the research and development of CO_2 capture technologies. Oxy-fuel carbon capture, which uses pure streams of oxygen gas for fuel combustion to aid the carbon capture afterwards, is considered, for example, a viable solution for cement kilns. This technology increases fuel efficiency and promotes a comparatively low-cost alternative for CO_2 decrease in cement plants compared to other technologies (Plaza & Rubiera, 2020). This method requires re-building and re-engineering the cement plant, being most suitable for new kilns due to the costly retrofit of replacing the existing kilns (ECRA, 2017).

The clinker production could also take advantage of the use of post-combustion CO_2 capture technologies. This method captures the carbon-rich flue gas after the production process. Only after emitting the flue gas, the capturing process starts, with the flue gas going through several steps of separation that vary according to the post-combustion technologies. The most intensively studied options are chemical absorption, membranes, and adsorption with solid materials (Plaza & Rubiera, 2020). It represents a relevant option for the cement industry for allowing it to keep its manufacturing equipment and installations (that usually present long lifespan and represent big investments) with no major changes, investing mostly in the additional capture unit. However, for this technology to be effective, the CO_2 concentration in the flue gas is quite relevant. Thus, for the clinker production, it could be applied in kiln-off gas, which has a higher CO_2 ratio, up to 30% of the flue gas volume (Plaza & Rubiera, 2020).

4.2.2 Re-carbonation or CO_2 uptake

Re-carbonation is the reaction process of carbon dioxide with the calcium hydroxide that constitutes the cement and is one of the most debated research points in the cement and concrete industry today. The precise quantity of CO_2 that concrete can retain has a peak of 100% from the amount released through the calcination of limestone in the cement production process. The real amount of carbon uptake will vary according to different parameters such as the resistance class, exposure circumstances, diameter of the concrete element, recycling situation, and exposure time. A reasonable estimation of the global carbon sequestration contributed by all concrete is 25% of the process emissions released during the manufacturing process (GCCA, 2020). Besides, to improve the CO_2 uptake in the construction industry at the end of a building lifetime, it is necessary to guarantee that proper construction and demolition waste sorting and recycling methods are applied. Nearly all cement-based substances undergo a certain extent of carbonation reaction with the carbon dioxide content in the atmosphere during their service life. At first, the re-carbonation was considered an unfavorable post-reaction for the concrete industry, as it was admitted to lower its durability performances (European Union, 2013). However, in recent years, more awareness of the beneficial features of this process is growing based on two main valuable features: rapid strength increases when exposed to curing with CO_2; and the significant potential for CO_2 sequestration in concrete. For those reasons, techniques for improving the re-carbonation in cement-based materials have been considered as a possibly significant contribution of this industry towards lowering CO_2 concentrations in the atmosphere. One constraint to consider re-carbonation as a legit contribution to carbon storage is its prolonged rate reaction, due to the low carbon dioxide relative concentrations in the atmosphere air. Usually, accelerated carbonation systems are obtained on a laboratory scale using a higher CO_2 level and controlled environment, which does not occur naturally. A recent way discovered for improving carbonation curing time is to subject fresh cement or concrete mix (within a few hours after mixing) to carbonation reaction (Ashraf, 2016).

4.2.3 Efficient cement use in concrete

The most extensive use of cement is in the composition of concrete for the construction industry. This material works as the binder responsible for hardening and gathering the other concrete components like sand and gravel. Cement is also responsible for most of the embodied carbon in concrete (European Comission, 2018). For that reason, efficiently using the cement and, perhaps, reducing its use, it is also a way to reduce greenhouse gas emissions. Different ways to use cement more efficiently are described in the literature, but those are mostly related to:

1. Using less cement into the concrete mix

Even with new methods of less carbon-intensive production, the use of low clinker cement is limited and monitored by standards in the construction sector. Those norms also regulate the composition mix of concrete, which, if respected, could be a way of achieving savings with more efficient use of cement (Favier, De Wolf, Scrivener, & Habert, 2018). However, there is a difference between the amount of cement currently used per cubic meter in the construction field and the amount recommended. This is a result of the standards design that currently specifies the minimum safe quantity of cement in the concrete mix, but do not define the maximum amount allowed considering sustainable parameters. For that reason, on average, 20% exceeding cement is used in the concrete composition than the amount needed and recommended by the international standards (Favier, De Wolf, Scrivener, & Habert, 2018). Thus, designing better those standards and following the "minimum requirement" for the cement mix could reduce the embodied carbon of concrete without compromising the building's structure.

2. Choosing the right concrete composition

Different types of concrete are produced and used in the construction sector, thus varying the mix of components according to their application. Those various types are categorized in diverse exposure classes, that present different specifications for the most diverse concrete applications according to exposure conditions, structural, architectural, and durability requirements (Concrete Ontario, 2018). In fieldwork, the professional working on a construction project often designates just one concrete exposure class, usually the most conservative and resistant one. However, for example, the exterior and interior concrete of a building is not under the same constraints and does not need the exact specifications. As a simple situational example, if a house is constructed considering the different requirements between indoor and outdoor concrete, 20 kg of cement per cubic meter could be saved compared to the one concrete type solution (Favier, De Wolf, Scrivener, & Habert, 2018).

3. Avoiding overestimation of concrete in structures

The amount of concrete used in structures is frequently overestimated for additional safety or other practical reasons. Although being a usual and secure practice, it generates overconsumption of concrete and, consequently, of cement. In that sense, a more sustainable construction could be achieved by using the quantities stipulated in the criteria using the security norms. Favier et al. (2018) mentions a survey conducted with engineers and designers that showed there was no discussion or requirements for efficient use of concrete and a lack of design optimization in the projects. Dunant et al. (2018) concludes on its study *"How much cement can we do without?"* that a reduction of approximately 10%-20% can be achieved without design changes by using the correct amount of concrete in the structures.

4.2.4 Cement and concrete circularity

The circular economy is an economic system created to maximize the reusability of materials and products and reduce value loss. From the circularity view, the central point is how to ensure that those products, materials, and raw materials will be adequately retrieved and reused in the next cycle (Betonhuis, 2014). Concrete is an essential and recurring topic in the circularity discussions for being a material with a long-life cycle that can be reused several times without significant losses when correctly managed. Concrete can rightly be called a quality product with high standards demand and more than 100 years of technical life span; thus, it takes a long time of usage before being discarded. When it is ready to be discarded, it can be recycled to a high standard and used to make new products within the building sector. If demolition is done correctly, almost all of the concrete is available to be reused. The largest part can be used as a road foundation material, or aggregate component of new concrete since its granulated form can replace up to 20% of the demand for gravel (Betonhuis, 2014). In recent years, there has been growing interest around concrete recycling. The reprocessed concrete is principally applied to roadworks, a lower-quality application; this concrete aggregate also carbonates, absorbing CO_2. This re-carbonation of concrete after its demolition can play an essential role in reducing embodied carbon levels. Also, new studies about 'smart crushers' solutions can grind the concrete after demolition and separate its cement, sand, and gravel components, which could be customarily reused (Lehne & Preston, 2018).

The projects' design and planning stages also play a decisive role in increasing the potential for the circularity of concrete in the building sector. It goes from designing components to fulfil their function (using less material and optimizing their use within a given shape) to planning beforehand how to use the material after it is being used. In that case, an important topic is the application of modular and disassembled infrastructures as a way to facilitate material management, reduce waste, and increase its reuse potential. Designing this kind of project utilizing prefabricated elements assembled on-site has numerous advantages all along the value chain. It can speed up the construction process and decrease energy demand and labor costs. It is also more easily retrofitted, and its "demolition" produces less waste, uses less energy, and guarantees that it can be reused again until the end of its life cycle (Lehne & Preston, 2018).

Unfortunately, current recycling levels are low compared to the amount of mismanaged concrete demolition, and precast structures are still almost restricted to pattern homogeneous housing projects. Hence, there is room for improvement in this regard in the construction sector.

5 Discussion

The Dutch cement manufacturing sites present a particular industrial configuration compared to other sites abroad due to the lack of clinker production facilities. Therefore, the Dutch cement industry is dependent on importing this material, narrowing down the production process in The Netherlands to grinding and dosing. Both of those processes have low direct CO_2 emissions since they mostly use electricity from the grid. The most significant Dutch cement industry's emissions come from the Blast Furnace Slag pre-treatment because this primary raw material needs to undergo a drying process before being mixed with the other components to produce CEM III cement. Hence, the main decarbonisation options discussed for the Dutch Cement Industry were fuel substitution for the drying process, process design change for the grinding process, as well as feedstock substitution.

Finding an alternative for the drying process, currently done with natural gas as a thermal energy source, is the main solution for reducing the direct emissions from the Dutch cement industry. The simplest short-term solution is using biogas as an alternative fuel, since its characteristics allow the process to run almost in the same way as using natural gas and reach zero net emissions. However, the sustainability of using biomass for energetic applications is a publicly debated topic. The heat pump dryer, using renewable electricity, represents another alternative since it utilizes only electricity to produce heat, providing better temperature control and energy efficiency. This method could be even more enhanced if coupled with solar drying and waste heat as a pre-drying process, especially considering the location of the IJmuiden site, near the Tata Steel site. Those options would require more investment and more equipment changes; however, they allow higher drying efficiency and can potentially reduce operational costs.

The grinding process represents a significant part of the electricity consumption in cement manufacturing. Different configuration schemes of more efficient grinding technologies can potentially achieve significant electricity savings, especially for the Rotterdam site that uses ball mill only, which is not the most energy efficient grinding technology for the cement industry. From the technologies studied, the roller press and vertical roller mill configuration coupled with a high-efficiency classifier would achieve the most significant electricity savings, up to 38% in the IJmuiden site and up to 50% for the Rotterdam factory. First, for having the lowest electricity consumption, and secondly, because the IJmuiden industrial site already uses a roller press for its grinding process. In the short term, changing the grinding facilities can be a costly investment, mainly because of the significant production capacity needed. However, the electricity savings and the sustainable potential of this alternative can be positive financially in the long term.

The ENCI industrial sites have already shown a great initiative with replacing the carbon-intensive clinker with blast furnace slag. Even though other opportunities could also be explored, like using natural pozzolanas, natural calcined pozzolanas, limestone, or belite cements. However, the location of both industrial sites and scarce limestone and other pozzolanas availability in the Netherlands are barriers for developing the use of this alternatives. Fly ash was already used I the past of the Dutch production, but its manufacturing process was ended in 2019 for internal preferences of the company. Thus, giving its availability within the Dutch industrial cluster in Rotterdam and IJmuiden, the use of BFS is still the most relevant alternative for the Dutch cement industry. Fly ash should be also be reconsidered for the future, according with its availability.

One barrier today for an even bigger production of this type of cement are the regulations on the use of low clinker cement, which still stimulates the consumption of Portland Cement. Another challenges are the high demand for cements with rapid strength development (which benefits Portland cement) and the dependency on other industry side-products for CEM II and CEM III. Competing efforts for a more sustainable production and changes in the production processes foreseen for the whole industrial sector could lead to products such as blast furnace slag and fly ashes to become scarcer, and at some point, not being able to supply the cement demand.

It is relevant to mention that substantial decarbonisation impacts can be achieved by broadening the analysis to include scope 2 and 3 emissions. Those can represent up to 95% of the carbon dioxide released by the Dutch cement production chain, largely due to the carbon-intensive production of clinker outside the Dutch borders. For that reason, this report discusses also alternatives that go beyond scope 1, such as ways to improve sustainability in clinker production; increase the recarbonation process, improving the cement ability to absorb CO_2; more efficient cement use with the different standards and regulations; optimizing the circular use of concrete and cement. Among those alternatives, less carbon-intensive clinker production and circularity innovations are the most promising topics towards a more sustainable cement industry. However, there are still challenges for those options. Reducing carbon emission during the clinker production, for example, is still costly for the large cement industrial sites capacity, which together with the lack of regulations to enforce their use, lead to low uptake of these alternatives by the industries. Also, improving circularity would require better integration of the cement, concrete and building industries towards smart projects focusing on the use of modular assembled structures and recycling concrete, which is complex and have logistics and production hurdles. Those solutions are beyond the extent of the MIDDEN initiative, but they are extremely important to guarantee better and more sustainable cement and concrete products in the near future.

6 References

Alves-Filho, O., Walmsley, T. G., Varbanov, P. S., Su, R., & Klemeš, J. J. (2018). Energy Effective and Green Drying Technologies with Industrial Applications. *Chemical Engineering Transactions*, 145-150.

Ashraf, W. (2016). Carbonation of cement-based materials: Challenges and opportunities. *Construction and Building Materials*, 558-570.

Betonhuis. (2014). *#duurzaambeton – trending topics.* Cementenbeton. Retrieved 08 07, 2020, from https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwjNr-Gf-4nrAhUNC-wKHZYuDngQFjAAegQIAhAB&url=http%3A%2F%2Fwww.cementenbeton.nl%2Fduurzaam-bouwen%2Fbeton-en-milieu%2Fduurzaam-beton-trending-topics&usg=AOvVaw3nBmyH1QW7

Bjacek, P. (2019, 05 16). *Cementing growth in an oversupplied market*. Retrieved from Accenture: https://www.accenture.com/us-en/blogs/chemicals-and-natural-resources-blog/cementing-growth-in-an-oversupplied-market

CBS. (2020, 09 01). *Goederensoorten naar EU, niet-EU; minerale brandstoffen en chemie*. Retrieved from CBS Statline: https://opendata.cbs.nl/#/CBS/nl/dataset/81261ned/table?searchKeywords=cement

Cembureau. (2020, 08 06). *Cement What, why & where*. Retrieved from Cembureau: https://cembureau.eu/about-our-industry/cement/

Cement & Beton. (2018). *CO2-top cement Visie voor verdere verduurzaming*. Retrieved 08 03, 2020, from Cement en beton: http://www.cementenbeton.nl/duurzaam-bouwen/cement-en-co2/co2-top-cement

Cement & Beton Centrum. (2019). *Roadmap duurzaam cement - Duurzaam bouwen.* Woerden: Betonhuis.

Cement Online. (2017, 11 27). *CO2-reductie cement vraagt om innovaties*. Retrieved from Cement Online: https://www.cementonline.nl/co2-reductie-cement-vraagt-om-innovaties

CEN. (2011). *EN197-1 Cement -Part1: Composition, specifications andconformity criteriaforcommon cements.* Ireland: NSAI. Retrieved from https://infostore.saiglobal.com/preview/is/en/2011/i.s.en197-1-2011.pdf?sku=1492629

Chrysostomou, C., Kylili, A., Nicolaides, D., & Fokaides, P. A. (2015). Life Cycle Assessment of concrete manufacturing in small isolated states: the case of Cyprus. *International Journal of Sustainable Energy*, 825-839.

Chua, K. J., Chou, S. K., Ho, J. C., & Hawlader, M. N. (2002). Heat pump drying: Recent developments and future trends. *Drying Technology*, 1579-1610.

Concrete Ontario. (2018). *Technical Specifications - Concrete Exposure Classes.* Ontario: Concrete Ontario. Retrieved from https://3qcake159kca33qhh23so84g-wpengine.netdna-ssl.com/wp-content/uploads/2018/09/Concrete-Exposure-Classes-Sept2018.pdf

de Best, R. (2019, November 19). Forecast in percentage change in cement prices worldwide from 2013 to 2016 with a forecast from 2017 to 2020. Statista.

Dunant, C., & Shanks, W. D. (2018). How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling*, 441-454.

ECRA. (2015). *Future Grinding Technologies - Report about Phase 1.* Duesseldorf: ECRA - European Cement Research Academy.

ECRA. (2017). *A-2016/2305 CSI/ECRA-Technology Papers 2017 Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead.* Dusseldorf: European Cement Research Academy GmbH.

Edwards, P. (2018). *Global Cement Top 100 Report 2017 - 2018.* Brussels: Global Cement.

EIR. (2019, February 2). *CemZero project the next step towards a climate neutral cement*. Retrieved from Energy Industry Review: https://energyindustryreview.com/construction/cemzero-project-the-next-step-towards-a-climate-neutral-cement/

El-Mesery, H. S., & Mwithiga, G. (2012). *Comparison of a gas fired hot-air dryer with an electrically heated hot-air dryer in terms of drying process, energy consumption and quality of dried onion slices.* Pietermaritzburg, South Africa: African Journal of Agricultural Research Vol. 7(31),.

Elzenga, H., & Lensink, S. (2020). *Conceptadvies SDE++ 2021 Waterstofproductie via elektrolyse.* The Hague: PBL.

Emissieregistratie. (2020). *Emissieregistratie Rijksoverheid database.* The Hague: Rijksoverheid. Retrieved from http://www.emissieregistratie.nl/erpubliek/erpub/facility.aspx

ENCI . (2017). *ENCI Rotterdam / IJmuiden Veiligheid en milieu - Feiten & cijfers 2017.* Rotterdam: ENCI.

ENCI. (2020a, August 04). *Blast furnace cement CEM III / A*. Retrieved from ENCI: https://www.enci.nl/nl/hoogovencement-cem-iii-a

ENCI. (2020b, 08 06). *Portlandcement CEM I*. Retrieved from ENCI: https://www.enci.nl/nl/portlandcement-cem-i

ENCI. (2020c, 08 06). *Portlandvliegascement CEM II/B-V*. Retrieved from ENCI: https://www.enci.nl/nl/portlandvliegascement-cem-ii-b-v

ETS. (2020). *EU Emissions Trading System (ETS) Database.* Brussels: ETS.

European Comission. (2018). *Energy Efficiency and CO2 Reduction in the Cement Industry.* Brussels: European Comission. Retrieved from https://setis.ec.europa.eu/system/files/Technology_Information_Sheet_Energy_Efficiency_and_CO2_Reduction_in_the_Cement_Industry.pdf

European Commission. (2019). *Deep decarbonisation of industry: The cement sector.* Brussels: European Commission. Retrieved from https://ee-ip.org/fileadmin/user_upload/IMAGES/Articles/JRC120570_decarbonisation_of_cement__fact_sheet.pdf

European Union. (2013, 01). *Cement recarbonation*. Retrieved from European Circular Economy Stakeholder Plataform: https://circulareconomy.europa.eu/platform/en/good-practices/cement-recarbonation

Favier, A., De Wolf, C., Scrivener, K., & Habert, G. (2018). *A sustainable future for the European Cement and Concrete Industry Technology assessment for full decarbonisation of the industry by 2050.* Zurich: ETH Zurich.

GCCA. (2020, 08 21). *Carbon Uptake*. Retrieved from GCCAssociation - Global Cement and Concrete Association: https://gccassociation.org/carbon-uptake/

Global Cement. (2012 , March 07). *Cement in Belgium and the Netherlands*. Retrieved from Global Cement: https://www.globalcement.com/magazine/articles/663-cement-in-belgium-and-the-netherlands

Global Petrol Prices. (2020, September 10). *Netherlands natural gas prices, March 2020*. Retrieved from GlobalPetrolPrices.com: https://www.globalpetrolprices.com/Netherlands/natural_gas_prices/

Gorazd Krese; Boštjan Strmčnik; Vera Dodig; Boris Lagler . (2019). *Review of successful Industry Symbiosis methods and systems for the cement industry.* Switzerland: EPOS.

Gorre, J. O. (2019). Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage. *Applied Energy*, 253. doi:10.1016/j.apenergy.2019.113594

Horrichs, S. (2019 , 12 9). *Directie bevestigt: ENCI Maastricht volgend jaar dicht*. Retrieved from 1limburg: https://www.1limburg.nl/directie-bevestigt-enci-maastricht-volgend-jaar-dicht

Huang, Y. A., Weber, C. L., & & Matthews, H. S. (2009). Categorization of Scope 3 Emissions for Streamlined Enterprise Carbon Footprinting. . *Environmental Science & Technology*, 8509-8516.

ICR. (2019). Lafarge raises price of Baobab cement. *International Cement Review*, 140-147.

IEA. (2018). *Technology Roadmap Low-Carbon Transition in the Cement Industry.* Paris: IEA.

IEA; CSI. (2019). *Technology Roadmap Low-Carbon Transition in the Cement Industry.* Paris: International Energy Agency (IEA); Cement Sustainability Initiative (CSI).

IFC. (2017). *Improving thermal and electric energy efficiency at cement plants: International best practice.* Washington, D.C.: International Finance Corporation.

Kamfa, I., Fluch, J., Bartali, R., & Baker, D. (2020). Solar-thermal driven drying technologies for large-scaleindustrial applications: State of the art, gaps, andopportunities. *Energy Research*, 21-25. doi:10.1002/er.5622

Keys, A., Van Hout, M., & Daniels, B. (2019). *Decarbonisation options for the Dutch steel industry.* Den Haag: PBL Environmental Assessment Agency and ECN part of TNO.

Krese, G., Strmčnik, B., Dodig, V., & Lagle, B. (2019). *Review of successful IS methods and systems for the cement industry.* EPOS.

Kudra, T. (2012). Energy Performance of Convective Dryers. *Drying Technology*, 1190-1198.

Leetham, D. (2015, 08 20). *The Cement Manufacturing Process*. Retrieved from thermofisher: https://www.thermofisher.com/blog/mining/the-cement-manufacturing-process/

Lehne, J., & Preston, F. (2018). *Making Concrete Change Innovation in Low-carbon Cement and Concrete - Chatham House Report.* London: Energy, Environment and Resources Department.

Lensink, S. (2020). *Eindadvies Basisbedragen SDE++ 2020.*

Mohammod, S., & Rahman, A. (2003). *Performance evaluation of a solar assited heat pump drying system.* Singapore: National University of Singapore.

Napier-Munn, T. (2013). *Comminution Energy and How to Reduce it.* Australia: CEEC.

NEA. (2020). *Emissiecijfers 2013 - 2019.* The Hague: NEA - Nederlandse Emissieautoriteit.

PBL. (2020). *KEV - Klimaat- en Energieverkenning 2020.* Den Haag: PBL.

Plaza, M. G., & Rubiera, S. M. (2020). CO2 Capture, Use, and Storage in the Cement Industry: State of the Art and Expectations. *Energies*, 1-28.

RVO. (2019). *From biogas to green gas Upgrading techniques and suppliers.* The Hague: RVO. Retrieved from https://www.rvo.nl/sites/default/files/bijlagen/From%20Biogas%20to%20Green%20Gas%20-%20Upgrading%20techniques%20and%20suppliers.pdf

Scrivener, K. L., Cabiron, J.-L., & Letourneuxb, R. (2009). High-performance concretes from calcium aluminate cements. *Cement and Concrete Research*, 1215-1223.

Scrivener, K. L., John, V. M., & Gartner, E. M. (2016). *Eco-efficient cements: Potential, economically viable solutions for a low-CO2, cementbased materials industry.* Paris: UNEP.

Statista. (2020, September 10). *Industrial prices for electricity in the Netherlands 1995-2019* . Retrieved from Statista: https://www.statista.com/statistics/596254/electricity-industry-price-netherlands/#:~:text=The%208.63%20euro%20cents%20per,middle%20of%20European%20industrial%20prices.

Vattenfall. (2019). *Press release - Vattenfall and Cementa take the next step towards a climate neutral cement.* Vattenfall. Retrieved from https://group.vattenfall.com/press-and-media/news--pressreleases/pressreleases/2019/vattenfall-and-cementa-take-the-nextstep-towards-a-climate-neutral-cement.

Zijlema, P. (2018). *Nederlandse lijst van energiedragers en standaard CO2 emissiefactoren, versie januari 2018.* The Hague: Rijksdienst voor Ondernemend Nederland.