Flexible electricity use in the cement industry: Laying the foundation for a not so concrete future

A scenario analysis about the flexibility potential of European cement plants in 2050 to estimate the potential electricity costs savings and the impact on the electricity grid.

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Key words: Carbon neutral industries, Cement industry, Deep decarbonization, Demand response, Flexible industries, Linear programming, Scenario analysis

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PREFACE

The reason I began this master's programme was because I wanted to learn how I can contribute to a sustainable future. At the end of this master's program I can safely say that I achieved my goals and I am thankful for all the wonderful support I got from the University of Utrecht.

I would mainly thank both my supervisors, dr. ir. Wina Crijns-Graus and Annika Boldrinini MSc for the great support they provided during this thesis. Finally, I would like to thank my parents for encouraging me to enrol in this master's program.

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ABSTRACT

Limiting the global warming levels to 1.5 °C above pre-industrial levels will substantially reduce the effect of global warming on our everyday lives. Because greenhouse gasses are the main contributor to climate change, the EU aims to combat global warming by shifting towards carbon neutral industries in 2050.

By implementing more variable renewable energy sources (VRES) the EU aims to decarbonize the electricity system. Because it is costly to store electricity the demand must become more flexible so VRES can be better integrated. This thesis estimates the flexibility demand of a cement plant. Focussing on the cement industry is interesting since it is a mayor emitter of CO_2, it is energy intensive, and it is at present not clear which decarbonation pathway the industry should choose. The main research question this thesis aims to answer is: *"What is the technical and economic flexibility potential of a carbon neutral cement plant in 2050?"*

At currently operating cement plants, the carbon emissions originate from two sources: the burning of fossil fuels and the formation of clinker (calcination emissions). To answer the research question, the flexibility potential of cement plants when using the four most likely decarbonization pathways were estimated - one scenario where all emissions are captured of a plant with a conventional fuel mix, three scenarios where a renewable heat source is used and only calcination emissions are captured. By understanding the flexibility potential, the future role of cement plants in matching electricity supply and demand can be understood.

This thesis estimates the amount of cost savings and the amount of electrical load that can be shifted. Price signals were used to incentivise flexible operation.

Using a linear program the monthly savings and amount of electricity shifted for the four most likely decarbonization pathways were calculated. Use of hydrogen fuel has the highest load shift potential, followed by the reference fuel. Both scenarios also show the highest electricity consumption, and therefore put the most strain on the electricity grid. Using 100% biofuels puts the least strain on the electricity grid and has the benefit that some of the fuel used (sewage sludge) can be prepared flexibly. It was found that the electrification scenario has the lowest flexibility potential, but has the benefit that it uses less electricity than the hydrogen scenario.

Word count summary (maximum 400): 380

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LIST OF ABBREVIATIONS

BFS	Blast Furnace Slag
CCS	Carbon Capture and Storage
CF	Capacity Factor
CO_2	Carbon Dioxide
CV	Consumption Value
DR	Demand Response
LP	Linear Program
TSO	Transmission Service Operator
VRES	Variable Renewable Electricity Sources

1. INTRODUCTION

Cement is the main component used to make concrete, plaster, blocks and mortar, which are essential for the construction industry (CEMBUREAU, 2020a; Scrivener et al., 2018). As of 2014 cement was the second most consumed material worldwide (Gagg, 2014). This wide use is one of the reasons why about 4.3 %-8% of the annual CO_2 emissions originate from the cement industry (Our World in Data, 2021; Rogers, 2018). To limit global warming a strong reduction in CO_2 emissions is needed. The EU has as goal to become completely carbon neutral by 2050 to combat climate change (European Commission, n.d.). Multiple scenarios are proposed by the industry on how to decarbonize by 2050. These scenarios range from using CCS to capture all emissions, biofuels to supply the heat, electrification or using hydrogen for heat (Bataille et al., 2018; European Union, 2020; Mathisen, 2019). Because the calcination of limestone releases CO_2 and is an essential process for the creation of cement, using a carbon neutral heat source is not enough to decarbonize the cement industry. Currently there are no substitutes for limestone. Therefore, even with a carbon neutral heat source, Carbon Capture and Storage (CCS) is the only method to completely decarbonize the cement industry.

Parallel to the cement industry the electricity sector also needs to become carbon neutral by 2050. In almost all pathways the share of Variable Renewable Electricity Sources (VRES) (European Commission, 2012; Gasunie & TenneT, 2020) will increase. The increase of VRES will also lead to the need of Demand Response (DR) (adopting the electricity demand to better match the energy supply). The integration of VRES into the energy mix will require joint action across the whole economy (European Union, 2019). Especially industries with large thermal loads, such as the cement industry, could have a big flexibility potential and thus could help with the integration of VRES (IEA, 2019). An analyst of BrainPool predicts that because of the increase of VRES into the electricity mix the electricity prices will fluctuate more in 2050 (Perez-Linkenheil, 2019). The combination of more fluctuating electricity prices and the possible change in electricity consumption for the cement plants could create an incentive for cement plants to link their production to the electricity prices. Linking the production process to the electricity prices lowers the electricity costs and could help with the integration of VRES.

Studies have shown that operating flexible is currently possible at cement plants and that it already could be economically beneficial (Lidbetter & Liebenberg, 2014; Summerbell et al., 2017; Zhao et al., 2014). According to Madlool et al. (2011) at the world’s most efficient cement plant 8% of the total energy is consumed in the form of electricity. It is expected that the share of energy from electricity will increase for carbon neutral cement plants because of the implementation of CCS and possible other extra production processes associated with alternative methods of supplying heat.

No studies were found that incorporate the extra flexibility potential of these pathways, this thesis addresses this research gap and estimate the economic and technical flexibility potential of a typical carbon neutral cement plant in 2050 in the EU for the following scenarios (Bataille et al., 2018; European Union, 2020; Mathisen, 2019):

- reference fuel mix (uses the current fuel mix but all emissions are captured with CCS)
- bio-fuel (fuel mix consists of only bio-fuels and CCS for the emissions caused by the calcination)
- hydrogen (hydrogen generated on-site as fuel source and CCS for the emissions caused by the calcination)
- electrification pathways (uses an electric kiln and CCS for the emissions caused by the calcination)

Both technical (how much electricity could maximum be shifted during a day) and economic potential (how much could the plant save on electricity costs) were estimated. The technical potential is beneficial for integrating VRES into the electricity infrastructure of 2050, while the economic potential helps mapping the costs and benefits for every decarbonization pathway. The main research question this thesis will answer is:

"What is the flexibility potential of a carbon neutral cement plant in 2050?"

2 BACKGROUND INFORMATION

This chapter briefly explains background information needed for the research objective in *Chapter 3.* The topics that are explained in this chapter are:

- Description of how cement is manufactured, *paragraph 2.1*
- Which processes emit CO_2, *paragraph 2.2*
- Flexible operation of electric equipment, *paragraph 2.3*

2.1 CEMENT PRODUCTION PROCESS

Cement is an adhesive material which is used as a binding material for construction. Limestone is used as raw material and through chemical reactions and adding certain additives cement is created. After the limestone is mined from a quarry it is mixed with clay to form a powder. The moisture contained in this mix is evaporated inside the raw mill or with help of a dryer (Alsop, 2019). Once most water is evaporated the mix will be preheated to 800 °C and feed into a rotary kiln where it is further heated to 1400°C to create clinkers (Afkhami et al., 2015; ENCI, n.d.). These clinkers will later be cooled down, crushed and mixed with additives. Depending on the amount and type of additives different types of cement can be created. Once these production steps are completed the cement is ready and it can be packed and transported to the costumer. The typical unit capacity for plants in Europe is around 3000 to 5000 tonnes clinker/day (Schorcht et al., 2013). A more detailed overview of the production process is shown in Figure 1.

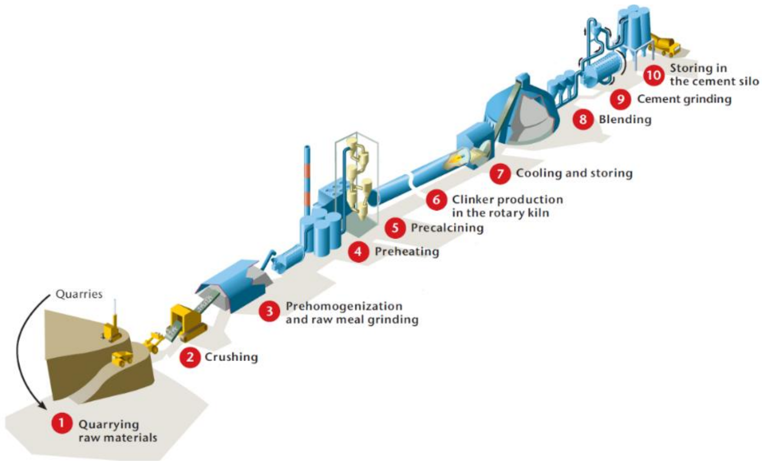

Figure 1: Production process of cement, adopted from (International Energy Agency, 2018b)

Of all processes described in Figure 1 steps 4,5 and 6 uses fossil fuels in a conventional cement plant, the rest of the processes uses only electricity.

2.2 CO_2 EMISSIONS FROM THE CEMENT INDUSTRY

The cement production is a highly carbon intensive industry and emits around 4.3%-8% of all CO_2 globally (Our World in Data, 2021; Rogers, 2018), see Figure 2.

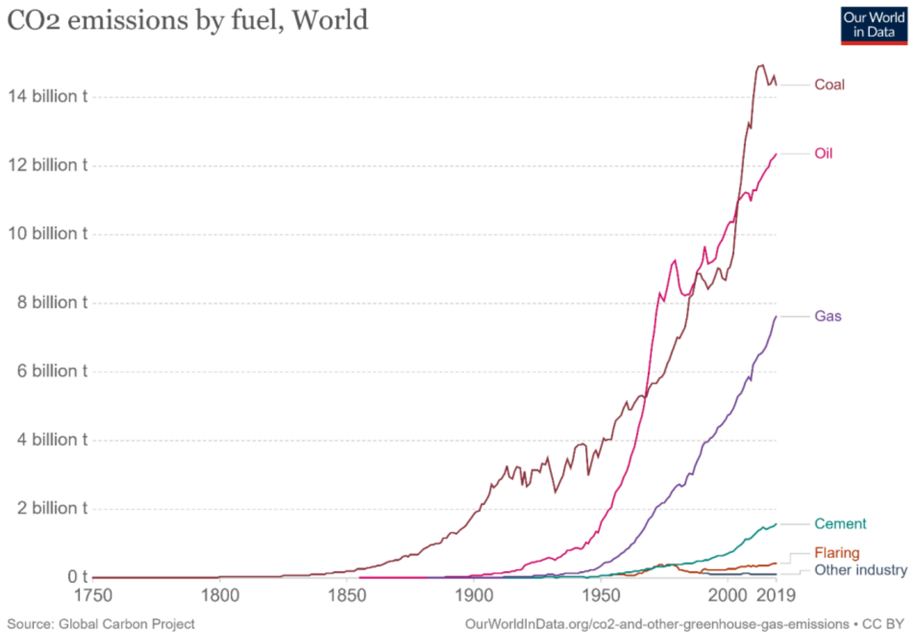

Figure 2: CO_2 emissions of different industry sectors (Our World in Data, 2021).

The CO_2 emissions can generally be divided into two categories. The calcination process which transforms the raw materials into clinker is responsible for approximately 62% of the CO_2 emissions (*raw material emissions*). The other emissions (38%) are related to the combustion of fossil fuels (*fuel-derived emissions*) to supply heat for the pyrochemical processes but also to generate electricity which is used by the cement plant (Gartner & Sui, 2017; Schorcht et al., 2013; Thomas et al., 2020). Because the clinker production is the most carbon intensive process the general emissions of cement can greatly be reduced by substituting clinkers with other materials. Europe already moved from original Portland cement (95-100%) to a clinker-cement ratio of 77% in 2017. By substituting more parts of the clinker with other material this ratio and thus the emissions can be lowered (CEMBUREAU, 2020b; Favier et al., 2018; Kermeli et al., 2019).

Raw material emissions

To create clinkers which can be used as a binder for cement the limestone must be decarbonated to form calcium oxide. This is done by heating the limestone to around 900 °C:

$$CaCO_3(limestone) + \ (Heat) \rightarrow CaO(Solid) + CO_2(gas)$$

(Gartner & Sui, 2017)

The CO_2 emissions from the calcination process could be reduced by using different materials but could only become carbon neutral if Carbon Capture and Storage (CCS) is utilized. According to Gartner & Sui (2017), it could be possible to create carbon negative cement by using magnesium oxides derived from magnesium silicates (MOMS), instead of limestone. MOMS based cement does not contain any carbon an thus no carbon could be released during the chemical process. MOMS uses CO_2 from the atmosphere to harden itself and therefore the process could become carbon neutral or carbon negative. However, after the bankruptcy of the company in 2012 that produces MOMS based cement no industrial companies invested in researching the feasibility of this type of cement and the research on this subject came to a stop (Gartner & Sui, 2017). Since CO_2 emissions are unavoidable when cement is produced using CCS the only method of making the cement industry carbon neutral (Favier et al., 2018).

Next to the calcination process which emits CO_2, cement products also uptake carbon from the atmosphere through the carbonation process (Lukovic, 2016):

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

According to one study up to 25% of the emitted CO_2 could be absorbed back into the cement during its lifetime, something which is not considered into current carbon inventories (Xi et al., 2016). This effect is however undesirable when cement is used in combination with steel reinforcements because this process increases the corrosion rate of steel. According to Gartner & Sui (2017) this is the reason why the industy does not claim CO_2 credits for this absorbed CO_2. Because not all emissions could be reabsorbed in the cement a CCS system is still necessary to make this industry carbon neutral.

Fuel-derived emissions

Currently most cement plants use the combustion of fuels to heat up the limestone. The carbon emitted from the combustion is dependent on the carbon intensity of the fuel, adding biofuels to the mix will result in lower overall emissions. The Dutch cement plant in Maastricht for example decreased their CO_2 emissions by switching to a more bio-based fuel mixed (Junginger et al., 2007). Decarbonizing this process would mean to switch to 100% bio fuels or using alternative methods for heating such as electric heaters or hydrogen as a fuel source. Electricity consumed for other processes (Conveyers, Crushers, mill, etc.) indirectly cause CO_2 emissions because the electricity mix is not carbon neutral. It will be assumed that in 2050 all electricity needed will be generated using carbon free methods.

2.3 DEMAND RESPONSE.

Demand Response (DR) refers to the ability to change the consumption of electricity according to electricity generation. This can be incentivised with price signals, when wind and solar energy is largely available the electricity prices will drop (Perez-Linkenheil, 2019; Suraj & Sentil, 2016). With an increase of VRES into the mix the need for flexible electricity consumption also increases. A report from 2017 for example estimated that the need for demand flexibility (both up and down) in the Netherlands needs to increase by around 9 times to make it possible to decarbonize the electricity mix

(Sijm et al., 2017). The cement industry could provide part of this flexibility by for example make more use of the mill when there is an excess of electricity produced. According to Suraj & Sentil (2016) flexibility can be achieved by the following strategies:

- Reducing the demand by improving the efficiency.
- Encourage customers to shift their demand to off-peak, this can be done by lowering the electricity prices during off-peak.
- Utilities could pay a fee to force a costumer to lower their demand in real time to decrease the demand. An example is the Smart AC program in California which pays users to turn their AC off for a short period.
- Adjusting the consumption to keep the frequency of the grid stable, this adjusting will be done in a timescale of seconds.

Depending on the chosen decarbonization pathway the energy consumption of a cement plant could increase or decrease in 2050. Furthermore, because of the possible introduction of extra processes the flexibility of a cement plant could increase. This potential increase in flexibility and the potential increase of electricity price fluctuations could increase the incentive to operate a cement plant flexible.

3 RESEARCH OBJECTIVE

In this chapter the objective of the research will be explained by stating the Research gap (3.1), research aim (3.2), scope (3.3), relevance (3.4), research questions (3.5) and the research framework (3.6)

3.1 RESEARCH GAP

Multiple articles have been published on how to decarbonize the cement industry by 2050 (Favier et al., 2018; Hasanbeigi & Springer, 2019; Karlsson et al., 2020; Obrist et al., 2021; Schneider, 2015). However, these articles have mostly a broad view of the industry and do not look in depth at the new energy or electricity consumption profiles of these new plants. These demand profiles could be useful for designing the energy system in 2050 so the energy supply can better match the demand.

Another research gap was found in the lack of information there is about the flexibility potential of carbon neutral cement plants. Some research is already conducted on the application of DR in the cement industry (Lidbetter & Liebenberg, 2014; Summerbell et al., 2017; Zhao et al., 2014). The scientific consensus is that cement plants have a DR potential. For example, Summerbell et al. (2017) concluded that a cement plant in the UK could save 4.2% of the electricity cost (£350,000) and lower the electricity generation during peak times with around 1 MW. However, no study is found that tries to estimate the flexibility potential of carbon neutral cement plants in 2050.

3.2 RESEARCH AIM

This thesis addresses the aforementioned research gaps. Energy demand profiles were estimated for carbon neutral cement plants. Because there are multiple pathways of decarbonizing the cement industry, the electricity demand profiles of all pathways were estimated.

The second aim is to address the knowledge gap of what the technological and economic flexibility potential of a carbon free cement plant could be. This flexibility potential is expressed in possible change in electricity consumption (e.g. it could shift 10 MWh per day). The flexibility potential is also economically expressed in how much a cement plant could save on electricity costs if it were to operate flexible.

3.3 SCOPE

The research conducted is limited to all the production processes of a cement plant (e.g. transport is not included). As mentioned previously, assessing when a cement plant would be carbon neutral is highly complex since some of the CO_2 emissions will later be absorbed by cement products and therefore act as a carbon sink (Gartner & Sui, 2017; Xi et al., 2016). Moreover, it is hard for CCS systems to capture all CO_2 emitted. To demarcate this problem it was assumed that it possible for CCS technologies to capture 100% of the emissions. To stay within the timeframe of 30 ECTS it is decided to only research the costs savings of electricity based on the day-ahead market. This means that costs such as installation and operating costs will fall outside the scope of this research. Additional costs savings that could be achieved by acting as a frequency containment reserve for the electricity grid will not be investigated. Furthermore, it was assumed that all electricity supplied in 2050 will come from carbon neutral sources.

3.4 RELEVANCE

The ambition of the European cement association is to become carbon neutral by 2050 (CEMBUREAU, 2020b), this is in line with the green deal with as goal to create carbon neutral industries in 2050 (European Commission, 2012; Government of the Netherlands, 2020). Since no alternatives are available for cement it will remain an essential industry for the entire world. This thesis will add to the knowledge base to map out the economic benefits associated with certain pathways to decarbonize the cement industry.

Flexibility is also beneficial for the TSO (Transmission System Operator) since it can be used for balancing the electricity grid. Estimating the flexibility potentials gives the TSO a better insight in the role that industries could play in maintaining a stable electricity grid. Understanding the flexibility potential of the cement industry could also help by estimating the feasibility of integrating VRES into the fuel mix. The methodology of this study can also be used to determine the flexibility potential of other industries.

3.5 RESEARCH QUESTIONS

The main research question of this thesis will be:

"What is the flexibility potential of a carbon neutral cement plant in 2050?"

To answer this research question the following sub-questions will be answered.

"What are the CO_2 *emissions and energy consumptions for every production step of a European cement plant"*

"Based on different decarbonization pathways how does the energy consumption of a European cement plant change?"

"What is the technical flexibility potential of a European carbon neutral cement plant in 2050?"

"What is the economic flexibility potential of a European carbon neutral cement plant in 2050?"

3.6 RESEARCH FRAMEWORK

The research is divided into three parts. Part A is about estimating the energy and electricity demand of the reference scenario and the decarbonization scenarios (RQ1 and RQ2). In Part B the flexibility potential was estimated. After these demand profiles were constructed the maximum technological flexibility potential of these scenarios was estimated based on the storage capacity of the intermediate goods and the installed capacity of the cement plant (RQ3). After the maximum flexibility potential was estimated the actual flexibility was estimated in (RQ4). With help of a linear program (LP). The purpose of the LP was to estimate the electricity costs savings and estimate how much electricity is shifted when the costs are minimized. Figure 3 shows the research framework of this thesis.

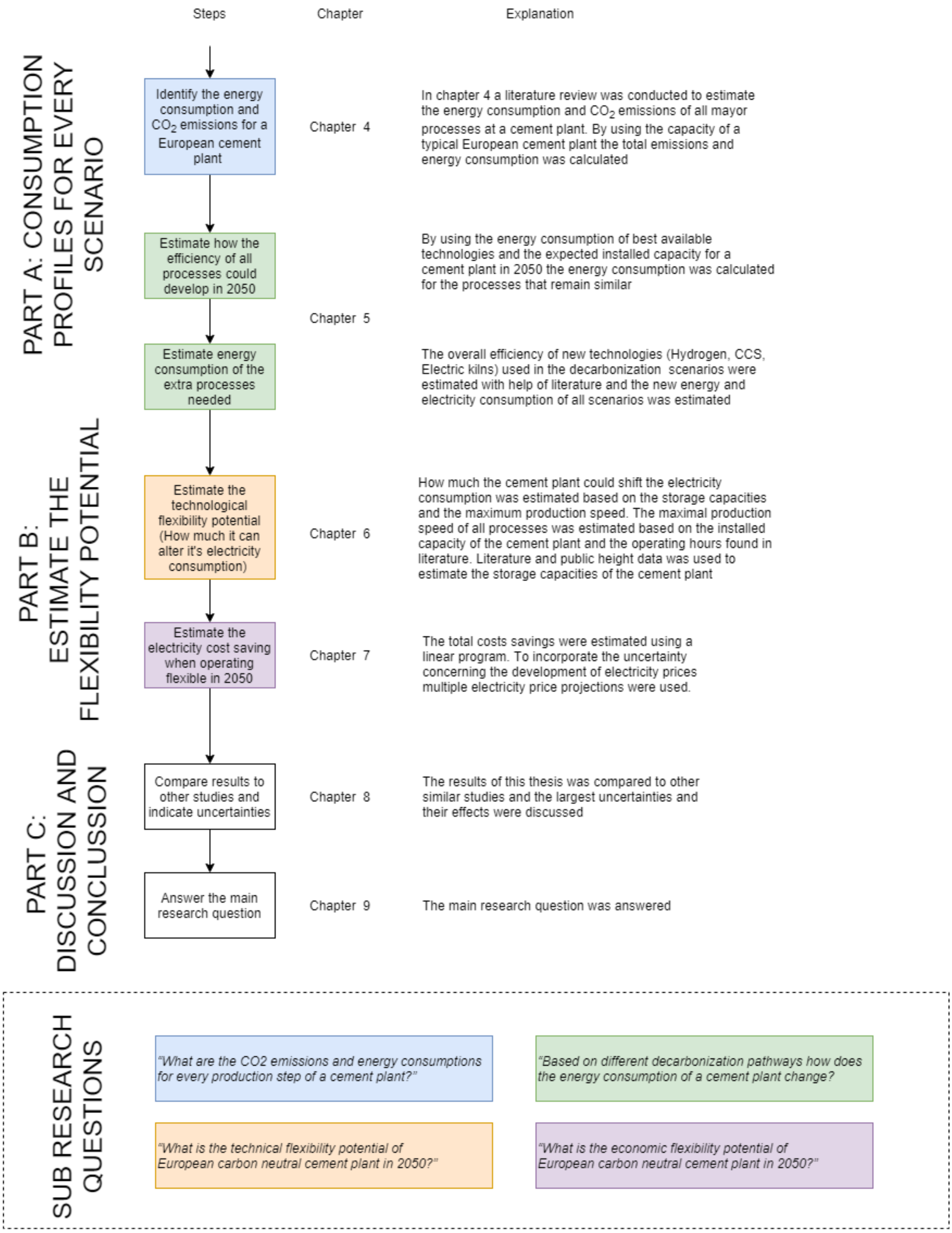

Figure 3: Research framework used in this thesis.

4 ENERGY DEMAND PROFILE AND CO2 EMISSIONS OF A EUROPEAN CEMENT PLANT (RQ1)

This chapter answers the following research question:

"What are the CO_2 *emissions and energy consumptions for every production step of a European cement plant"*

In the first section of this chapter (*4.1*) the methodology was described to estimate the CO_2 emissions and thermal & electrical energy consumption of a typical European cement plant. The end of the methodology paragraph concludes with key assumptions which were used to answer the research question. These key assumption were used in the result section (*4.2*) where the total CO_2 emissions and energy consumption was calculated. The conclusion (*4.3*) provides a brief answer to the research question. The results of this chapter will be used in RQ2 to estimate how the energy consumption would differ in a carbon neutral cement plant.

4.1 METHODOLOGY

To estimate the energy consumption a theoretical plant will be constructed based on values found in literature. Based on the total produced goods (tonne material) and the thermal & electrical consumption values (GJ/tonne material or kWh/tonne material) found in literature the energy consumption is estimated. The consumption value used in this study lie between feasible range based on values found in literature. According to literature (CEMBUREAU, 1999; CSI-ECRA, 2017; Deolalkar, 2009; Galitsky et al., 2008; Worrell et al., 2001) the electricity consumption of a cement plant can be generally broken down in the following production steps: grinding raw materials, milling raw materials, Preheater, kiln and cooling, fuel preparation, milling cement and packaging. Figure 4 shows an overview of all parameters needed to estimate the energy consumption and CO_2 emissions. In Figure 4 the CO_2 clouds represent the production steps directly emit CO_2. It was assumed that in 2050 all electricity will be generated using carbon neutral sources. Therefore, the emissions associated with the electricity consumption were not calculated for the current cement plant.

In *paragraph 4.1.1* the main formula are described used to answer the research question. In *paragraph 4.1.2* to *4.1.5* literature reviews are conducted to estimate the parameters needed for the main formulas.

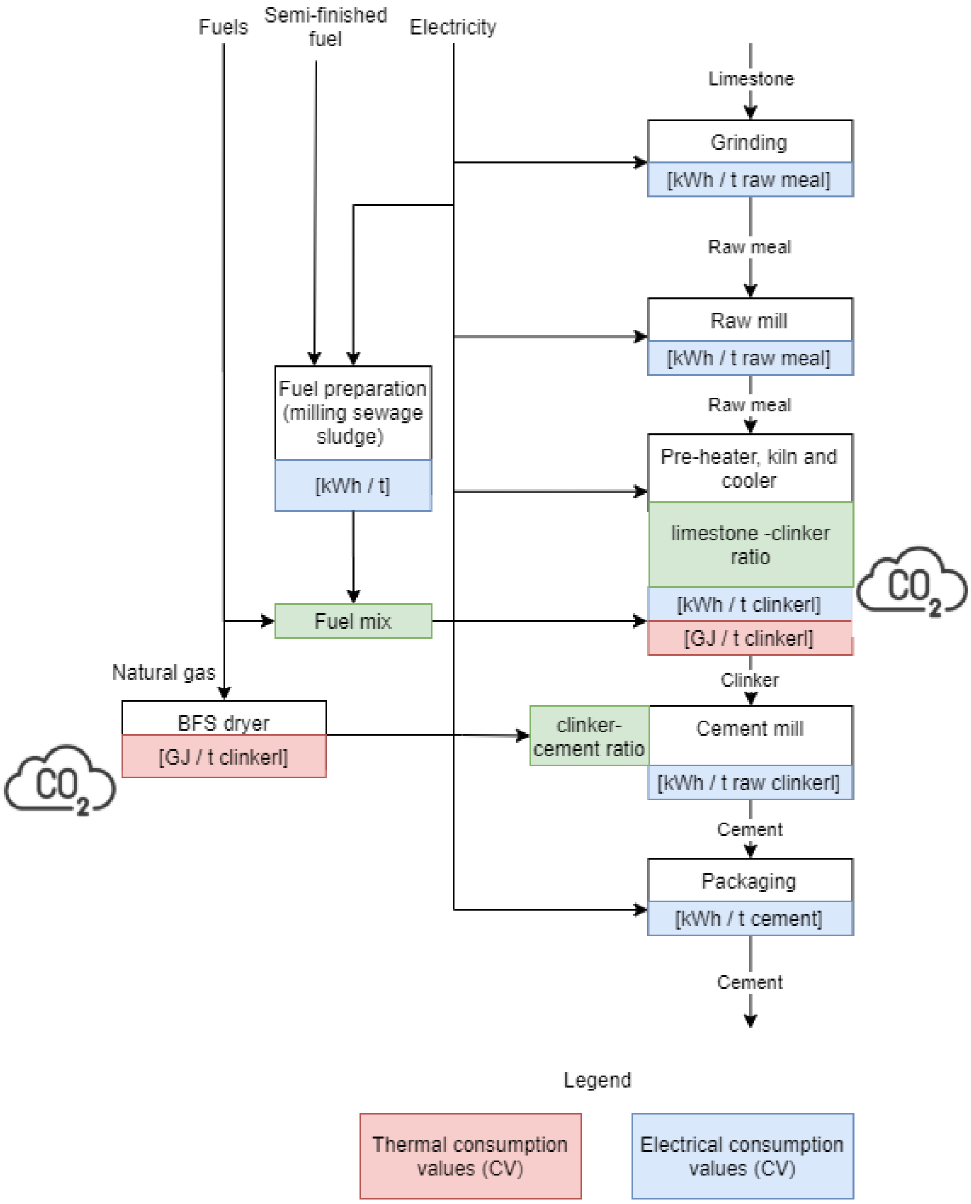

Figure 4: Overview of the energy and material flows in a cement plant, the red boxes represent the thermal processes, the blue boxes represent the processes which uses electricity and the green box represent certain ratios.

4.1.1 Main formulas

To answer the research question both emissions and energy consumption needs to be determined. Both the thermal and electrical processes were estimated. In *4.1.1.1* formulas are given to estimate the thermal energy consumption, *4.1.1.2* describes how the emissions were estimated and *4.1.1.3* provided the formulas used to estimate the electricity consumption.

Emissions associated with the consumption of electricity will not be incorporated because it is assumed that in in 2050 all electricity is generated without emitting CO_2.

4.1.1.1 Thermal energy consumption

According to literature thermal energy is primarily used in the kiln, preheater, cooler and in the dryer to dry the blast furnace slag (BFS) which will me mixed with clinkers to create cement. Therefore, the thermal energy used is calculated with the following formula:

$$E_{Thermal\ processes} = E_{kiln,thermal} + E_{drying\ BFS}$$

Where:

$E_{Kiln,\ thermal}$ is the thermal energy required for the kiln, preheater and cooling installation. These values are calculated based on values found in literature.

$$E_{kiln,thermal} = Q_{clinker} * CV_{kiln\ thermal}$$

The amount of clinkers created at the plant is described in *4.1.2*, the thermal consumption value in GJ/ tonne clinker is given in *4.1.4.1*

$E_{Drying\ BFS}$ is the energy required to dry the blast furnace slag before it can be mixed with the clinker to create cement. The following formula was used to estimate the energy consumption for the drying process

$$E_{drying\ BFS} = Q_{BFS} * CV_{drying\ BFS}$$

The estimated energy required to dry a tonne of BFS at the plant in Rotterdam is given in a consultancy report from (Down to Earth BV, 2013), see paragraph 4.1.4.2.

4.1.1.2 Emission estimation

The total emissions where estimated by using the following formula:

$$e_{total} = e_{rm} + e_{fd}$$

Where:

e_{fd} is the fuel derived emissions based on the fuel intensity of the fuel mix used for the clinker formation but also for the drying of BFS. It should be noted that in the emission from bio-based fuels are not included in the total in emissions since it is assumed that biobased fuels are carbon neutral.

e_{rm} are the raw material emissions associated with the formation of clinker from limestone (Calcination process).

The raw material emissions is depending on the amount of clinkers produced ($Q_{clinker}$). For the production of 1 tonne clinker around 507 kg of CO_2 will always be emitted (Andrew, 2018). Therefore:

$$e_{rm}[kt\ CO_2/yr] = Q_{clinker}[kt/yr] * 0.507$$

The amount of clinkers produced at the cement plant was estimated in *4.1.2.*

The fuel derived emissions where calculated as by using the thermal energy demand (E) and the fuel intensity (FI) of that process :

$$e_{fd}[kt\ CO_2/yr] = E_{kiln,thermal} * FI_{kiln\ fuel} + E_{drying\ BFS} * FI_{drying\ BFS}$$

4.1.1.3 Electricity consumption

The total annual electricity consumption was calculated with the formula:

$$E_{electricity\ total} = E_{grinder} + E_{raw\ mill} + E_{kiln,electrical} + E_{cement\ mill} + E_{packaging} + E_{sewage\ sludge\ mill}$$

Where:

$E_{grinder}$, $E_{raw\ mill}$, E_{kiln} , $E_{cement\ mill}$, $E_{packaging}$, and $E_{sewage\ sludge\ mill}$ are the electricity consumption and will be calculated with the production quantity (Q) and their corresponding consumption value (CV) in kWh / tonne

$$E_{Grinder} = Q_{raw\ meal} * CV_{grinder}$$

$$E_{raw\ mill} = Q_{raw\ meal} * CV_{raw\ mill}$$

$$E_{kiln} = Q_{clinker} * CV_{kiln}$$

$$E_{cement\ mill} = Q_{Cement} * CV_{cement\ mill}$$

$$E_{packaging} = Q_{cement} * CV_{packaging}$$

$$E_{sewage\ sludge\ mill} = Q_{cement} * CV_{sewage\ sludge\ mill}$$

The amount of produce goods (Q) was estimated in *4.1.2* and the CVs in *4.1.3*.

4.1.2 Parameters: Quantity of (semi-)finished goods

The production capacity of cement plants are generally expressed in their daily clinker production. Using the clinker-cement and limestone-clinker ratio an estimation can be made on the amount of limestone needed and the amount of cement that is created.

$$Q_{cement} = \frac{Q_{clinker}}{Ratio_{clinker\ Cement}}$$

$$Q_{limestone} = Q_{clinker} * Ratio_{limestone\ clinker}$$

According to the document: *"Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide"* a typical European cement plant can produce 3000 tonne to 5000 tonne clinkers per day (Joint Research Centre, 2013), using typical load hours of 330 days a year (Deolalkar, 2009) this results in a production capacity of 1089 kt to 1650 kt per year. For a typical European cement plant the value of 4000 tonne clinker per day (1320 kt clinkers per year) was chosen. The ratios for raw material conversion are shown in Table 1.

Table 1: Ratio's cement European cement plant

	Maastricht	**Average**	**BAT**	**Used in this study for the reference scenario**	**Explanation**
limestone to clinker ratio	1.84 (ENCI, 2017)	Estimation of 1.73 (Deolalkar, 2009)	1.5 (Alsop, 2019)	1.84	Some limestone is wasted and CO_2 escapes from the limestone
clinker to cement	0.70 (ENCI, 2017)	73.7% (CEMBUREAU, 2018)	0.5 (CSI-ECRA, 2017; Kemp et al., 2017) (Joint Research Centre, 2013)	74%	Additives will be added to the clinker to create cement

Using the average ratios shown in Table 1 the mass of materials used / created is calculated, see Table 2

Table 2:Annual material consumption and (Semi-) finished goods produced at a typical European cement plant

	Typical European cement plant
Cement produced [kt/yr]	1,808
Clinker produced [kt/yr]	1,320
limestone input [kt/yr]	2,435

4.1.3 Parameters: Consumption values Electrical processes

The total electricity consumption is calculated based on the electricity consumption values (kWh/tonne) of all processes and the estimated quantities, see *4.1.2.*

Four different sources were used to estimate the consumption values (CEMBUREAU, 1999; Deolalkar, 2009; Galitsky et al., 2008; Worrell et al., 2001). It is acknowledged that these sources are old and it is possible that these consumption values do not represent state of the art. The assumption is made that there was not much innovation in terms of energy efficiency in the cement industry and that these numbers represent a current plant, an assumption that is supported by the fact that technology is replaced every 20-30 years at a cement plant (CSI-ECRA, 2017). Therefore it is plausible that these old technologies still operate at current cement plants.

Table 3 shows the consumption values for the electrical equipment according to various sources and the values used in this study. According to Novem (2016) the electrcity consumption of the sewage sludge mill is 40 kWh per tonne of sewage sludge processed.

Table 3: Electrical consumption values found in literature

	(CEMBUREAU, 1999)	**(Deolalkar, 2009)**	**(Worrell et al., 2001)**	**(Galitsky et al., 2008)**	**Chosen value for the typical plant**
Grinding [kWh/t raw meal]	-	2	0.5-1.6	0.5	1
Raw mill [kWh/t raw meal]	7 - 20	12 - 24	12 - 22	14.45	20
Preheater, kiln and cooling [kWh/t raw meal]	7.5	25	26	22.5	24
Cement mill (type not specified) [kWh /t clinker]	-	-	-	16 - 19.2	-
Ball mill [kWh/t cement]	32 - 36.5	35	47	-	45
Roller press + Ball mill [kWh/t cement]	21 - 25.5	26	39 - 41	-	-
Packaging [kWh/t cement]	-	1.5	-	-	1.5

4.1.4 Parameters: Thermal energy consumption

4.1.4.1 Energy consumption of the kiln

The energy consumption is highly dependent on the type of kiln that is used. In Europe the energy consumptions range from around 2.9 GJ/t clinker to 6.7 GJ/t clinker, see Figure 5. According to the GNR database (Getting the Numbers Right) the average energy consumption in Europe for the clinker creating is 3.68 GJ per tonne clinker (GNR, 2018). To have access to more detailed information the energy consumption from a Dutch cement kiln was used which was 3.6 GJ/t clinker (Heidelberg cement, 2007).

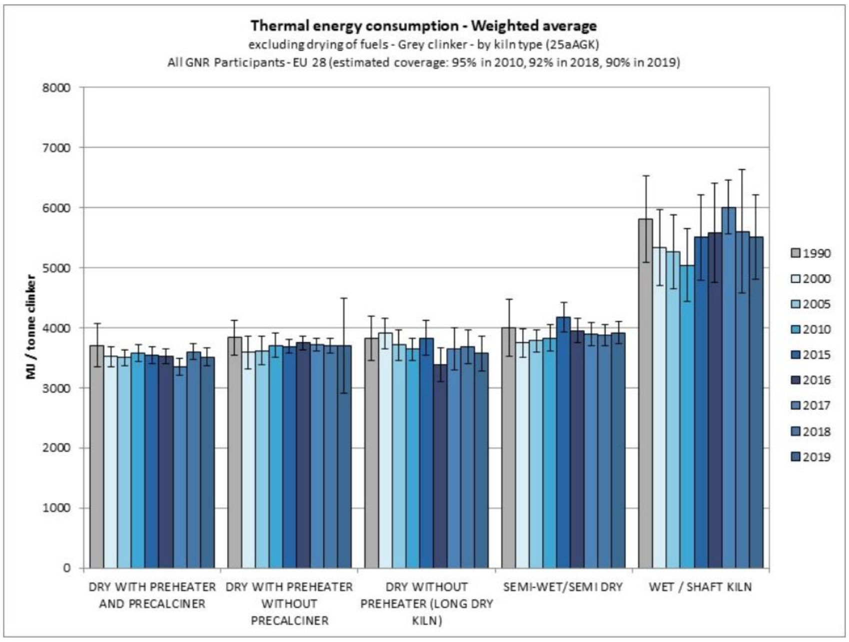

Figure 5: Average thermal energy consumption of different types of kilns in Europe (GNR, 2018).

It should be noted that the drying of the raw meal also consumes some thermal energy. However, because the drying step is combined with the raw mill (Alsop, 2019) and the waste heat from the kiln is used for this process which leads to an increased efficiency (ENCI, 2009) the thermal energy requirements for the drying of raw meal is neglected in this study.

4.1.4.2 Energy consumption drying BFS

As mentioned previously cement can be substituted with fly ash or blast furnace slag to reduce the clinker to cement ratio. In Europe BFS is mostly used as cement substitute, see Figure 6.

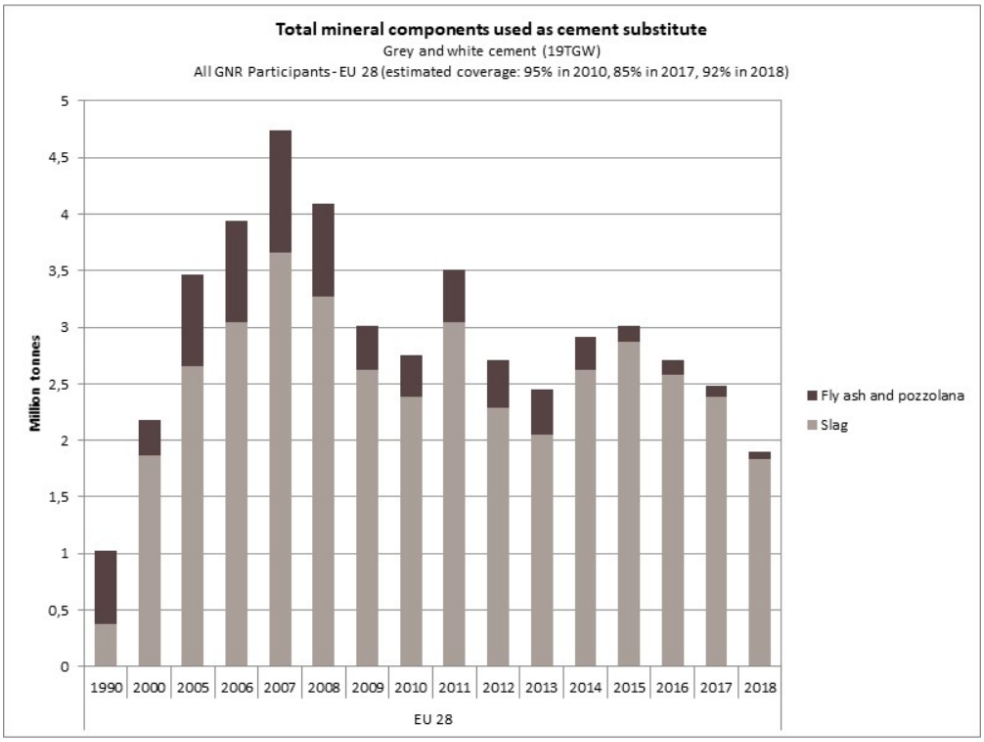

Figure 6: Cement substitutes used in the EU-28 (GNR, 2018)

The old cement plant in Maastricht used to imports wet blast furnace slag and dry it onsite (ENCI & Haskoning, 1997; Xavier & Oliveira, 2021) with a natural gas fired dryer. A report from a consultancy company (Down to Earth BV, 2013) estimates that an optimised dryer consumes 18.09 m^3 (693 MJ) natural gas per tonne blast furnace slag. If we assume that cement only consist of clinker and BFS it can be concluded that cement with a clinker-cement ratio of 74% has a BFS share of 26%. Based on these values the amount of energy and CO_2 emissions associated with the drying BFS were estimated, see Table 4. Waste heat could theoretically be used to dry BFS but no sources were found that supported this.

Table 4: Installed capacity, cement production and estimated natural gas consumption and CO2 emissions for the drying of blast furnace slag.

	European cement plant
Cement produced	1,808 kt /year
BFS used (26 % of the cement)	476 kt /year
Energy needed to dry 1 tonne of BFS	693 MJ /year
Total energy used for the heating of BFS	338 TJ /year

4.1.5 Parameters: Emissions

4.1.5.1 Fuel derived emissions, kiln

As mentioned in *4.1.4.1* the old cement plant in Maastricht was used for reference. Using an reference plant instead of the average the values of all European plants has the benefit that this allows for access to more detailed information such as the fuel mix.

According to ENCI (2017a) the fuel mix of the plant in Maastricht's consists of 27.6% biofuels, 36 % alternative fuels (waste) and 36.4% fossil fuels, for a more description of the fuel mix see Figure 7. This mix uses more alternative fuels compared to average fuel mix of Europe which consist of 18.1% biofuels, 32.1% alternative fuels and 49.8% fossil fuels (GNR, 2018).

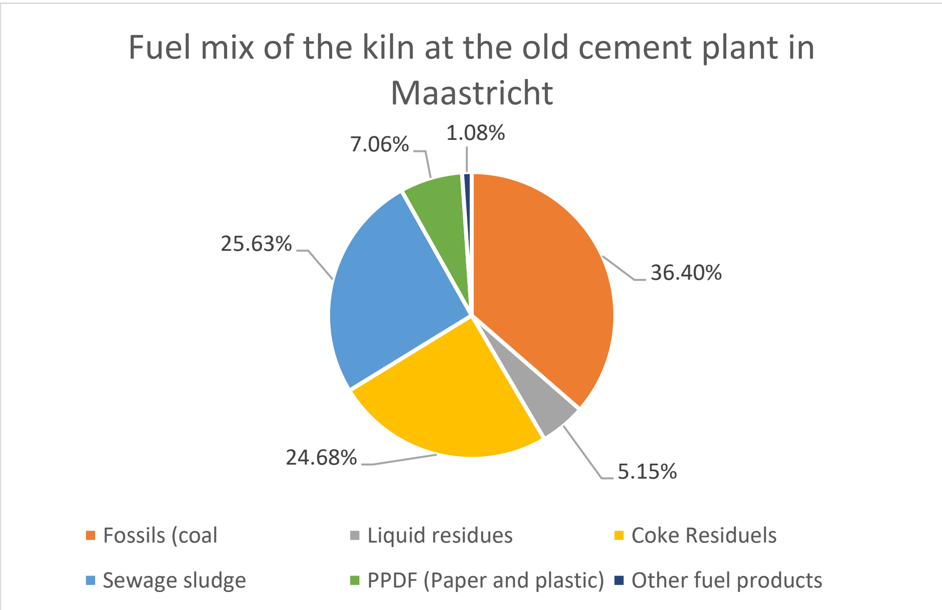

Figure 7: The fuel mix of the ENCI plant in Maastricht when it was still operational (ENCI, 2017a)

It is stated that the 798 kg CO_2 will be emitted when 1 tonne clinker is produced (ENCI, 2017a). Due to the calcination process 507 kg of CO_2 will always be emitted when 1 tonne clinker is formed (Andrew, 2018) and because biofuels are considered to be carbon neutral we can estimate that 291 kg CO_2 per tonne clinker produced originate from fossil and alternative fuels combined. These emissions are slightly lower than the average emissions of 813 kg per tonne clinker for all European countries in 2017 (GNR, 2018).

When the kiln of the plant in Maastricht was still in operation around 27.6% of the energy originate from biobased fuels (0.90 GJ per tonne clinker) (ENCI, 2017), the exact emissions associated with these biobased materials is not provided by ENCI but according to Vreuls (2004) the emission intensity of solid biofuels is 109.6 kg CO_2 / GJ which would correspond to 108.5 kg CO_2 per clinker produced. Based on these assumptions the total emissions were calculated, see Table 5.

Table 5: Estimated CO_2 emissions

Reference fuel mix	Share from fuel mix	CO_2 intensity [kg/GJ]	Emissions [kg CO_2/tonne clinker]
Sewage sludge	25.63%	109.60	98.32
other biomass	1.97%	109.60	7.55
non biomass fuels	72.40%	138.60	291
Calcination process	-	-	507
Total emissions including biofuels and the calcination emissions	100%	251.1	903.87

It was estimated that on an annual basis 90.39 kt of sewage sludge is fed into the kiln, this is estimated by using the calorific value of sewage sludge 13.1 MJ/kg (Junginger, 2007) and the amount of energy originated from sewage sludge (1184 TJ). At the reference plant sewages sludge was dried using natural gas before it was imported by ENCI Maastricht (Waterschapsbedrijf Limburg, 2013). Because the drying step is performed by a company which is not part of the cement company the energy consumption of the drying of sewage sludge lies outside the scope of the reference scenario. The milling of sewage sludge however occurs onsite and is therefore part of the scope.

4.1.5.2 Fuel derived emissions, BFS

As mentioned in *paragraph 4.1.4.2*, 338TJ of natural gas is used to dry the BFS. By using the CO_2 emission factor of natural gas the total emissions were calculated, see Table 6.

Table 6: Installed capacity, cement production , estimated natural gas consumption and CO2 emissions for the drying of blast furnace slag.

	European cement plant
Total energy used for the heating of BFS	338 TJ / year
Emissions factor natural gas (Vreuls, 2004)	56.1 kg / GJ
CO2 emissions drying [kt CO2]	18.98 kt /year

4.1.6 Key assumptions

Based on the previous paragraphs the key assumptions are constructed used to estimate the electricity consumption, thermal energy consumption and the CO_2 emissions of a cement plant, see Table 7.

Table 7: Key assumption of a current cement plant.

Process	Energy consumption		Emission intensity[1] [kg CO_2 emissions / tonne material processed]	Mass of material processed
	Electric	Thermal		
Grinder	1 kWh/t			2,345 kt /yr
Raw mill	15 kWh/t			2,345 kt /yr
Cement kiln	24 kWh/t	3.6 GJ/t	798 kg /t	1,320 kt /yr
Drying BFS		693 MJ/t	39 kg / t	488 kt /yr
Cement mill	40 kWh/t			1,808 kt /yr
Packaging	1.5 kWh/t			1,808 kt /yr
Milling sewage sludge	40 kWh/t			90 kt /yr

4.2 Results

Using the formulas and key assumption described in *paragraph 4.1.1* the following characteristics of a typical European cement plant were calculated:

- The annual electricity consumption of all processes, *paragraph 4.2.1*
- The annual thermal energy consumption of all processes, *paragraph 4.2.2*
- The annual CO_2 emissions, *paragraph 4.2.3*

The results of these calculations were used to answer the research question in *paragraph 4.3.*

4.2.1 Electricity consumption different processes

Using the consumption values of the electrical equipment and the quantity of produced (semi-) finished goods the electricity consumption for all processes was estimated. Figure 8 shows the estimated annual electricity consumption.

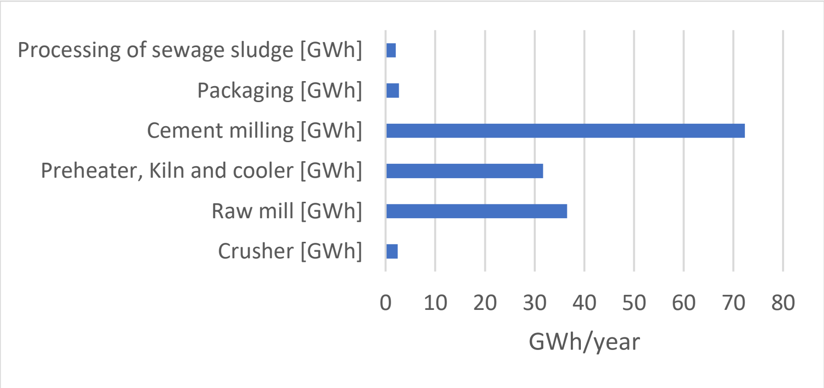

Figure 8: Annual electricity consumption of European cement plant

It was calculated that the electricity consumption per tonne cement is 83 kWh which is in line with the estimation of 85 kWh/t cement for the best in class cement plant (CSI-ECRA, 2017). This results is also

[1] Because the emissions form biofuels are considered to be carbon neutral these emissions are excluded.

consistent with the MER (Dutch: Milieueffectrapportage, English: Environmental impact report) of 2009 (ENCI) where it is stated that for 1,325 kt of cement 120 GWh electricity is needed (90 kWh/t cement). The values found in Madlool et al. (2011) are also similair to the calculated electricity consumption.

4.2.2 Thermal energy consumption

There were two processes identified where thermal energy is consumed. BFS is dried with an gas-fired dryer and the raw meal is heated in the pre-heater and kiln to create clinkers. The drying of BFS consumes only 7% of the energy compared to the energy required to create clinkers, see Figure 9.

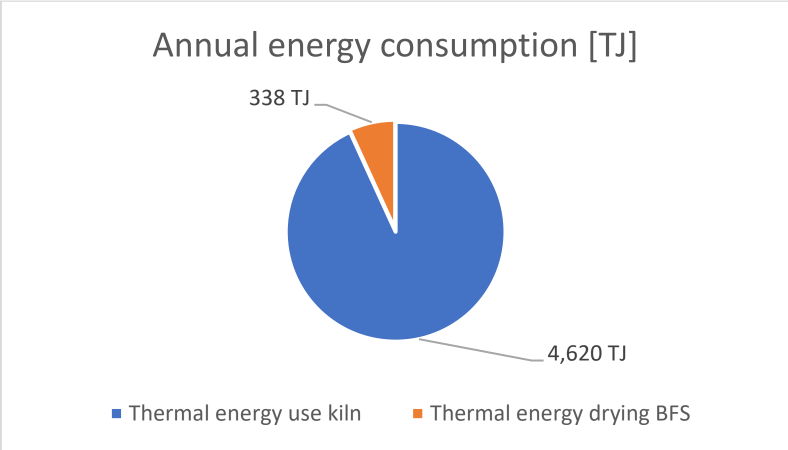

Figure 9: Thermal energy consumption of a European cement plant that produced cement with 30% BFS and 70% clinkers.

4.2.3 CO_2 emissions

Three different sources of CO_2 emissions were identified.

- Burning natural gas to dry of BFS
- Calcination emissions, the CO_2 released from the limestone when clinkers are created
- The burning of alternative-fuels, bio-fuels and fossil-fuels in the kiln to provide heat for the creation of clinkers.

The annual emissions are shown in Figure 10. Because the biofuels are considered to be carbon neutral the emissions form these fuels do not need to be accounted for.

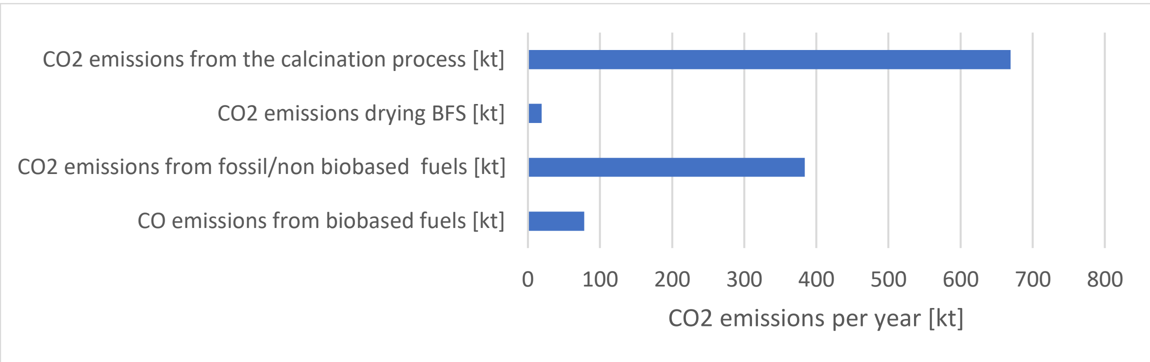

Figure 10: Annual CO2 emissions of a typical European cement plant

When the bio-fuel emissions are excluded the calcination emissions account for 62% of the total emissions which is in line the findings of *paragraph 2.2*(Gartner & Sui, 2017; Schorcht et al., 2013; Thomas et al., 2020).

4.3 CONCLUSION

In this chapter the following research question was answered.

"What are the CO_2 *emissions and energy consumptions for every production step of a European cement plant"*

A typical European cement plant produces 4,000 tonne clinkers per day which would translate to an annual cement production of 1,808 kt cement. For the production of 1,808 kt clinker it was estimated that 1,320 kt clinkers are needed and 2,435 kt of limestone.

To produce 1,808 kt of cement around 5,622 TJ of energy is consumed. only 9% of the energy consumption is used for electrical processes. The processes which consume the most electricity are: the cement mill, the raw mill and the operation of the kiln. No emissions were calculated associated with the use of electricity. This is done because for the main research question a cement plant in 2050 is envisioned where it was assumed that the electricity originates from carbon neutral sources.

85% of the energy is mainly used for the production of clinker and only 6% is used for drying of BFS. When the emissions of biofuels are excluded a typical cement plant emit around 1072 kt CO_2 annually. CO_2 emissions mainly occur in the kiln where fuels are burned and the CO_2 is released from the limestone when clinkers are created. The calcination process contribute to 62% of all emissions.

In RQ2 the development of the energy consumption for multiple decarbonization pathways was analysed.

5 ENERGY CONSUMPTION OF THE DIFFERENT DECARBONIZATION PATHWAYS (RQ2)

The aim of this chapter is to provide an overview of technologies used in the different decarbonization pathways and how this impact the total energy consumption. The results were used in RQ3 and RQ4 of this thesis to model how much electricity could be shifted, and how much electricity cost could be saved. The following research question was used for this:

"Based on different decarbonization pathways how does the energy consumption of a European cement plant change?

As mentioned in the introduction, four likely decarbonization scenarios were identified and for these four scenarios the energy consumption was estimated. These decarbonization scenarios are described more in-depth *paragraph 5.1.*

The methodology used to answer the research question is described in *paragraph 5.2*, this paragraph will conclude with a table showing all the key assumptions used to calculate the energy consumption. The results of this research question can be found in *paragraph 5.3*. The main research question is answered in *paragraph 5.4*.

5.1 DESCRIPTION DIFFERENT SCENARIOS

According to the literature multiple methods are possible to decarbonize the cement industry in 2050 (Bataille et al., 2018; European Union, 2020; Mathisen, 2019). As mentioned previously the CO_2 emissions are caused by the burning of fossil fuels and due to the creation of clinker. The burning of fossil fuels could be replaced by a carbon neutral alternative but the CO_2 emissions from the calcination cannot be prevented and always need to be captured.

In all scenarios is was assumed that the current technologies at a cement plant will be replaced by the current best available technologies, this was done because it was assumed that in 2050 due to technological improvement these efficient technologies become more affordable. Another energy efficiency measure that was implemented was the use of more clinker substitutes. It was estimated that the production of cement remains similar in Europe from 2015-2017 till 2050 (European Commission, 2020; International Energy Agency, 2018a), see Figure 11. Therefore it is assumed that the installed capacity of a typical European cement plant will remain the same. According to Alsop (2019) the stabilization of demand in Europe is caused by fact that Europe has a mature economy and urbanization has already taken place.

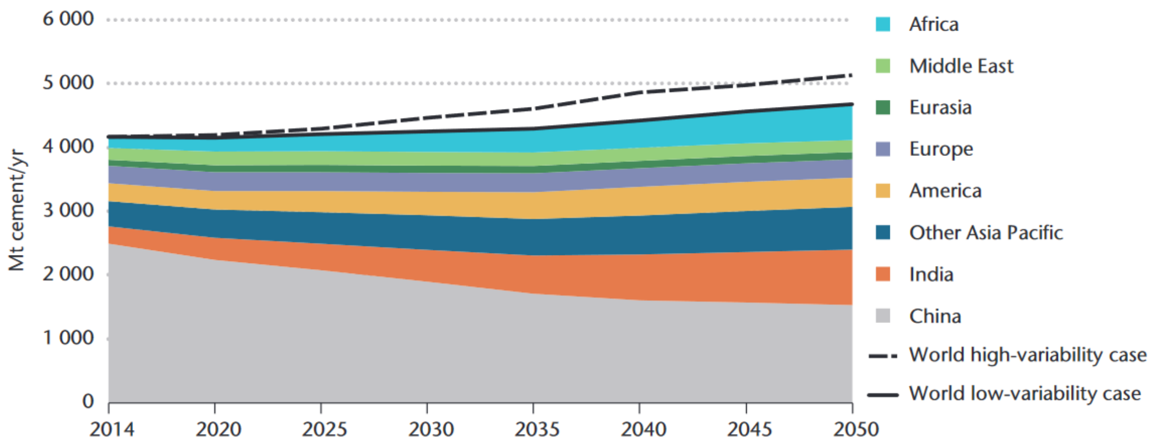

Figure 11:Forecast of the global cement demand, adopted from (INTERNATIONAL ENERGY AGENCY, 2018A)

The different decarbonization pathways that were included in this thesis were:

- Reference fuel mix scenario, keep using the reference fuel mix but add CCS (Carbon Capture and Storage) to capture all emissions
- 100% biofuels scenario, replace the conventional fuel mix with biofuels and add CCS to only capture the calcination emissions
- Hydrogen scenario, replace the conventional fuel mix with hydrogen, add CCS to capture the calcination emissions
- Electrification scenario, replace all heat sources with electric heaters and add CCS to capture the calcination emissions.

The decarbonization pathways and their difference are shown in Figure 12. A brief description of the scenarios is given in *paragraphs 5.1.1* to *5.1.4*

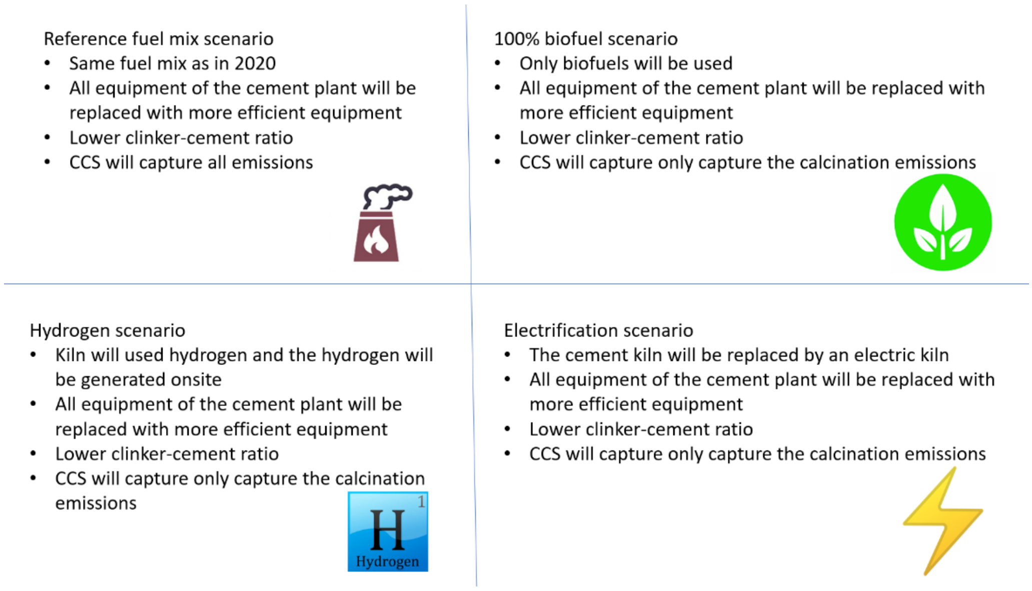

Figure 12: Characteristics of the different decarbonization pathways

5.1.1 Reference fuel mix scenario

In the reference fuel mix scenario it was assumed there is not much technological development regarding alternative fuels and CCS systems. Therefore, the fuel mix described in *4.1.5.1* will also be use in 2050. A CCS system will be used to capture the CO_2 emission from both clinker production and the burning of fossil fuels. Because of the slow innovation of CCS technology in this scenario a proven CCS technology will be used to capture all emissions. In paragraph *5.2.5.1* a literature study is conducted about the technological characteristics in this scenario.

5.1.2 100% biofuel scenario

Here it was assumed that the production process of bio fuels has greatly increased. Because of this development it was assumed that biofuels are widely available and could easily be imported. In this scenario biofuels are considered to be cheaper than using the reference fuel mix with CCS and therefore the fuel mix will consist of 100% biofuels. In paragraph *5.2.5.1* a literature study is conducted about the usage of biofuels in a cement plant.

5.1.3 Hydrogen scenario

In this scenario the installation cost of electrolysers are greatly decreased and it is profitable for a cement plant to install an electrolyser to generate their own hydrogen. The kiln of a cement plant will be replaced so it can fire hydrogen. In paragraph *5.2.5.3* the efficiency of electrolysers were estimated

5.1.4 Electrification scenario

The installation costs for using electric heaters in industries is greatly decreased in this scenario. Because of these low costs the cement industry has switched to electric cement kilns. In paragraph *5.2.5.4* it was estimated which electric heating technology is most suited for a cement kiln and what their efficiency would be.

5.2 METHODOLOGY

5.2.1 Main formulas

The energy consumption is calculated similar to in *chapter 4* (RQ1) with the only difference that:

- Because of the lower clinker-cement ratio there will be less limestone used and more BFS.
- More efficient technology will be used for all processes, the consumption values used in the 2050 scenario are based on the BAT of the reference scenario.
- CCS will be added to all scenarios.

By lowering the quantities of limestone and clinker (Q), and using more efficient technologies (CV) the energy consumption can be lowered. However, adding CCS will increase the energy consumption. The new quantities of (semi-)finished goods (Q) were estimated in *paragraph 5.2.2* and the new consumption values (CV) were estimated in *paragraph 5.2.3.*

The thermal processes are replaced by a carbon neutral alternatives which depending on the scenario consumes electricity or carbon neutral fuels. Therefore, the total energy consumed by the new plant was calculated with the following formula:

$$E_{new\ scenario} = E_{CCS,new\ scenatio} + E_{non\ thermal\ processes,new\ scenario} + E_{thermal\ processes,new\ scenatio}$$

Where

E_{CCS} is the electricity required for the CCS system, this will be calculated based on the consumption values found in literature (GJ_e / t CO_2) and the mass of CO_2 being emitted. It should be noted that in the scenario of where fossil fuels or biomass is used in the kiln the amount of emitted CO2 is higher and therefore more energy is required for the CCS installation. The energy needed for CCS is calculated with the formula:

$$E_{CCS} = m_{CO_2} * CV_{CCS}$$

Where

m_{CO2} is the mass of CO_2 that needs to be captured and CV_{CCS} is the consumption value of a CCS system found in literature in GJ per tonne CO_2 .

In both the reference fuel mix and the 100% biofuel scenario it was assumed that the imported fuels (with the exception of sewage sludge) could directly be used in the kiln without pre-treatment. Therefore, the same formula can be used as shown in chapter 4 but with updated values for the quantities (Q) and consumption values (CV). In the hydrogen scenario the hydrogen first needs to be generated. Therefore, the energy consumption for the kiln in the hydrogen scenario was calculated as:

$$E_{kiln,hydrogen} = \frac{Q_{clinker} CV_{kiln,BAT}}{\eta_{electrolyzer}}$$

The efficiency of the electrolyser was estimated in *5.2.5.3.*

The consumption value of an electric kiln could not be found (GJ needed for the creation of one tonne clinker) and therefore the CV of an electric kiln is calculated with the following formula:

$$CV_{electric\ kiln} = \frac{E_{theoretical\ energy\ needed\ for\ one\ tonne\ clinker}}{\eta_{electric\ heating\ technology}}$$

In *5.2.5.4* a literature study is conducted about suitable technologies for the electrification of the kiln so the efficiency (η) of an electric kiln can be estimated.

It was assumed that in all scenarios the natural gas dryer used for the drying of BFS will be replaced by an electric dryer. The reasoning behind this assumption was that in all scenarios in 2050 the electric heater would be the most cost-effective option. The electricity consumption of an electric heater was estimated by first estimating the actual heat required for the drying process and then converting it to the actual electricity consumption, see *5.2.4*.

$$E_{electric\ BFS\ dryiner} = \frac{E_{dryer\ BFS,natural\ gas} * \eta_{gas\ fired\ dryer}}{\eta_{electric\ dryer}}$$

5.2.2 Quantity of (semi-) finished goods in 2050

It was estimated that in 2050 the cement production processes would improve so that almost no raw materials are wasted. Moreover, it was expected that a typical European cement plant would lower their clinker-cement ratio. By conducting a literature study on the conversion ratios in a cement plant the BAT was identified and it is assumed that a cement plant in 2050 would use these ratios. Table 8 shows the result of this literature study and the values used in this study.

Table 8: conversion ratios used in the 2050 scenarios

	Maastricht	Average	BAT	Used in this study for the decarbonization scenarios
limestone to clinker ratio	1.84 (ENCI, 2017)	Estimation of 1.73 (Deolalkar, 2009)	1.5 (Alsop, 2019)	1.5
clinker to cement	0.70 (ENCI, 2017)	73.7% (CEMBUREAU, 2018)	0.5 (CSI-ECRA, 2017; Kemp et al., 2017) (Joint Research Centre, 2013)	50%

However, it should be noted that it is predicted by Worrell & Kermeli (2017) that in 2050 it is likely that there is not enough BFS available for the cement industry. Therefore, alternatives clinker substitutes could be used which required different preparation process which will also change the energy requirement. To keep withing the timeframe of 30 ECTS it is decided that this challenge will not be addressed in this thesis and therefore it is assumed that sufficient BFS will be available in 2050.

5.2.3 Efficiency electrical equipment in 2050

In all 2050 scenarios it was assumed that the electrical processes will become more efficient in caparison to the reference scenario. It was assumed that the electricity consumption of electrical equipment in 2050 will be similar to the most efficient values found in current literature. The estimated consumption values of the 2050 plant are shown in Table 9.

Table 9: Electrical consumption values of the reference plant and the new 2050 plant.

	(CEMBUREAU, 1999)	(Deolalkar, 2009)	(Worrell et al., 2001)	(Galitsky et al., 2008)	Chosen value for the reference	chosen value for the 2050 scenario
Grinding [kWh/ton]	na	2	0.5-1.6	0.5	1	0.75
Raw mill [kWh/ton]	7 - 20	12 - 24	12 - 22	14.45	15	12
Preheater, kiln and cooling [kWh/ton]	7.5 - 16.0	25	26	22.5	24	22
Cement mill (type not specified) [kWh/ton]		-	-	16 - 19.2	40	27.5
Ball mill [kWh/ton]	32 - 36.5	35	55	-		
Roller press + Ball mill [kWh/ton]	21 - 25.5	26	39 - 41	-		
Packaging [kWh/ton]	-	1.5	-	-	1.5	1.5

5.2.4 Drying of blast furnace slag

Before the BFS can be mixed with cement the BFS needs to be dried, ENCI Rotterdam uses gas fired drum dryers that heat up the BFS to 470 °C (Down to Earth BV, 2013; ENCI, 2013).

Xavier & Oliveira (2021) estimated in report about the decarbonization of the Dutch cement indusrty that the efficiency of the dryer used by ENCI has an efficiency of 0.7. This assumption was based on the estimation that a convective dryer is used by ENCI (personal communication with Xavier, 2021) which has an efficiency of 0.7 (Kudra, 2012). Xavier & Oliveira (2021) suggested that a possible decarbonization option of a gas-fired dryer could be heat pumps but current heat pumps cannot achieve temperatures of conventional dryers (Arpagaus et al., 2018; Madeddu et al., 2020). This has the effect that the drying process with heat pumps will takes longer than gas fired and therefore it is assumed that using heat pumps is not desired. Infrared heaters are however a suitable replacement since Infrared heaters could reach temperatures of 470 °C. Because electric dryers are more efficient than gas fired dryers, and hydrogen fired dryers all BFS dryers will be replaced with IR heaters in the decarbonization scenarios. However, as later mentioned in RQ3 due to time constraints the flexibility of drying BFS will not be researched.

Table 10: Efficiency of drying the blast furnace slag

BFS drying technology	Efficiency (η)
Gas (Kudra, 2012)	0.7
IR heaters (Madeddu et al., 2020)	0.6 – 0.9
Value used for the electric dryer	0.75

5.2.5 Energy and fuel consumption cement kilns in 2050

The theoretical energy needed to form clinkers from raw meal is around 1.6-1.85 GJ per tonne clinker but due to heat losses in the kiln the energy requirements are higher (Habert, 2013; Madlool et al., 2011). In this paragraph the different technological parameters for all scenarios were estimated though a literature study. In paragraph *5.2.5.1* the characteristics of the kiln in 2050 is described when it uses the reference fuel mix. *Paragraph 5.2.5.2* shows how biofuels could be used in a cement kiln. *Paragraph 5.2.5.3* describes the use of hydrogen in cement kilns and in *paragraph 5.2.5.4* the characteristics of an electric kiln are described.

5.2.5.1 Cement kilns in the reference fuel

Before the only Dutch cement plant with a kiln in the Netherlands was closed in 2020 it was known for its high share of alternative fuels used in the fuel mix (Kemp et al., 2017). It is assumed that a reference fuel mix of a typical cement plant in 2050 will look similar. As mentioned in RQ1 the fuel mix of the Dutch cement plant consisted of 27.6% bio-fuels, 36% alternative-fuels and 36.4% fossil-fuels (ENCI, 2017). Of these bio-fuels the largest share of energy comes from sewage sludge which is milled at the ENCI plant. Using biofuels in combination with CCS could even create a negative carbon emission for the cement industry. Having negative emissions could be beneficial to compensate for other processes where the CO_2 could not be captured or the negative CO_2 credits could be sold on the European emission trading system (European Commission, 2015). Due to the scope of this thesis it is assumed that all emissions related to biofuels will be released into the atmosphere so the electricity costs of the CCS system will be reduced.

As mentioned earlier, the energy consumption of the kiln used in RQ1 is around 3.5 GJ/t clinker (efficiency of 46% - 53%). This is slightly lower than the average cement kiln in Europe. Literature shows that is possible to have more efficient kilns and therefore it was assumed that in 2050 most of the kilns will be replaced by more efficient ones. This assumption is based on the fact that kilns have a lifetime of 30 to 50 years (CSI-ECRA, 2017) so it is likely that in 2050 most kilns will be replaced. A literature study was conducted where the efficiencies of different kilns were compared and it was found that lowest energy consumption for the creating of 1 tonne clinker is around 2.9 GJ (efficiency of 55% - 64%), see Table 11.

Table 11: Thermal consumption values of the clinker production

Sources	**Consumption Value (CV) Kiln, preheater[GJ/t Clinker]**
(CEMBUREAU, 1999)	2.9 - 3.2
(Deolalkar, 2009)	2.929 - 3.138
(Worrell et al., 2001b)	2.9 - 3.2
(Galitsky et al., 2008)	3.347
(Heidelberg cement, 2007)	3.5
(Alsop, 2019)	3.1-3.6
Average EU-28 in 2018 (GNR, 2018)	3.68
Chosen value for the reference scenario	3.5
chosen value for the 2050 scenario	2.9

As mentioned in *paragraph 4.1.4*, 25.63% of the energy comes from sewage sludge. In all scenarios a total of 904.1 kt clinkers will be created annually and with a consumption value of 2.9 GJ/t clinker we can estimate that the total amount of energy from the sewage sludge will be around 672 TJ. By assuming that the sewage sludge has a calorific value of 13.1 MJ/kg (Junginger, 2007) it was estimated that 51.3 kt of sewage sludge will be co-fired.

5.2.5.2 Cement kilns in the 100% biofuel mix scenario

Because biofuels are considered carbon neutral increasing the share of biomass decreases the CO_2 emissions that need to be captured. Combining biofuels with CCS could even achieve negative emissions (Platform, 2012). A fuel mix consisting of 100% biomass could however not directly be used in the kiln, according to CSI-ECRA (2017) the calorific value of fuels should be at least 20 to 22 GJ/t while the calorific value of biomass is around 10 to 18 GJ/t. Therefore, biomass should be mixed with other fuels to increase the calorific value of the fuel mix. To keep within the timeframe of this thesis the fuel mix of 100% biofuel scenario will consist of the same share sewage sludge as the reference fuel mix but all the other energy comes for synthesised methane. It was assumed that methane fired cement plants have the same efficiency as conventional kilns. Theoretically other biofuels can also be used but because it was assumed that the biofuels will be imported and do not need to be prepared onsite (except sewage sludge) the type of biofuel used will not change the results of this study.

Synthetic methane can be produced by the anaerobic digestion of biomass, similarly how swamp gas is produced (IEA, 2020b; Müller-Langer et al., 2014; Nsair et al., 2020). Generally biogas consist CO_2 and CH_4:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

To create pure methane the CO_2 could be removed which gives a higher calorific value but according to Ellersdorfer & Weiß (2011) this is not needed for a cement plant.

Another method to create biogas is to break down woody biomass at high temperature in a high pressure and low oxygen environment (IEA, 2020b). The share of CH_4 in the biogas is mainly determined by the feedstock used (Falk, 2011).

Due to time constraints an in depth analysis of different biofuels could not be conducted. However because of the cost and emissions of biogas is comparable to other bio fuels, see Figure 13, it was assumed that a mix of sewage sludge and biomethane/biogas is a feasible fuel mix in this scenario.

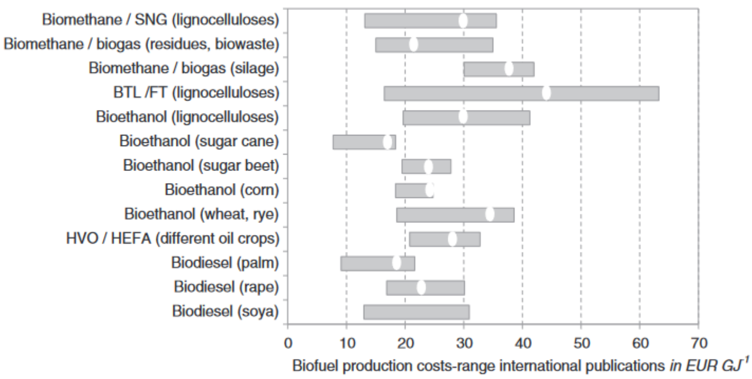

Figure 13: Production costs of different biofuels from (Müller-Langer et al., 2014)*, the white dots show the show the production cost gathered from the Deutsches Biomasseforschungszentrum (DBFZ) database.*

A benefit of using bio-methane over other biofuels is that it can be injected into the gas grid which reduces transportation costs, see Figure 14. For this reason it could be that biomethane is a more cost efficient than using biogas. Theoretically it is possible to create biogas/ biomethane onsite but it was assumed that it would be more cost effective to import the biomethane.

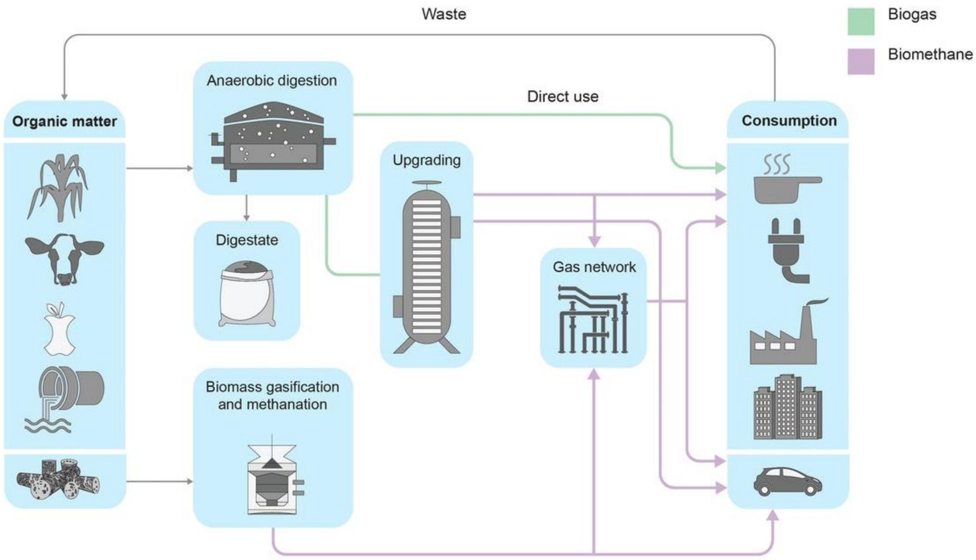

Figure 14: Proposed infrastructure for the usage of bio-methane (IEA, 2020b).

5.2.5.3 Cement kilns in the hydrogen scenario

Combusting hydrogen prevents the emission of CO_2 because no carbon is present in the fuel. The hydrogen will be generated on site with help of electrolysers. An electrolyser could separate hydrogen atoms from a water molecules with help of electricity (Chemistry Library, 2021). To control the combustion of hydrogen and decrease the explosion potential of hydrogen CO_2 could be added to the fuel mix (Mathisen, 2019).

It was assumed that Hydrogen kilns have the same efficiency as conventional cement kilns because the properties of hydrogen are similar of that of natural gas (Koohi-fayegh, 2016; Lowe et al., 2011). Therefore, the efficiency of the electrolysers and the efficiency of a conventional cement kiln will be used to estimate the electricity consumption needed. However, it should be noted that the design of a cement kiln would be different if it uses hydrogen instead of conventional fuels because of the flame produced by burning hydrogen is different (European Commission, 2020). The efficiency of electrolysers is shown in Table 12.

Table 12: Efficiency of hydrogen generation (Bičáková & Straka, 2012)

Technology	Efficiency
Alkaline electrolyzer Water	0.50-0.70
PEM electrolyzer	0.55-0.70
Value used	0.60

Alkaline and PEM electrolyzers are different methods of electrolyzing water. However, because both efficiencies are similair and only the efficiency value will be used in the model a value was chosen that could represent both technologies.

5.2.5.4 Cement kilns in the electrification scenario

In the electrification scenario all heat will be provided by directly using electricity instead of combusting fuels. According to a study which estimates the feasibility of electrifying the calciner (part before the rotary kiln where most of the calcination occur) possible technologies are: Microwave heating, plasma heating, electric resistance heating and induction heating (Mathisen, 2019). The temperature in the calciner is around 900 °C which is lower than the temperature in the rotary kiln (1400 °C-1450 °C). Because of the lower temperatures it easier to electrify this part of the kiln. It is assumed that in 2050 it is possible to also electrify the kiln and that the technologies mentioned to heat of the calciner have the same advantages and disadvantages when applied to the kiln. The benefits and disadvantages of those technologies are shown in Table 13. Mathisen (2019) deemed resistance heating the most feasible technology for the cement industry.

Table 13: Advantages and disadvantages of electric heating technologies for the cement industry adopted from Mathisen (2019)

Technology	Description	Advantage	Disadvantage
Microwave	Use electromagnetic waves from a magnetron to make molecules vibrate to generate heat.	Temperature is easy to control, could calcinate faster than an electric furnace	Local hot spots could occur which could melt the raw meal, safety concerns for personnel.
Plasma heating	Ionising gas so it becomes conductive which makes heat transfer from an electric arc to the process possible. In the cement industry CO_2 could be used as gas.	Lower operating costs, high thermal efficiency. A pilot study has been conducted which concluded that plasma heating could be feasible for the cement industry (Vattenfall, 2019)	Short operating hours (600 – 1000 hours) water cooling is required.
Electrical resistance heating	Heat a metal through resistance heating so the raw meal be heated through convection, radiation or by putting the raw meal in direct contact with the hot surface.	Simple and proven technology, relatively safe.	
Induction heating	Heating a conductive object through electromagnetic induction. The currents in the conductive object heat up the material by resistive heating.	Proven technology, relatively safe.	Inductive heating equipment must be cooled, raw meal is not electrically conductive and could therefore not be heated directly. Challenging to generate steady temperatures.

Vattenfall (2019) conducted a pilot study and concluded that plasma technology could be used for the creation of clinker. Because of the study from Vattenfall (2019) and the analysis by Mathisen (2019) it was decided that electrical resistance heating or plasma technology could be a feasible technology for the cement industry in 2050. A benefit of using an electric kiln is that this the flue gas consist of pure CO_2 from the calcination of limestone which makes it easier to capture (Mathisen, 2019).

The efficiency of these technologies are estimated with help of a paper from Madeddu et al. (2020) and Rao et al. (2013), see Table 14. By using the theoretical energy requirement for the calcination process of 1.7 GJ/ clinker (Habert, 2013; Madlool et al., 2011) it is estimated that the energy consumption of an electric kiln would be 2.3 GJ/clinker.

Table 14: Efficiency of electrical heating technologies

	Value
Efficiency plasma technology (Madeddu et al., 2020)	0.6-0.9
Efficiency plasma technology (Rao et al., 2013)	0.7
Efficiency resistance technology (Madeddu et al., 2020)	0.5-0.95
Efficiency used for an electric kiln	0.75
Consumption value electric kiln [GJ/ t clinker]	2.3

Even though both technologies are different their efficiency is relatively similar. Because only the efficiency values were used in this study and it was assumed that the technologies will not change the flexibility potential, a efficiency was used that is realistic for both technologies.

5.2.6 CCS

Emissions from the cement plant could be captured with the use of a CCS system, because of the emissions associated with calcination CCS is essential for decarbonization in the cement industry. A CCS system captures the CO_2 from the flue gas, separates all other gasses from the flue gas (gasses resulting from combustion and atmospheric gasses such as water and nitrogen) and compresses the CO_2 so it can be stored.

Possible CCS technologies which can be used in the cement industry are:

- Post-combustion: amine scrubbing
- Post-combustion: calcium looping
- Oxyfuel
- Direct CO_2 capture
- Membrane separation

(T. Hills et al., 2016; Metz et al., 2015; Plaza et al., 2020)

5.2.6.1 Description different CCS technologies

Post-combustion: amine scrubbing CCS systems are an end-of-pipe solution and could capture both process and fuel derived emissions. Post combustion CCS has the benefit that it can be implemented in existing cement kilns without altering the production process too much (CSI-ECRA, 2017; Plaza et al., 2020). According to Plaza et al. (2020) post combustion CCS has the highest potential in the cement industry because existing kilns could retrofitted before 2050 to become carbon neutral. Amine scrubbing is an post-combustion CCS technology which already has a high technological readiness level. In an amine scrubber the flue gas is passed through a scrubber where the CO_2 is absorbed by a solvent, this solvent is passed later through a stripper where the CO_2 is separated from the solvent where it is compressed and stored.

Post-combustion: calcium looping uses calcium oxide to absorb the CO_2 from the flue gas through the carbonation process (reverse of calcination process) and later this CO_2 is removed and the calcium oxide is looped back.

Oxy-fuel CCS systems uses pure O_2 provided by an Air Separation unit (ASU) instead of air for combustion which creates a pure CO_2 stream which is easier to capture but this method also requires a modification of the kiln (Carrasco-maldonado et al., 2016; Plaza et al., 2020).

Direct CO_2 Capture systems use a modified calciner where the raw meal is heated indirectly with the use of an heat exchanger so that the calcination and fuel emissions are separated, see Figure 15. This way the CO_2 from the calcination is separated from air or other emissions and therefore prevent the need for separation technologies (T. P. Hills et al., 2017). The fuel derived emissions could be captured with other CCS technologies but when biofuels or hydrogen are used this is not needed to achieve carbon neutrality. Because heat exchangers are used instead of directly heating the raw meal it is expected that the energy consumption will slightly increase (Plaza et al., 2020). It was estimated that the energy consumption will increase with around 2% (T. Hills et al., 2016). the pure CO_2 still needs to be compressed before it can stored which consumes around 100 kWh/ tonne CO_2 (Aspelund & Jordal, 2007; Roussanaly et al., 2017).

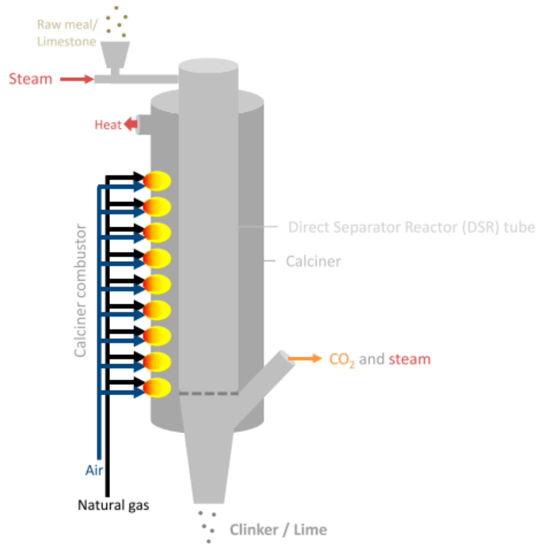

Figure 15: Schematic of a direct CO_2 capturing CCS system (Plaza et al., 2020)

Membrane separation separates the CO_2 from the flue gas with a membrane. Because membrane systems need to operate under pressurised conditions an additional compressor is needed. According to Plaza et al. (2020) membrane separation has a capture range of 60%-70%. Despite the low energy consumption of membrane separation the retrofit costs are higher than other technologies.

The technological readiness levels of all discussed technologies are shown in Figure 16.

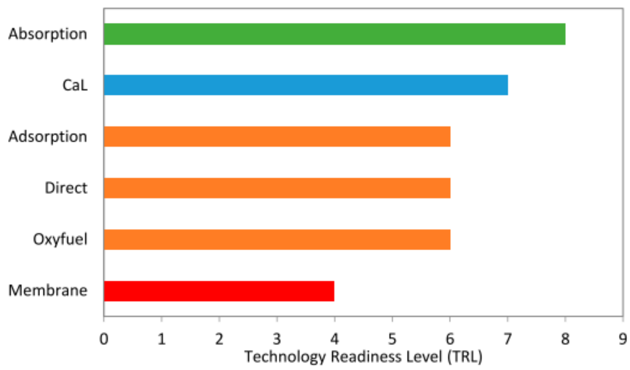

Figure 16: Technology Readiness Level of different CO_2 post combustion and oxyfuels capture methods for the cement industry (IEA, 2020a) *as shown in Plaza et al.* (2020).

5.2.6.2 CCS technology for the different decarbonization scenarios

According Hills et al. (2016) and Plaza et al. (2020) if the current cement industry is pressured in decarbonizing the sector Amine scrubbing technology will likely be chosen due to his high technological maturity. However, if CCS is not directly needed and other technologies have enough time to develop these technologies would likely be more cost efficient than amine scrubbing. In the reference fuel scenario it was estimated that there is not much technological development and therefore amine scrubbing will be used in the reference fuel mix scenario.

One method to decrease the energy consumption of CCS is to utilize the waste heat from the kiln (Bjerge & Brevik, 2014; Metz et al., 2015). However, is should be noted that most waste heat is already used for the drying of material and therefore in some cases it is estimated that only 15% of waste heat can be used (Koring et al., 2013). In this study it was assumed that the reuse of waste heat is not possible.

An overview of the different CCS technologies for a cement plant are shown in Table 15.

Table 15: Overview CCS technologies that can be used in the cement industry, adopted from Plaza et al. (2020), T. Hills et al. (2016) *and* Wang et al. (2017)

Separation technology	**Energy consumption (GJe/t CO_2)**	**Capture rate**	**Main benefits and disadvantages**
Chemical absorption	8.3	>90%	+ Proven technology - High energy consumption
Amine scrubbing	2.0 - 4.0	>90%	+Proven technology, considered benchmark technology -if other technologies have time to develop they would likely outperform amine scrubbing
Membrane separation	1.2-3.22	60-70%, could go higher but this greatly increases the electricity costs	+Small footprint +Low energy consumption -Low capture rate
Calcium looping	3.17-4.42	98%	+high capture rate +considered by Plaza et al. (2020) to be one of the more promising technologies +materials needed for this technology are present at cement plants (limestone)
Oxyfuel	1.63	>90%	+high capture rate and increased fuel efficiency -need to generate pure O_2 -could not be retrofitted
Chilled ammonia process	3.75	90%	+could be retrofitted +lower energy consumption than amine scrubbing
Direct capture	0.36 GJ/t for compressions (Aspelund & Jordal, 2007; Roussanaly et al., 2017) , +2% fuel consumption	Only calcination emissions	+Low energy/electricity consumption +Could be retrofitted -Can only capture the calculation emission

Based on the characteristics shown in Table 15 a suited CCS technology was chosen for the different decarbonization pathways. Direct capture is a promising technology which separates the calcination emissions from the fuel derived emissions. A benefit of direct capturing is that it has the lowest energy requirements of all CCS systems mentioned in this chapter. It was assumed that in scenarios were carbon neutral heat sources are used direct capture will be implemented. The direct capture technology in the electrification scenario is slightly different than the other scenarios because here there is no combustion thus the fuel derived emissions do not need to be separated. This has the effect that there will be no energy penalty of 2% in the electrification scenario. As mentioned in *paragraph 5.1*, in the reference fuel mix it was assumed that there will not be much technological development on CCS technologies. For this reason it was assumed the reference fuel mix would use a proven technology, it was assumed that amine scrubbing would be used in the reference fuel mix scenario. Table 16 shows which CCS technologies will be used in the different decarbonization scenarios.

Table 16: Chosen CCS systems and their assumed effect for all decarbonization scenarios.

Scenario	**Type CCS**	**Assumed capture rate**	**Effect**
Reference fuel mix	Amine scrubbing	100%	3.5 GJ/ tonne CO_2
100% fuel mix	Direct capture	100% of the calcination emissions	2% extra fuel use + compression of CO_2 (100 kWh / tonne CO_2)
Hydrogen	Direct capture	100% of the calcination emissions	2% extra fuel use + compression of CO_2 (100 kWh / tonne CO_2)
Electrification	Compression only	100% of the calcination emissions	compression of CO_2 (100 kWh / tonne CO_2)

For simplification it was assumed that the amine scrubbing CCS system has a capture rate of 100%. Moreover, it was assumed that the thermal energy needed for this CCS system can be provided by electrical sources.

5.2.7 Key assumptions

All parameters needed to estimate the energy consumption of the different decarbonization scenarios are shown in the tables below. Table 17 shows the parameters of the generic cement processes (the production steps that are included in all scenarios). Table 18 shows the parameters needed for the milling of sewage sludge which is used in the reference fuel and biofuel scenario. The energy consumption of the kilns in the different decarbonization scenarios are shown in Table 19

Table 17: Quantities of processed materials (Q) and the consumption values (CV) of generic cement processes.

Process	**Material processed (Q)**	**Consumption Value (CV)**
Grinder	1,356 kt raw meal /yr	0.75 kWh / tonne
Raw mill	1,356 kt raw meal /yr	12 kWh / tonne
Cement kiln, electric	904 kt clinkers /yr	22 kWh / tonne
Cement mill	1,808 kt cement /yr	27.5 kWh / tonne
packaging	1,808 kt cement /yr	1.5 kWh/ tonne
Drying BFS	904 kt BFS /yr	164 kWh/ tonne

Table 18: Parameters needed to estimate the electricity consumption of the milling of sewage sludge in the reference fuel mix and 100% biofuel scenario.

Process	**Material processed (Q)**	**Consumption Value (CV)**
Milling sewage sludge	51.3 kt	40 kWh/tonne

Table 19: energy consumption and CO_2 emissions associated with the different decarbonization scenarios.

	Energy use kiln CV [GJ/ tonne clinker]	**CO_2 emissions [kg CO_2/ tonne clinker]**	**CCS technology**	**Energy requirement CCS**
Reference fuel mix	2.9	Calcination: 507 Biomass Fuel:87.7 Non-biomass fuel: 291	Amine scrubbing	3.5 GJ/ t CO_2
100% biofuels	2.929	Calcination: 507 Fuel: can be neglected because direct capture CCS is used.	Direct capture	100 kWh /t CO_2 (Aspelund & Jordal, 2007; Roussanaly et al., 2017).
Hydrogen	4.93	Calcination: 507 Fuel: none	Direct capture	100 kWh /t CO_2 (Aspelund & Jordal, 2007; Roussanaly et al., 2017).
Electrification	2.27	507 Fuel: no combustion takes place	Direct capture	100 kWh /t CO_2 (Aspelund & Jordal, 2007; Roussanaly et al., 2017).

5.3 RESULTS

Using the methodology described in the previous paragraph the energy consumption of all decarbonization scenarios were estimated. The energy consumption of the CCS depends on the amount of CO_2 that needed to be captured. The total CO_2 emission of all scenarios were calculated and are shown in Figure 17.

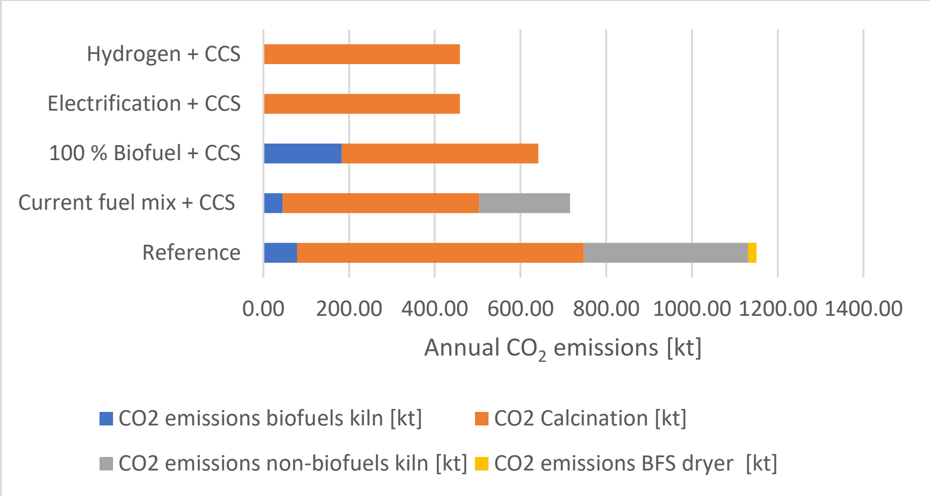

Figure 17: Annual emissions of different decarbonization scenarios and the current cement plant

In all pathways CCS is added to capture the raw material emissions from the calcination process. in the reference fuel mix scenario an amine scrubbing CCS system is added and in all other scenarios the calcination emissions will be separated so they can directly be captured which greatly reduces the electricity consumption. The electricity consumption of the generic cement production processes are lowered because of the more efficient clinker-cement ratio, limestone-clinker ratio and the use of more efficient technologies. The annual energy consumption of the different scenarios is shown in Figure 18. Because more BFS will be used in 2050 the total energy needed to dry the BFS slightly increases.

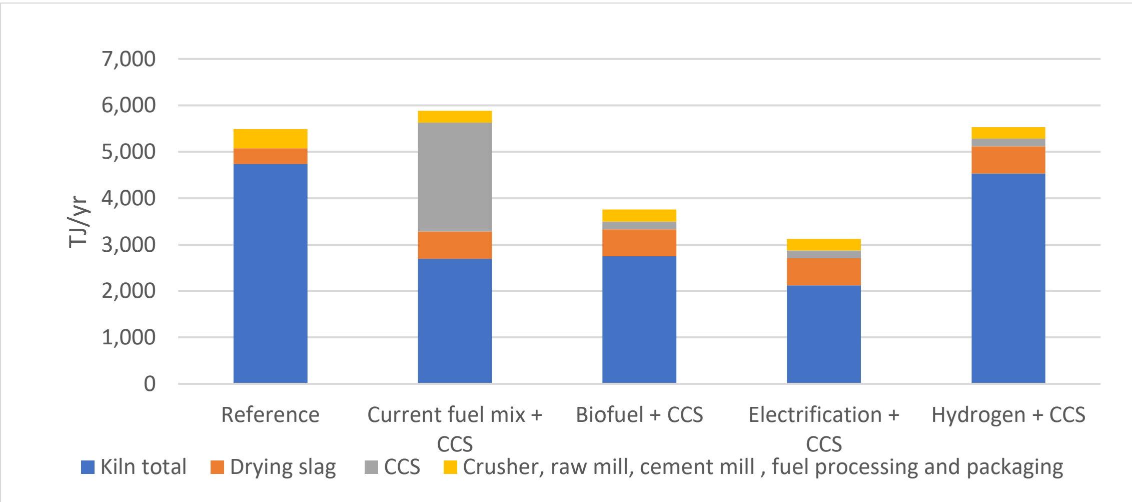

Figure 18: Annual energy consumption of the different scenarios

5.4 CONCLUSION

In this chapter the following research question was answered:

"Based on different decarbonization pathways how does the energy consumption of a European cement *plant change?*

The four most likely decarbonization pathways for the cement industry were identified as:

- Reference fuel mix scenario (keep using the same fuel mix but implement an amine scrubbing CCS system to capture all emissions)
- 100% biofuel mix scenario (Switch to a fuel mix consisting of 100% biofuels and capture all the calcination emissions)
- Hydrogen scenario (Generate hydrogen onsite so it can be used in the kiln and use a CCS system to capture all the calcination emissions)
- Electrification scenario (Use electricity directly to provide heat and capture all the calcination emissions with a CCS system)

The hydrogen and the reference fuel mix scenario consume the most energy and their total energy consumptions are comparable to that of a current cement plant without CCS. This is because despite the use of a more efficient kiln and electrical equipment the CCS system and the hydrogen generation requires much more energy. In the reference fuel scenario it was assumed that an amine scrubbing CCS system would be used which is highly energy intensive. In the hydrogen scenario a direct capture CCS system could be used which has a much lower energy requirement but because the generation of hydrogen has a relative low efficiency the overall energy remains similar compared to the reference scenario.

Direct capture is also used in the 100% biofuel scenario, using direct capture slightly increases the energy requirements of the kiln with 2% but greatly decreases the energy consumption of the CCS system because the CO_2 does not need to be separated from the flue gas. Because biofuels are used the fuel derived emissions can be released into the atmosphere while still remaining carbon neutral.

It is estimated that a cement plant in the electrification scenario consumes the least amount of energy because electric kilns have a high efficiency. The pure CO_2 stream of an electric kiln makes it possible to directly compress these CO_2 emissions without the need for an energy intensive separation process.

6 FLEXIBILITY OF A EUROPEAN CEMENT PLANT (RQ3)

This chapter will answer the following research question:

"What is the technical flexibility potential of European carbon neutral cement plant in 2050?"

In chapter *5 Energy consumption of the different decarbonization pathways (RQ2)* the technological characteristics of cement plants for all decarbonization pathways were described. This chapter estimate which processes could be made flexible and what their flexibility is. The flexibility potential was expressed in how much energy could be shifted during a day in MWh/day.

Some processes identified in previous chapters are only applicable in certain scenarios while other are present in all scenarios, for comparison the production processes are divided into the following categories.

- Generic cement production processes (grinding, milling and packaging)
- Processing sewage sludge
- Hydrogen production
- CCS

The aim of this chapter is to quantify the flexibility of all the flexible processes. This chapter provides most of the constraints which will be used in *chapter 7*

Economic flexibility potential of a European cement plant (RQ4) to model the economic the potential of a cement plant in 2050.

6.1 Methodology

The methodology section of this chapters provides the key assumptions, parameters and formulas to determine the flexibility potential of the identified processes. The flexibility of the different processes are analysed using a cascading stock-flow modelling approach. Figure 19 shows a bathtub represented as a stock-flow model for illisutration.

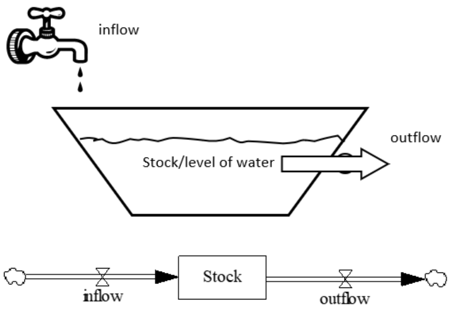

Figure 19: Stock flow model representation of a bathtub (Shepherd, 2014).

where:

1. The inflow represent the production speed of a process (e.g. milling speed [tonne/h])
2. The stock represents the storage capacity of the (semi-)finished good (e.g. raw meal storage [tonne/h]
3. The outflow of a process is the inflow of the next cascading process (e.g. kiln feed [tonne/h])

As mentioned the load shift potential will be represented in how much electricity could be shifted per process per day. Some processes of a cement plant are limited by their maximum operating hours and other can operate continuously. The load shift potential is calculated slightly different these two types of processes

For *Processes limited by maximum operating hours*, the daily load shift potential will be calculated by comparing the energy consumption of a process that occurs at the beginning of the day with the process at the end of the day. *Continuous processes* could occur multiple and therefore the cycle period is needed to estimate how much times per day these processes could occur (T_{Cycle}). The difference between both processes is shown in Figure 20.

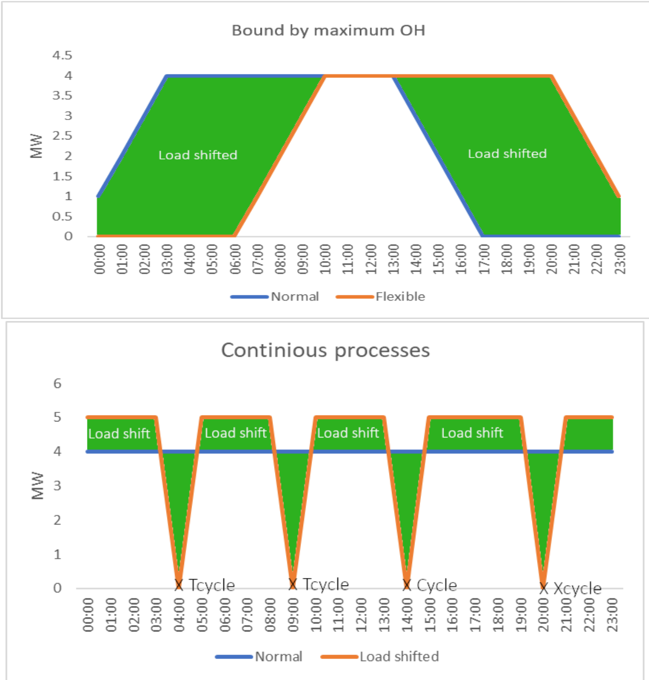

Figure 20:Difference between processes that are bound by operating hours and continuous processes. Processes bound by OH can only "shift" once a day while the continuous processes can shift multiple times per day. the green area shows the maximum load shift potential of the process.

It should however be stressed that the calculated load shift potential is the combination of both increasing and decreasing load, see Figure 21.

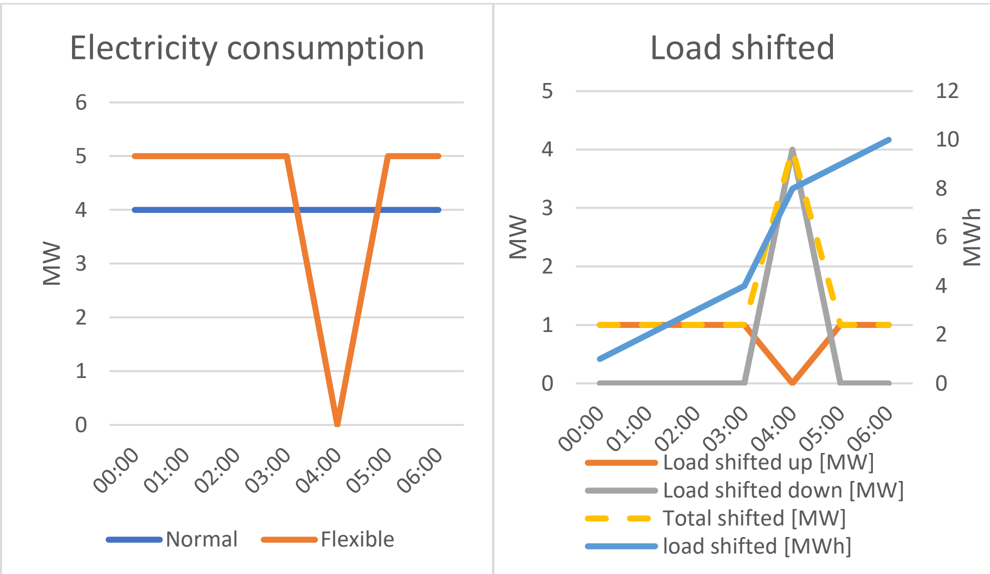

Figure 21: Visualization of how the load shift potential is calculation, on the left the electricity consumption is shown and on the right the amount of electricity load shifted is presented.

Processes bound by OH are defined as processes that can be shifted throughout the day and do not need to supply materials for 24 hours a day. Generally these processes have a relatively large storage capacity. An example would be the milling of cement, enough cement needs to be milled so the weekly/monthly/ yearly quota is reached but it is not necessary when this happens. The load shift potential of these processes will be expressed in (1) how much hours and energy per day these processes could be shifted and (2) what the minimum time is to completely fill the storage and empty it.

The daily load shift potential of processes bound by maximum operating hours were calculated as the difference in electricity consumption when operating flexibly compared to normal operations:

$$E_{Daily\ shifted,bound\ by\ OH} \sum_{i}^{24} \left| E_{normal\ operation,i} - E_{most\ flexible,i} \right|$$

When calculating the daily load shift potential the assumption was made that the storage of materials was not a limiting factor. To also provide a metric for the storage capacity it the minimum time it takes to fill up and empty the storage was calculated. The purpose of this metric is to provide information on how long a process can be turned off without disrupting the material flows. This metric was calculated with the formula:

$$t_{fill\ and\ empty,process} = t_{fill,process} + t_{empty,process}$$

Where the time it takes to fill up the storage and empty the storage is calculates with the maximum inflow ($\dot{m}_{inflow}$), outflow ($\dot{m}_{outflow}$) and the storage capacity (S) of the process:

$$t_{fill,process} = \frac{S_{process}}{\dot{m}_{inflow,process\ ,max}} \qquad t_{empty,process} = \frac{S_{process}}{\dot{m}_{outflow,process,max}}$$

Continuous processes: Processes that need to supply materials for 24 hours a day and the only flexibility potential is through the addition of a buffer. Generally continuous processes have a small storage capacity because storage is not needed and costly. An example would be the production of hydrogen in the hydrogen scenario, here hydrogen always need to be supplied to the kiln but it is possible to build up a small buffer so the electrolyser can be turned off. In addition to the amount of electricity shifted the daily load shift potential of these processes was calculated using the time needed to completely fill up the storage and the time it takes to empty it (T_{cycle}). The daily load shift potential of continuous processes was calculated as:

$$E_{Daily\ shifted,continious} = \sum_{i}^{T_{cycle}} \left| E_{normal\ operation,i} - E_{most\ flexible,i} \right| * \frac{24h}{T_{cycle}}$$

Table 20 on the next page shows which processes show flexibility potential, are considered the be continuous and in which chapter their methodology is described.

Table 20: Flexibility potential of the identified cement production processes

Category	Cement processes	Considered to be a flexible process in this thesis	Continiuous / bound by OH	Reference fuel mix	100% biofuels	Hydrogen	Electrification	Explanation and main sources	Chapters
Generic cement production	Crushing limestone	**Yes**	Bound by OH	X	X	X	X	Plants have a crushed limestone storage (Deolalkar, 2009) and it was assumed that the quarried limestone can also be stored before it is crushed.	6.1.1
	Milling limestone	**Yes**	Bound by OH	X	X	X	X	Plants have a crushed limestone storage and raw meal storage (Deolalkar, 2009) .	
	Clinker production	No	Bound by OH	X	X	X	X	The kiln runs 24 hours per day and because of the high fuel costs it is assumed the kiln always runs at full capacity (Deolalkar, 2009).	
	Drying BFS	No	Bound by OH	X	X	X	X	Due to the lack of literature about the drying of BFS and time constraints the flexibility potential will not be determined	
	Milling cement	**Yes**	Bound by OH	X	X	X	X	Plants have a crushed limestone storage and raw meal storage (Deolalkar, 2009).	
	Packaging	**Yes**	Bound by OH	X	X	X	X		
Processing sewage sludge	Milling Sewage sludge	**Yes**	Bound by OH	X	X				6.1.2
	Co-firing sewage sludge	**Yes**	Continious	X				Is considered to be flexible because by co-firing sewage sludge the emissions will change which changes the consumption of a CCS system.	
Hydrogen	Generation of hydrogen	**Yes**	Continious			X		By including a buffer before the hydrogen is fired in the kiln flexibility can be introduced	6.1.4
Electrification	Electric kiln	No	Continious				x	Due to the precise temperature regulation of the kiln it was assumed that this process could not be made flexible	
CCS	Bypassing	**Yes**	Continious	X				Bypassing the CCS system can only occur when biofuels are used to compensate for the negative emissions (Chalmers, 2010)	6.1.5
	Buffering	**Yes**	Continious	X				It was estimate that buffering would only be possible when amine scrubbing is used (Chalmers, 2010)	
	Compressions	No	Continious	X	X	X	X	Theoretically the uncompressed CO_2 could temporary be stored before it is compressed but no literature was found to support this	

6.1.1 Generic cement production processes

All production processes categorized as generic cement production process occur sequentially, do not need to run for 24 hours per day (except the kiln) and have a storage potential. Therefore, all cement steps could introduce flexibility to the cement production. All generic production steps were categorized as an intermitted process. Figure 22 shows the stock-flow model representation of the generic cement production processes and the parameters needed to estimate its flexibility.

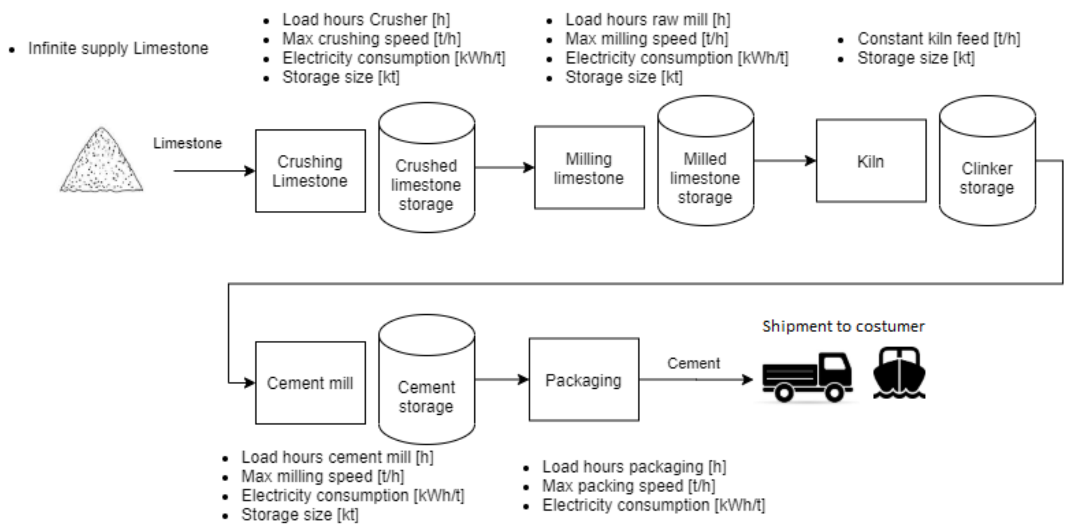

Figure 22: Generic cement production processes as a stock-flow model and the key parameters needed to estimate the flexibility

As shown in Figure 22 the parameters needed to estimate the flexibility are:

- Electricity consumption, was estimated in RQ2 (*Paragraph 5.2.3*)
- Maximum working hours of the process, *paragraph 6.1.1.1*
- Maximum production speed of the process, *paragraph: 6.1.1.2*
- Storage capacity of the (semi-) finished goods, *paragraph: 6.1.1.3*

The electricity consumption for the different processes was estimated in *paragraph 5.2.3*. The methodology of determining the other parameters are described in the following three paragraphs.

6.1.1.1 Operating hours processes

The load hours of the process steps are found a book published by Deolalkar Consultants, a cement consultancy company (Deolalkar, 2009). These operating hours are shown in Table 21 and are similar to a the values from Cement Equipment (2018) and are therefore deemed realistic.

Table 21: Operating hours for different processes of the cement industry from (Deolalkar, 2009).

	Hours per day	**Days per year**	**Load hours per year**
Grinding and quarrying	12	312	3,744
Milling raw materials	20	360	7,200
Preheater	24	330	7,920
Kiln	24	330	7,920
Milling cement	20	360	7,200
Cement packing	18	360	6,480
Mill for sewage sludge	20	360	7,200

No operating hours where found for the sewage sludge mill but it was assumed that this process has the same operating hours as the other two milling processes (20 hours a day).

It was assumed that these processes could not operate for 24 hours a day because they need to be inspected/maintained in the hours it they are not operational.

6.1.1.2 Maximum production speed of the process

Using the operating hours given in *6.1.1.2*, the processed materials given in *5.2.2* and the capacity factor of the maximum production speed was estimated. For the calculation of the capacity factor the reference plant (old plant Maastricht) is used and is calculated to be :

$$CF_{Current\ cement\ plant} = \frac{Actual\ production\ \left[\frac{kt}{yr}\right]}{installed\ capacity\ \left[\frac{kt}{yr}\right]} = \frac{839\ ^{kt}/_{yr}}{900\ ^{kt}/_{yr}} = 93\%$$

By using the capacity factor the maximum production speed of all processes was estimated

$$\dot{m}_{\text{process,max}} \left[\frac{kt}{h}\right] = \frac{Q_{process} \left[\frac{kt}{yr}\right]}{CF\ [\%]} * t_{OH\ per\ year} \left[\frac{h}{yr}\right]$$

For comparison the average production speed (using all available operating hours) was also calculated:

$$\dot{m}_{\text{process,average}} \left[\frac{kt}{h}\right] = \frac{Q_{process} \left[\frac{kt}{yr}\right]}{t_{OH\ per\ year} \left[\frac{h}{yr}\right]}$$

Table 22 shows the results of these calculations.

Table 22: Production speed of different production steps at a typical European cement plant, maximum speed is based on the installed capacity and the average speed is based om the actual produced values.

	Load hours [h/year]	Actual produced values [kt/year]	Installed capacity [kt/year]	Maximum Production speed [tonne / hour]	Average production speed [tonne/hour]
crusher	3,744	1,356	1,454	388.4	362.2
raw mill	7,200	1,356	1,454	202.0	188.3
preheater kiln and cooler	7,920	904	904	114.2	114.1
cement mill	7,200	1,808	1,939	269.3	251.1
packaging	6,480	1,808	1,939	299.2	279.0

6.1.1.3 Storage semifinished goods and finished goods

Storage capacities of semi-finished goods and finished goods differs from plant to plant. According to the book *"handbook for designing cement plants"* (Deolalkar, 2009) the main factors determining the storage are:

1. *" The distance over which these items are brought, time taken in processing the order and actual receipt of material at site have to be taken into account.*
2. *Continuity factor, reliability of sources.*
3. *Climate or weather factor, like differences in moisture content in dry and wet seasons and necessity to maintain stocks dry."*

To estimate the storage of a typical European cement plant the storage capacity estimated by three different methods where compared:

- The storages of the old cement plant in Maastricht was analysed with help of height data, the values were scaled to the size of the cement plant in 2050
- Using documentation about a Canadian cement plant and scale it to the size of the cement plant in 2050
- Using two different design guidelines for determining the storage capacities of the cement plant

By comparing the storage sizes from these different sources a realistic storage capacity for the carbon neutral cement plant was determined.

Identifying the storage capacity of the cement plant of Maastricht.

With data from literature and online articles (Batec, 2014; ENCI, 2009; van Dijk, n.d.) the different storages at the Maastricht plant are identified and with a dataset containing the height data (AHN dataset) (Rijkswaterstaat, n.d.) the volumes of those storages are estimated, see Figure 23. The storage capacity for the crushed limestone could not be found and therefore it is assumed that the crushed limestone is added to a small storage and later the same day is fed to the raw mill. The crusher only operates for 6 days a week while the raw mill operates for 7 days a week. Therefore, the grinded limestone storage need to hold at least enough limestone for 1 day operation of the raw mill. As mentioned in *paragraph 6.1.1.2* the maximum production speed of the raw mill is 202 Tonne per hour and it can operate 20 hours a day. Therefore it is assumed that the grinded limestone storage should have a minimum capacity of 4040 tonne. Because compared to other storages the grinded limestone storage is relatively small and therefore relatively inexpensive it was assumed a storage of 7,500 tonne is feasible.

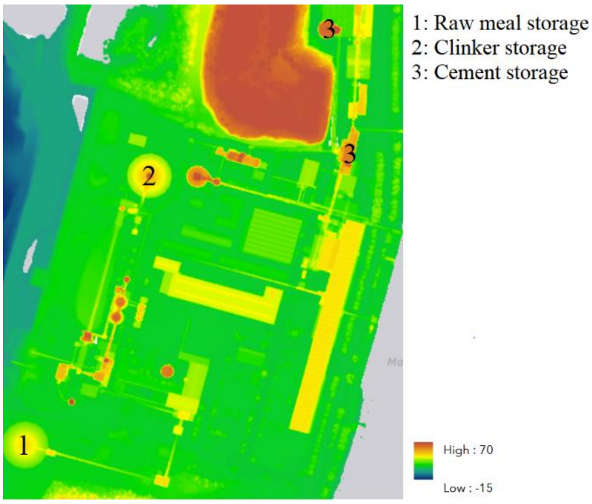

Figure 23: Height data of the cement plant in Maastricht (Rijkswaterstaat, n.d.) *where the storage are identified using* (Batec, 2014; ENCI, 2009; van Dijk, n.d.)

The raw meal is stored at (1) and has the shape of a cylinder with a cone as roof, see Figure 24.because of the equipment which homogenize is also located in the storage, see Figure 24, it was assumed that only 70% the cylinder can be used as storage. The silo has an height of 8.8 m and a radius of 35m.

$$V_{Raw\ meal\ storage,maastricht} = \pi * r^2 * h * 70\% = \pi * 45^2 m * 70\% = 34{,}024\ m^3$$

Using the density of 1,250 kg/m^3 for raw meal (Alsop, 2019) the storage capacity is calculated to be:

$$S_{raw\ meal\ ,maarticht}[kt] = 34{,}024\ m^3 * 1{,}250\ kg/m^3 * 10^{-6} = 35.7\ kt$$

Figure 24: Raw meal storage of the Dutch cement plant in Maastricht (van Dijk, 2018).

The clinker storage (2) has also the shape of a cylinder and cone as top but different from the raw mill storage this storage can be completely filled (Pretorius, 2020). To estimate the clinker storage it is assumed that 90% of the volume of this storage can be used to store clinkers. The radius of the cylinder and cone is estimated to be 35 m, the height of the cylinder is estimated to be 12.33 m and the height of the cone is estimated to be 27 m. With these parameters the volume is calculated to be

$$V_{clinker\ storage,maastricht} = 90\% * (V_{cylinder} + V_{cone}) = 90\% * (\pi * r^2 * h) + \left(\pi * \frac{1}{3} * r^2 * h\right)$$
$$= 90\% * \left((\pi * 35^2 m * 12.33m) + \left(\pi * \frac{1}{3} * 35^2 m * 27m\right)\right) = 73{,}878\ m^3$$

Using the density of 1,360 kg/m^3 for clinker (Alsop, 2019) the storage capacity is calculated to be:

$$S_{clinker,maastricht}\,[kt] = 73{,}838\ m^3 * 1{,}360\ kg/m^3 * 10^{-6} = 100.5\ kt$$

Cement is stored is multiple silos (3). All different types of cement will have their own silo so the different types of cement will not be mixed. In this thesis we assumed that only one type of cement will be created so all silos are used to store the same type of cement. At the plant in Maastricht 16 small silos in the form of a cylinder and one big cement silo in the form of an cylinder where identified. The small silos have an height of 34.4m and a radius of 4.3 m. The big silo has an height of 51m and a radius of 12 m. The volume of these silos are estimated with the formula:

$$V_{cement\ silo,maastricht} = 90\% * (\ \pi * 4.3^2 m * 24m * 16m +\ \pi * 12^2 m * 51m) = 49{,}569\ m^3$$

Using the density of 1,500 kg/m^3 for clinker (Alsop, 2019) the storage capacity is calculated to be:

$$S_{cement,maastricht}[kt] = 49{,}569\ m^3 * 1{,}500\ kg/m^3 * 10^{-6} = 74\ kt$$

The estimated storages where scaled linearly to match the values of a typical cement plant using the clinker capacity of the cement plant in 2050 and capacity of the of the plant in Maastricht

$$S_{raw\ meal,plant\ 2050} =\ 35.7\ kt * \frac{4000\ clinkers\ per\ day}{2878\ clinkers\ per\ day} = 50\ kt$$

$$S_{clinker,plant\ 2050} =\ 100.5\ kt * \frac{4000\ clinkers\ per\ day}{2878\ clinkers\ per\ day} = 140\ kt$$

$$S_{cement,plant\ 2050} =\ 74\ kt * \frac{4000\ clinkers\ per\ day}{2878\ clinkers\ per\ day} = 103\ kt$$

Storage capacity of a Canadian cement plant

Websites of European cement manufacturers where consulted to find their storage capacities by due to the language barrier and time constraints no data was found. As substitution the storage capacities of a Canadian cement plant from the company McINNIS where used, see Table 23.

Table 23: storage capacity of the McINNIS cement plant in Canada (McInnis cement, 2021)

	McINNIS	Scaled to a typical European plant in 2050
Installed capacity [tonne clinkers/day]	6,000	4,000
Raw meal storage [tonne]	150,000	100,000
Clinker storage [tonne]	120,000	80,000
Cement storage [tonne]	120,000	80,000

Determine storage capacities with guidelines

Next to using existing plant as reference two design guidelines were used to estimate the storage capacity of the new cement plant:

1. A small cement plant with a capacity of 100 tonne clinker per day (Power Correction Systems, 2004).
2. Rule of thumps when choosing the capacity proposed by Deolalkar (2009)

The values estimated for a small cement plant (SCP) of 100 clinkers per day are scaled up to match the clinker capacity of the new cement plant, see Table 24.

Table 24: the storage capacity of a small cement plant (SCP) scaled to a European cement plant in 2050

	SCP (Power Correction Systems, 2004)	**Scaled to a typical European plant in 2050**
raw meal [kt]	0.75	30
clinker [kt]	1.5	60
cement [kt]	0.9	36

Deolalkar (2009) expresses the storage capacity as daily production, the daily production values are based on the load hours and production capacity which were described in *paragraph 5.2.2*. Table 25 shows the storage capacity of a European cement plant using this method.

Table 25: Storage capacity based on guidelines proposed by Deolalkar (2009)

	days	Daily production [t/d]	Storage capacity [kt]
Raw meal	2	6,764	13.53
Clinker	14	4,000	56.00
cement	7	5,022	35.16

Estimation of the storage capacities of an European cement plant in 2050

The results of all different methods of estimating the storage capacity were compared and a realistic storage capacity was chosen for a typical European cement plant, see Table 26.

Table 26: Storage sizes of different cement plants scaled to the same installed capacity of the typical European plant and the storage size deemed realistic for this study.

	Maastricht (scaled)	Guidelines from Deolokar	Guidelines from for Power Correction Systems (2004)	Mcinnis (scaled)	Assumed storage for a cement plant in 2050
Storage grinded limestone [kt]	n/a	n/a	n/a	n/a	8.0
Storage raw meal [kt]	49.6	13.5	30.0	100	60.0
Storage clinkers [kt]	139.6	56.0	60.0	80	80
Cement storage [kt]	103.3	35.2	36.0	80	70

6.1.1.4 Key assumptions

Based on the findings of this chapters key assumptions were made so the flexibility potential could be calculated, the key assumptions are shown in Table 27.

Table 27: Key assumptions for determining the flexibility potential of generic cement production processes

Process	Type of process	Inflow	Storage	Outflow	Maximum operating hours	Electricity consumption [kWh/ tonne]
Limestone grinding	Bound by OH	388.4 t/h	8.0 kt	202.0 t/h	12h/day, 312 days/year	0.75
Limestone milling	Bound by OH	202.0 t/h	60.0 kt	114.2 t/h	20h/day, 360 days/year	12.0
Clinker production	Bound by OH	114.2 t/h	80.0 kt	269.3 t/h	24h/day, 330 days/year	Not applicable because there is no flexibility potential, it is assumed that the kiln runs at maximum capacity at 24 hours a day
Cement milling	Bound by OH	269.3 t/h	70.0 kt	299.2 t/h	20h/day, 360 days/year	27.5
Cement packaging	Bound by OH	299.2 t/h	n/a	n/a	18h/day, 360 days/year	1.5

6.1.3 Milling sewage sludge

As mentioned in *paragraph 5.1*, in the scenario reference fuel mix and 100% biofuel the milling of sewage sludge occurs on-site. After the sewage sludge is milled it will be stored in a silo before it will be co-fired in the cement kiln. Similar to the milling of raw meal and cement the process is bound by operating hours. The usage of sewage sludge adds two possibilities for flexibility:

- Only mill sewage sludge when the electricity prices are low.
- Co-firing sewage sludge changes the CO_2 concentration in the flue gas which could shift the workload of the CCS system. This is only applicable in the reference fuel mix scenario where the fuel emissions are captured.

To estimate the flexibility the following parameters should be known:

- Storage size of the milled sewage sludge, see *6.1.3.1*
- Milling speed, see *6.1.3.1*
- Maximum amount of sewage sludge possible to co-fire, see *6.1.3.2.*
- The change in emissions from co-firing sewage sludge, because this process influences the electricity consumption of the CCS system these parameters where estimated in *6.1.5.1.*

It was assumed that the cement plant has a contract with the wastewater treatment facility. In this contract it is specified how much sewage sludge will be imported. Therefore, it was assumed that all imported sewage sludge needs to be co-fired. Figure 25 shows the stock flow diagram and all parameters needed to estimate the flexibility.

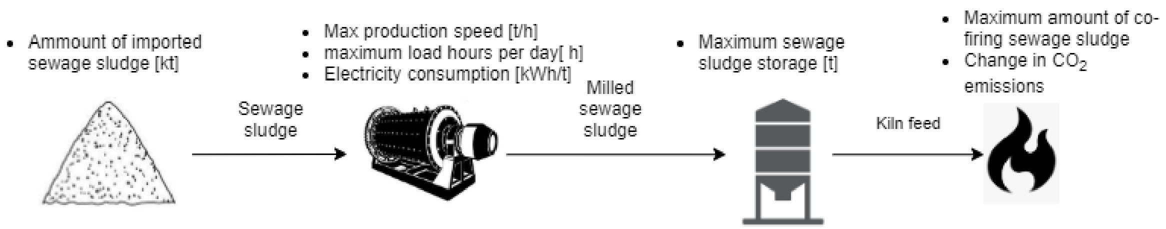

Figure 25: Flexibility option of processing and co-firing sewage sludge.

6.1.3.1 Flexibility of the cement mill

The Maastricht cement plant has a storage capacity 600 tonne of grinded sewage sludge (Novem, 2016), based on the installed clinker production capacity of the Maastricht plant (904 kt/ year) and that of the new European cement plant (1,320kt/year) it is estimated that a typical European cement plant has a milled sewage sludge silo with a capacity of around 900 tonne.

$$S_{Sewage\ sludge,typical\ EU\ plant\ 2050}\,[t] = S_{sewage\ sludge\ maastricht}[t] * \frac{clinker\ production_{maastricht}\left[\frac{t}{y}\right]}{clinker\ production_{typical\ EU\ plant\ 2050}\left[\frac{t}{y}\right]}$$

The production speed of the cement mills in Maastricht are 6 tonne per hour (Novem, 2016), scaling this capacity to the typical European cement plant in 2050 gives an maximum speed of 9.2 tonne per hour. To process the 51.3 kt imported sewage sludge (as calculated in *5.2.5.1)* around 5,557 full load hours are needed per year. It was assumed that de operating hours available for the milling of sewage sludge are the same as the other milling operations (7,200 h/yr).

6.1.3.2 Flexibility in co-firing sewage sludge

Using the fuel mix specified in *paragraph 5.2.5.1* it was estimated that around 51.3 kt sewage sludge will be co-fired annually. Based on the operating hours of the kiln (24 hours a day for 330 days per year) the average feed-in rate of sewage sludge to the kiln was calculated to be 6.5 tonne of sewage sludge per hour. The annual amount of sewage sludge co-fired was based a fuel mix where 25.63% of the energy originates from biomass. However, a report from ENCI (2017) showed that is possible to increase this share to 35.1%. Therefore it was assumed that a maximum feed in rate of 8.0 tonne sewage sludge per hour would be possible

6.1.3.3 Key assumptions

The key assumption used to calculate the flexibility potential of milling sewage sludge is shown in Table 28.

Table 28: Flexible feed in rate of sewage sludge to the kiln

	Type of process	**Amount of imported sewage sludge**	**Max inflow (milling)**	**Storage**	**Max outflow (kiln feed)**
Mass sewage sludge	Intermitted	51.3 kt	9.2 t/h	1,350 t	8.0 t/h
Energy content sewage sludge	Intermitted	672 TJ	121 GJ/h	17,686 GJ	104 GJ/h

6.1.4 Hydrogen

In the hydrogen scenario the fuel of the cement kiln will be replaced by hydrogen. Hydrogen will be generated onsite with an electrolyser. Flexibility can be introduced through generating more hydrogen than required and store it so it can be used later. According to expert from TNO on the topic of hydrogen an electrolysers can run 24 hours during the whole year (Van de Burg, Personal communication, April 23, 2021). Therefore, the generation of hydrogen was categorized as a continuous process. Because the kiln is in operation for 24 hours a day for 330 days the fuel requirement for the kiln will be constant. As calculation in Research Question 2 the total thermal energy requirement for an kiln in 2050 (assuming that a hydrogen kiln has the same efficiency as a conventional kiln) is around 2,674 TJ per year. During normal operation the cement kiln will therefore have a power consumption 337.7 GJ/ per hour. The stock-flow model of the this process is shown in Figure 26.

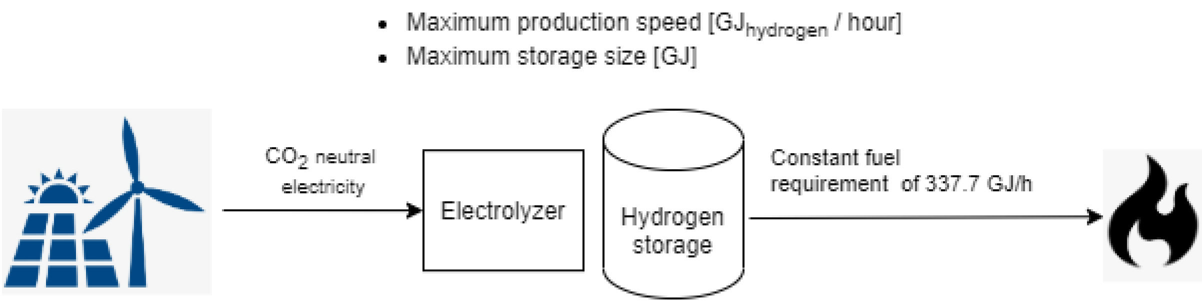

Figure 26: stock-flow model of the hydrogen generation in the hydrogen scenario

The maximum production speed of electrolyser and the size of the hydrogen storage are analysed in next sections to determine the flexibility.

6.1.4.1 Flexibility of the hydrogen production

Introducing more flexibility (higher installed capacity of electrolysers, bigger storage capacity) also increases the installation and operation costs. An in depth economic analysis would be needed to determine the optimal parameters for the hydrogen scenario. No economic analysis was found and because of the time constraints of this thesis no economic analysis was performed. To include the effect different parameters would have on the flexibility potential three different scenario will be constructed. The scenarios and parameters used in this thesis are*: Moderate flexibility, medium flexibility and high flexibility* where the electrolyser could generate 105%, 116.67% and 125% of the hydrogen needed for the cement kiln and the storage could hold enough fuel for 1h , 2h and 3h of kiln operations respectively. Future research should be conducted to estimate which scenario is the most cost efficient.

The installed capacity and storage size expressed in GJ will be calculated with the following formulas:

$$Installed\ capacity\ \left[\frac{GJ}{h}\right] = Installed\ capacity\ [\%] * Fuel\ consumption\ kiln\ \left[\frac{GJ}{h}\right]$$

$$Storage\ size\ [GJ] = \ Fuel\ consumption\ kiln\ \left[\frac{GJ}{h}\right] * storage\ size\ [h]$$

The flexibility is determined by using the following parameters

$$P_{load\ shift\ power}[MW] = \frac{Storage\ size\ [GJ] *\ 0.277778\ \text{MWh}}{T_{cycle\ time}[h]} * \frac{1}{\eta_{electrolyzer}[\%]}$$

$$E_{daily\ load\ shift\ potential}[MWh] = P_{load\ shift\ potential}\ [MW] * 24h$$

Where the efficiency of the electrolyser was assumed to be 0.6, see *paragraph 5.2.5.3.* The cycle period is considered to be the time it takes for the hydrogen storage to be filled and emptied.

6.1.4.2 Key assumptions

To introduce flexibility into the generation it was assumed that electrolysers could produce more than is needed for the kiln and temporary store this hydrogen. Due to the uncertainties about the installed capacity and storage size three different hydrogen scenarios were constructed see Table 29.

Table 29: Different scenarios for the generation of hydrogen.

Degree of flexibility	**Type of process**	**Installed capacity electrolyser [inflow]**		**Storage size hydrogen**			**Energy needed for the kiln [outflow]**
		Expressed in [%]	Expressed in [GJ/h]	Time to fill storage [h]	Time needed to empty storage [h]	Storage expressed in [GJ]	Energy consumption [GJ/h]
No flexibility	Continuous	100%	337.7 GJ/h	0 h	0 h	0 GJ	337.7 GJ/h
Moderate flexibility	Continuous	105%	354.7 GJ/h	20 h	1 h	337.7 GJ	337.7 GJ/h
Medium flexibility	Continuous	116.67%	394.0 GJ/h	12 h	2 h	675.4 GJ	337.7 GJ/h
High flexibility	Continuous	125%	422.2 GJ/h	12 h	3 h	1013.2 GJ	337.7 GJ/h

6.1.5 CCS

By looking at possible flexibility introducing measures found in powerplants three strategies were identified that could also be used in the cement industry (Chalmers, 2010; Chalmers et al., 2009, 2011; Stuart M Cohen et al., 2011; Nimtz & Krautz, 2013).

- Change the fuels so the flue gas consists of a higher or lower concentration CO_2
- Load shifting: The CO_2 from the flue gas will be stored before energy intensive processes occur so it can be processed at a later moment in time when the electricity prices are lower.
- Load shedding: the whole CCS system is bypassed so flue gas is released into the atmosphere. In powerplants this can be done when the price at which the plant it could sell its produced electricity is higher than the price it has to pay to release CO_2 into the atmosphere. Bypassing will only occur at times when the electricity prices are the highest and when biomass is used in the fuel mix.

However, it was assumed that all these measures can only be implemented in the reference fuel mix scenario. Only in the reference fuel mix emissions from biofuels will be captured which allows for bypassing and the flexible use of fuels. Theoretically, when adding a buffer load shifting should be possible in all scenarios but because no literature was found about a flexible direct capture system it was assumed that it is not likely this method will be employed.

Table 30 shows the flexibility options for CCS for different scenarios.

Table 30: Proposed type of CCS and possible flexibility methods for the different scenarios.

Scenario	Proposed type of CCS	Flexible concentration CO_2 to the CCS system	Possibility to bypass	Possibility to shift processes
Reference fuel	Amine scrubbing	X	X	X
100% biofuels	Direct capture			
Hydrogen	Direct capture			
Electrification	Flue gas consists of pure CO_2 and therefore it is assumed that only the compression of CO_2 is needed (Mathisen, 2019)			

6.1.5.1 Flexible concentration CO_2

As mentioned in *paragraph 5.2.5.1* the CO_2 concentration of the flue gas is dependent on the emissions from the calcination process and the burning of carbon based fuels. In all scenarios it is assumed that the kiln operates always at full capacity therefore the amount of CO_2 of the calcination process remains constant. In the reference scenario and 100% biofuel scenario sewage sludge is being co-fired. However, only in the reference fuel mix scenario the fuel emissions will be captured and therefore only in the reference fuel scenario flexibly co-firing the sewage sludge has benefits. By varying the amount of sewage sludge burned the CO_2 the concentration of the flue gas can differ.

When using the reference fuel mix, around 26% (0.76 GJ/ tonne clinker) of the energy for the calcination process comes from sewage sludge, the other 74% (2.16 GJ/ tonne clinker) will come waste materials and fossil fuels. By using the CO_2 intensity of all these fuel mixes and the fact that the sewage sludge fed into the kiln during normal operations is around 6.5 tonne/h a linear model for the emissions could be constructed. The CO_2 intensities of methane and sewage sludge was found in literature (Vreuls, 2004) and the CO_2 intensity of the reference fuel mix without sewage sludge is calculated with the formula:

$$CO_2\ intensity_{fuel\ mix\ without\ sewage\ sludge}\left[{}^{t\ CO_2}/_{GJ}\right] = CO_2 intensity_{ref\ fuel\ mix}\left[{}^{t\ CO_2}/_{GJ}\right] - \frac{share_{sewage\ sludge}[\%] * CO_2\ intensity_{sewage\ sludge}\left[{}^{t\ CO_2}/_{GJ}\right]}{share_{other\ fuels}[\%]}$$

Where

The CO_2 intensity of the reference fuel mix is 113.39 kg CO_2 / GJ, see *paragraph 5.2.7*

The CO_2 intensity of the sewage sludge (solid biomass) is 109.60 kg CO_2 / GJ (Vreuls, 2004).

This leads to the values presented in Table 31.

Table 31 Fuel derived emission intensity at different sewage sludge feed in rates.

	Feed in rate (tonne sewage sludge / h)	**Emission intensity reference fuel [CO_2 / GJ]**	**Emissions per hour of a European plant in 2050 (2.9 GJ/ clinker)**
No sewage sludge	0 t/h	114.74 kg CO_2 / GJ	38.0 tonne CO_2 / hour
Average sewage sludge feed in (Average fuel mix)	6.5 t/h	113.39 kg CO_2 / GJ	37.5 tonne CO_2 / hour

The linear model used to calculate the fuel derived CO_2 emissions (no calcination emissions) is shown Figure 27.

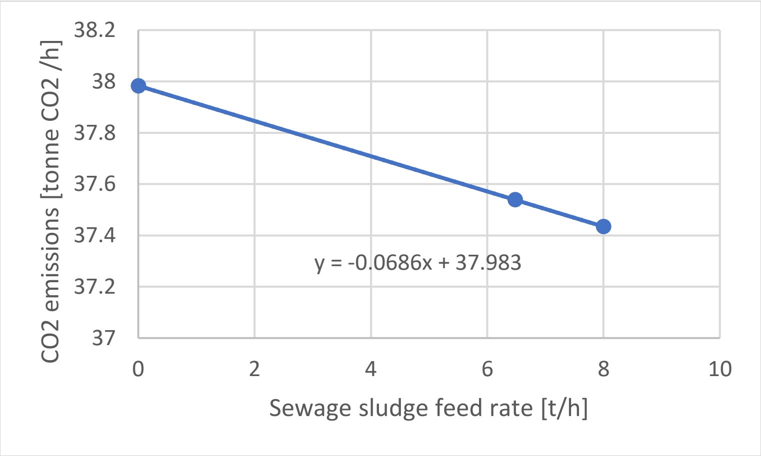

Figure 27: Fuel derived emissions reference fuel mix as a function of the sewage sludge feed in rate. It was assumed that a maximum of 8 tonne sewage sludge could be co-fired per hour

It should be noted that a linear approximation is not realistic because this would mean that if enough sewage sludge is co-fired the emission eventually could become lower than the CO_2 intensity of sewage sludge and eventually could become negative. However, in the ranges this formula is used (from 0 to 8 tonne sewage sludge per hour) it was deemed realistic.

6.1.5.2 CCS load shedding

Load shedding of a CCS system can be achieved by bypassing the CCS system so that CO_2 is released in the atmosphere instead of stored (Chalmers et al., 2009, 2011; Nimtz & Krautz, 2013). Because the constraint of this thesis is that the cement industry is carbon neutral bypassing the CCS system will only be utilised on scenarios where the CO_2 emissions could be potentially negative. Figure 28 shows how bypassing could be used.

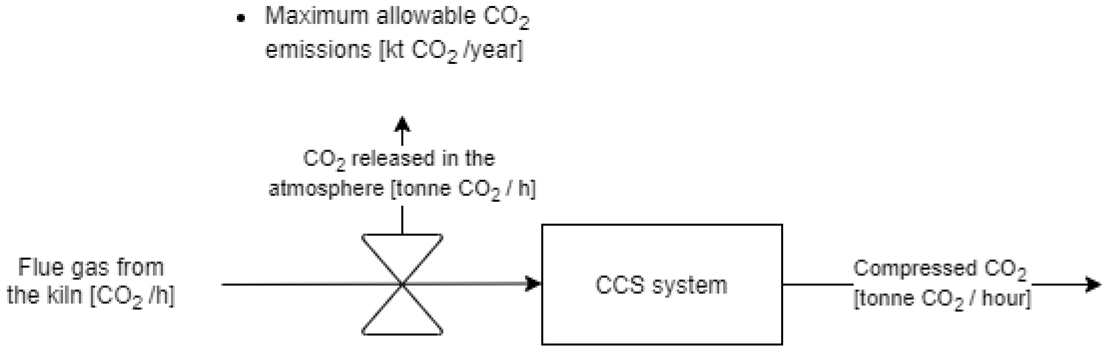

Figure 28: schematic overview of letting the CO_2 emissions bypass the CCS system

In full bypass mode the whole CCS system will be bypassed so none of the emitted CO_2 will be captured. It is assumed that while the system is in bypass mode the energy required for the CCS installation will be so small that the energy consumption can be neglected. Chalmers (2010) estimates that a power plant with CCS bypass system has a speed of response of tens of seconds to a few minutes.

The maximum hours the system can be in bypass mode while still remain carbon neutral are shown in the table Table 32.

Table 32:Hours the CCS system can by in bypass mode per year.

Annual load hours kiln	330 days
Kiln emissions current fuel mix[2]	715.3 kt/yr, 2.2 kt/day, 90t/h
Biofuel emissions	44.99 kt/yr, 0.1 kt/day, 5.7t/h
Hours in bypass mode	498 h/yr, 20 days/yr

It should be noted that it is also possible for the system to go in half-bypass mode so only a share of the CO_2 can be captured.

6.1.5.3 Load shifting with Amine Scrubbing

Load shifting of an CCS system can be achieved by adding a storage so part of the CCS process can occur at a later time.

Generally the post combustion Amine scrubbing CCS system can be divided into two different processes. The CO_2 rich flue passes through a scrubber which absorbs the CO_2 into a solvent and removes most CO_2 from the flue gas. The CO_2 which is absorbed by the solvent is later separated from the solvent in the stripper so the pure CO_2 can be stored (Metz et al., 2015). Adding a solvent storage to the CCS system can introduce flexibility. When the Electricity prices are high the CO_2 absorbed in the solvent can be stored so that the energy intensive process of removing the CO_2 the solvent can occur at a later moment. This method is proposed to be used in powerplants (Chalmers et al., 2009; Stuart M. Cohen et al., 2011; Nimtz & Krautz, 2013; Tait et al., 2018) but no study has been found where this is applied to the cement industry. Because the processes are similar in both industries (Metz et al., 2015)

[2] This value is the fuel derived and calcination emissions combined, it should not be confused with the fuel derived emissions shown in *paragraph 6.1.5.1*

it is assumed that this load shifting method is also possible in the cement industry. The workings of a flexible amine scrubbing CCS system with bypass and solvent storage is shown in Figure 29.

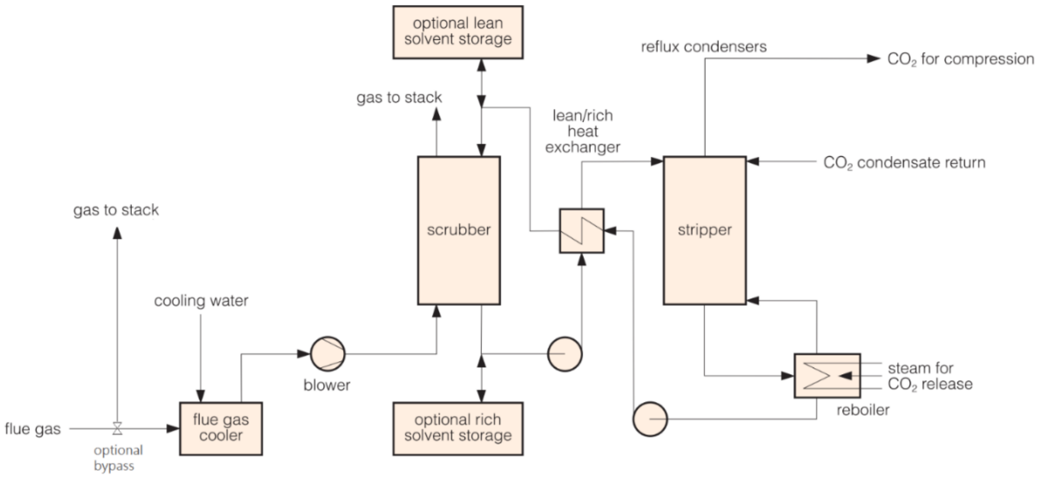

Figure 29: A flexible CCS system with bypass and solvent storage. The optional bypass is added to the original figure (Chalmers, 2010)

Cohen (2012) and Cohen et al. (2013) estimated that 90% of the energy for a CCS system at powerplant is attributed to the energy consumption of the stripping and compression. By using the assumed energy electricity of 3.5GJ/ tonne of cement it was found that 3.15 GJ per tonne CO_2 is needed for the stripping and compression part while only 0.35GJ per tonne CO_2 would be needed for the scrubbing.

After a buffer event occurs the stripper and compressor need to process the normal CO_2 emissions in addition to the stored CO_2. Chalmers et al. (2011) estimated that the stripper and compressor of a CCs system at a powerplant could operate at 125% of its normal capacity. This study will use the same assumption.

Stuart M Cohen et al. (2011) estimated based on a cost benefit analysis that the optimal solvent storage capacity coal-fired powerplant can hold up to 22.5 Minutes of CO_2 which is around 170 tonne of CO_2. It is therefore assumed that a solvent storage tank of 170 tonne CO_2 is a feasible option for the cement industry. It is assumed that the installed stripper and compressor can operate at 125% capacity compared to their normal capacity. Table 33 shows how long it takes to fill and empty the buffer.

Table 33:CO_2 storage capacity of the CO_2 buffer for the CCS system used in the reference scenario.

	Maximum CO2 absorption in solvent [Tonne CO2 per hour]	**Hours until storage tank is full [h]**	**Hours until CO2 in the tank is processed [h]**
Reference fuel mix (bypassing biomass)	136.9	1.3	4.6
Reference fuel mix (no bypass)	149.5	1.2	4.6

An economic analysis should be performed to estimate the optimum storage capacity but due to time constraints the size of the solvent storage will be based on existing literature.

6.1.5.4 Key assumptions

The table on the next page, Table 34, shows all key assumption made based on the findings of this section.

Table 34: Key assumptions CCS systems for all decarbonization sceanrios.

	CCS Technology	Type of process	Non biofuel CO_2 emissions [t CO_2 / h]	Maximal annual bypassing of the CCS system [t CO_2/year]	Electricity consumption scrubber [kWh/ tonne CO_2]	Solvent storage	Outflow stripper and compressor [t CO_2 /h]	Electricity consumption stripper and compressor [kWh/ tonne CO_2]	Explanation
Reference fuel mix	Amine scrubbing	Continuous	95.3t - 95.8 t CO_2 /h	64.48 kt CO_2/ year	97.22 kWh/ t CO_2	170 t CO_2	116.0 t CO_2 /h	875 kWh/ t CO_2	
100% biofuels	Direct capture	Continuous	57.9 t CO_2 / h	No bypassing	No scrubber	No scrubber	Only compression is required.	100 kWh /t CO_2 (Aspelund & Jordal, 2007; Roussanaly et al., 2017)	
Hydrogen	Direct capture	Continuous	57.9 t CO_2 / h	No bypassing	No scrubber	No storage	Only compression is required.	100 kWh /t CO_2	
Electrification	Only compression	Continuous	57.9 t CO_2 / h	No bypassing	No scrubber	No storage	Only compression is required.	100 kWh /t CO_2	It is assumed that in an electric kiln the flue gas consists of pure CO_2 and therefore only compression is needed

6.2 RESULTS

Based on the established key assumptions the daily load shift potential for all processes was calculated, the results are shown in *paragraph 6.2.1* to *paragraph 6.2.4.* The load shift potential will me expressed in how much electricity in MWh can be shifted per day. In *paragraph 6.2.5* an overview is given of the load shift potential for all different processes.

6.2.1 Generic cement production processes

The load shift potential of the generic cement production processes was determined by estimated how much the energy could be shifted per day while still producing enough to satisfy the daily production quota. This is done by comparing difference in electricity consumption when the process occurs at normal production speed in the morning and the at maximum production speed in the evening. The production speed was found in *Paragraph 6.1.1.2*. The load shift potential of all generic cement production processes is shown in Figure 30.

Figure 30: Daily load shift potential generic cement production processes. It should be noted that due to the software used to plot the graphs the lines appear to be skewed while they should be vertical.

The results are shown in Table 35.

Table 35: Daily load shift potential of the production processes of a 4000 tpd cement plant in 2050

Processes	Daily load shift potential [MWh/day]
Crusher	6.52
Raw Mill	23.96
Cement mill	73.20
Packaging	5.99
Total	109.66

The calculated maximum load shift potential was calculated by assuming that a certain quota must be met during each day. It could however be the case that on the previous day more is produced so that the quota of next day could be lowered. To quantify this behaviour the time it takes to fill up and empty the storage was also calculated, see Figure 31.

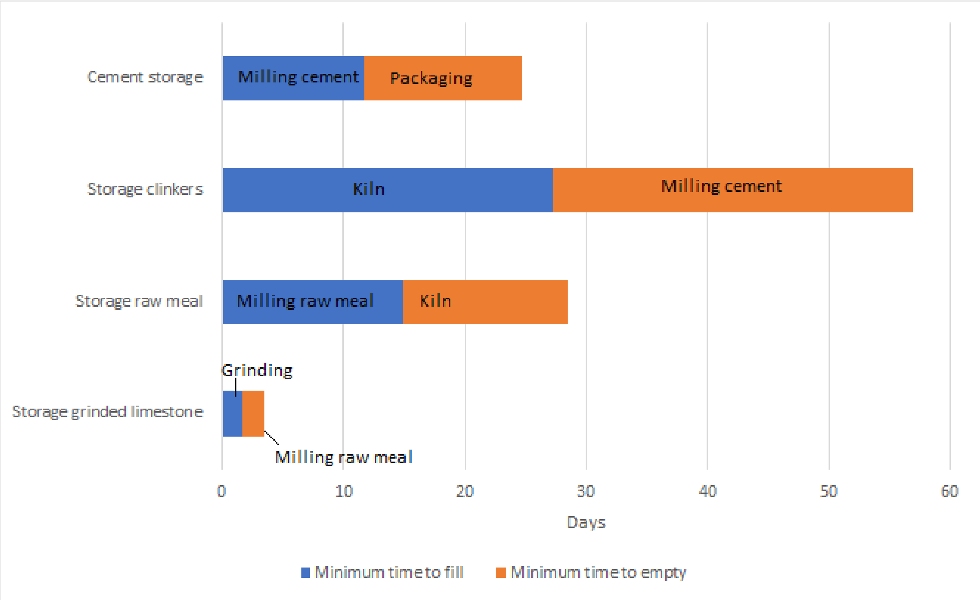

Figure 31: Days it take to fill and empty the different storages when the plant runs at full capacity.

6.2.2 Milling of sewage sludge

The sewage sludge which is used in the reference fuel scenario and the 100% fuel mix scenario has to be milled before it can be co-fired in the kiln. Because this sewage sludge is stored before it is co-fired and the sewage sludge mill does not operate at full capacity the milling processing can be shifted. By calculating the difference between the energy consumption of milling in the morning at average speed and maximum speed in the afternoon the daily load shift potential is estimated to be 4,391 kWh.

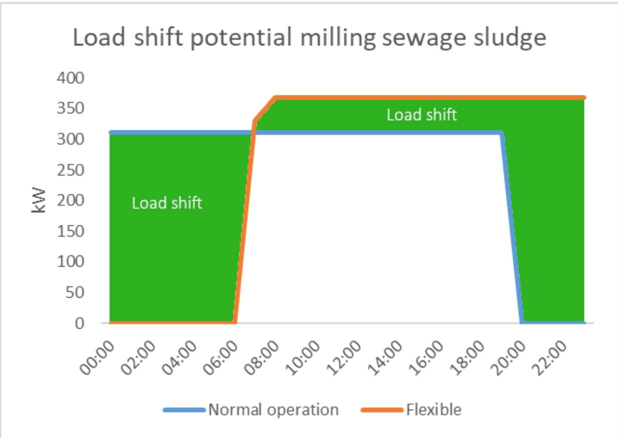

Figure 32: Daily load shift potential of milling sewage sludge. It should be noted that due to the software used to plot the graphs the lines appear to be skewed while they should be vertical.

It was calculated that if there is no outflow it takes a minimum of 147 hours (7.3 day assuming milling can only occur 20 hours a day) to completely fill the storage. If there no inflow it takes around 169 hours (7 days assuming the kiln operates for 24 hours day).

For comparison it was assumed that in the morning the same amount of sewage sludge was milled as in the evening. Because the storage could hold up to 7 days of sewage sludge it could happen that no milling is needed for several days and thereby greatly increasing the daily load shift potential.

6.2.3 Flexibility of the hydrogen production

In the hydrogen scenario hydrogen will be used as fuel for the kiln and is created through the electrolysis of water. The hydrogen can be fired directly in the kiln or stored in a storage so it can be used when the electricity prices are lower. An in depth economic analysis is needed to determine the optimal storage size and capacity of the electrolysers but due to time constraints multiple scenarios are constructed with different degrees of flexibility to show the effect of different installed capacities and storage sizes. The daily load shift potential was estimated by calculating the difference in electrcity consumption between the normal and flexible operating mode, see Figure 33.

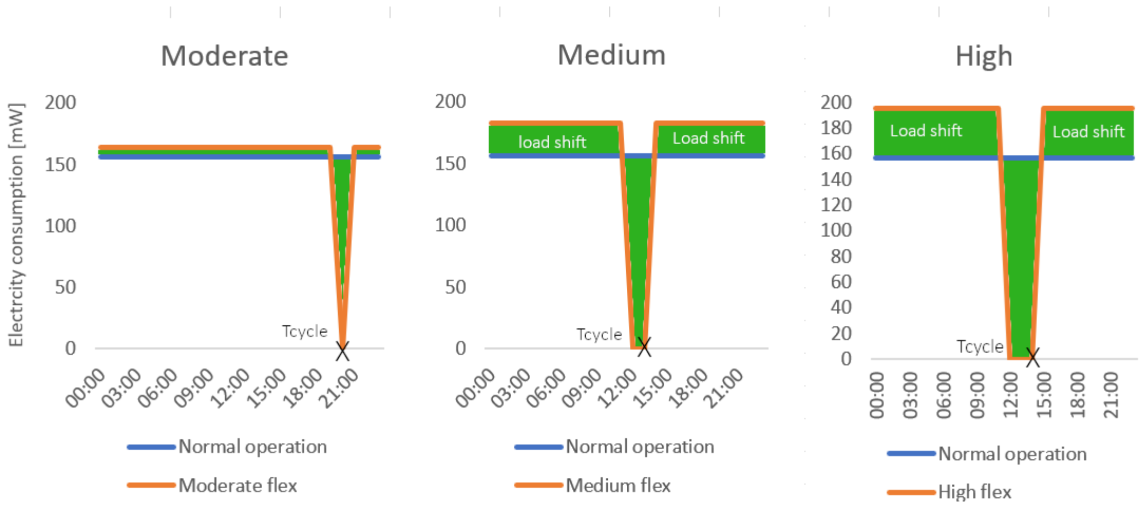

Figure 33: Load shift potential of the electrolyser in the three different flexibility scenarios. The X shows the cycle period (The time it takes to fill and empty the hydrogen storage). It should be noted that due to the software used to plot the graphs the lines appear to be skewed while they should be vertical.

The results are shown in Table 36

Table 36: Calculated daily load shift potential of the electrolyser

	Shifted per cycle	Cycle period [h charged and h discharged]	Maximum daily shifted
Moderate flexibility	312.7	20 + 1	357.3
Medium flexibility	625.38	12 + 2	1,072.1
High flexibility	938.0	12 + 3	1,500.8

6.2.4 Flexibility of the CCS system

As mentioned earlier it was assumed that a flexible CCS system is only feasible in the reference fuel mix scenario, three methods were identified to introduce flexibility:

- By changing the amount of sewage sludge co-fired the CO_2 emissions of the flue gas change and therefore the energy consumption of the CCS system.
- Let the flue gas bypass the CCS system (load shedding)
- Add a buffer to the CCS system so the energy intensive stripping process can be performed later.

The load shift potential of flexible co-firing sewage sludge was estimated by comparing the energy consumption of the normal operation with the flexible one. Here it was assumed that in the normal mode of operation a constant amount of sewage sludge was co-fired each hour. In the flexible scenario the same amount of sewage sludge was co-fired but this was spread out as far as possible (no co-firing in the morning, maximal co-firing in the evening), see Figure 34. It was estimated that the average daily load shift potential is 3.8 MWh

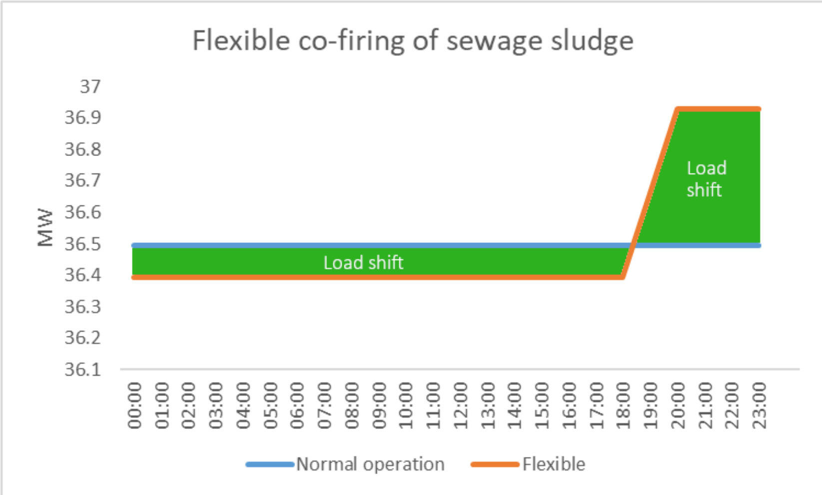

Figure 34: Flexibility potential of the co-firing of sewage sludge, the energy consumption shown is that of the CCS system. It should be noted that due to the software used to plot the graphs the lines appear to be skewed while they should be vertical.

Because biofuels are considered to be carbon neutral it is possible for those emissions to bypass the CCS system. It is estimated that is possible to save 43.8 GWh/y using a bypass, see Table 37.

Table 37: CCS bypass potential of the reference fuel mix scenario

	Reference fuel mix	Explanation
CO_2 emissions from biofuels [kt/y]	44.99	See 5.3
Total CO_2 emissions [kt/yr]	751.31	See 5.3
Total CO_2 emissions [t/h]	90.3	See 5.3
hours in bypass mode [h/y]	498	See 5.3
Energy saved [MWh/y]	43.8	based on energy consumption of 3.5 GJ/t CO_2

Adding a solvent storage to the CCS system could postpone the energy intensive step of the stripper. A solvent storage which could hold 170 t of CO_2 was chosen because this was found to be the most cost effective size for a buffer at powerplant that uses CCS. Due to time constraints it was assumed that this would also be the case for a cement plant but more in depth studies should be conducted to conclude what is the most cost effective option. The load shift potential of adding a buffer is shown in Figure 35, it was estimated that adding a buffer could add a load shift potential of 741 MWh/day.

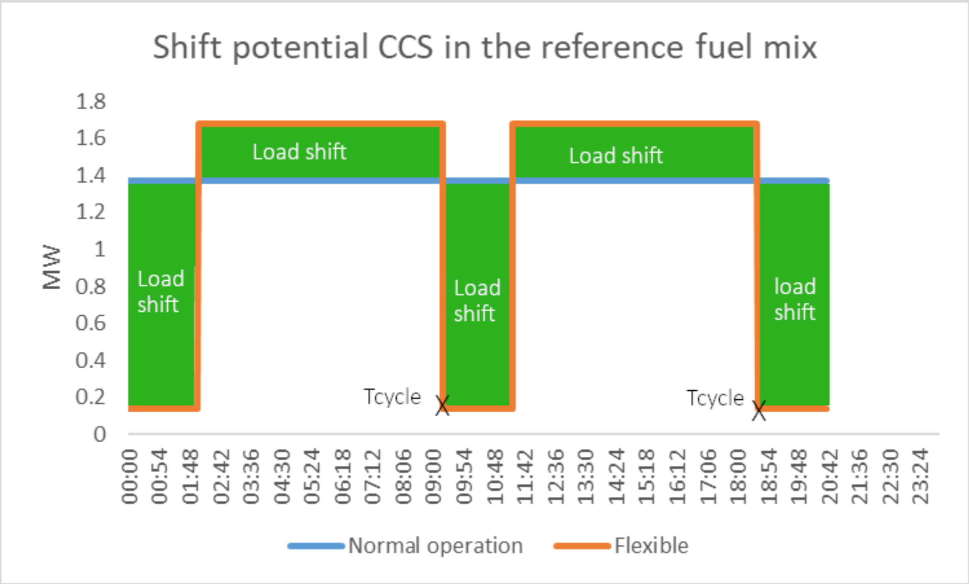

Figure 35: load shift potential of the CCS system in the reference fuel mix with a solvent storage which could hold 170 tonne of CO_2.

6.2.5 Overview daily load shift potential of all processes

An overview of the load shift potential of all processes covered in this chapter are shown in Table 38.

Table 38: Overview of the maximum load shift potential for all flexible scenarios of all processes.

	Reference fuel mix	**100% biofuel**	**Hydrogen**	**Electrification**
Generic cement production processes	109.7 MWh/day	109.7 MWh/day	109.7 MWh/day	109.7 MWh/day
Milling sewage sludge	4.4 MWh/day	4.4 MWh/day	-	-
CCS, Flexible co-firing sewage sludge	3.8 MWh/day	-	-	-
CCS, solvent storage	741 MWh/day	-	-	-
Hydrogen	-	-	Moderate:357.3 MWh/day Medium:1,072.1 MWh/day High:1,500.8 MWh/day	-
Total	858.9 MWh/day	114.1 MWh/day	466.0 MWh/day to 1,610.5 MWh/day	109.7 MWh/day

6.4 Conclusion

In this chapter the following research question was answered:

"What is the technical flexibility potential of a European carbon neutral cement plant in 2050?"

It was estimated that both the reference fuel mix and the hydrogen scenario have the highest flexibility potential. The hydrogen scenario has the benefit that it can flexibly use the most energy intensive process of a cement plant, the kiln. As described in chapter 5, the reference fuel mix scenario is the only scenario which uses amine scrubbing for CCS. A buffer could be added to this CCS system so the energy intensive process of stripping the CO_2 from the solvent can be postponed and thereby greatly introducing flexibility. The 100% biofuel scenario is ranked second last, here only the generic cement processes could be made flexible and the milling of sewage sludge. The electrification scenario has the lowest flexibility potential because no extra flexible steps were identified.

A cement plant operator would only operate if it is incentivised to do so. In this thesis it was assumed that price signals will provide an incentive to shift the production. The flexibility parameters estimated in this chapter were used in the next chapter to estimate the actual costs savings when operating flexible. Moreover, the maximum load shift potential calculated in this chapter was compared with the actual amount of electricity load shifted in *chapter 7*.

7 ECONOMIC FLEXIBILITY POTENTIAL OF A EUROPEAN CEMENT PLANT (RQ4)

In this chapter the economic flexibility potentials were estimated for all constructed scenarios to answer the research question:

“What is the economic flexibility potential of a carbon neutral cement plant in 2050?”

By answering this research question the main research question can be answered in the conclusion, *chapter 9.*

As mentioned in the introduction the flexible electricity prices could create an incentive for the cement plant to shift its processes to times with low electricity demand thus high renewable supply. This behaviour not only favours the integration of VRES, but it also reduces the electricity costs for the cement plant.

The economic flexibility is estimated with a linear program and the constraints of this program are based on data gathered in the previous chapters. Despite the goals of the European Union to create a carbon neutral electricity system by 2050, the effects this will have on the electricity prices is mostly unknown. To incorporate this uncertainty into the results, electricity prices from multiple scenarios are used. Due to time constraints, instead of analysing all countries in Europe, only four countries are analysed with each representing a specific part of Europe (Northern, Western, Southern and Eastern Europe).

7.1 METHODOLOGY

In the first *paragraph (7.1.1)* the theory behind a linear program (LP) is briefly explained followed by a description of the tools used to implement the linear program and its limitations. The *paragraph (7.1.2)* thereafter describes which electricity price time-series are applied for the estimation of the economic flexibility potential. As described in *chapter 6* the generic cement processes will be the same in all scenarios but their CCS technology and heat source differ. Therefore, one LP is constructed for the generic cement production processes and 3 different LPs are constructed for the reference fuel mix, 100% biofuel and hydrogen scenario. In *chapter 6* it was estimated that the electrification scenario has no extra flexibility potential. Creating four different LPs instead of one has the benefit that the models are smaller and therefore more comprehensive. Moreover, larger models have a larger computing time and therefore debugging becomes more time consuming. Because the different processes behave separate from each other it has no effect on the results.

The connection between the LPs and the decarbonization scenarios is shown in Table 39.

Table 39: Connection between the different linear programs and the constructed scenarios

Scenario:	**Purpose**
LP: Generic cement processes *Section: 7.1.3*	Estimates the economic flexibility potential of flexible operation of the grinder, raw mill, cement mill and packaging unit.
LP: Reference fuel mix ***Section: 7.1.5***	Estimates the economic potential of the milling of sewage sludge, flexible co-firing of sewage sludge and a flexible amine scrubbing CCS system
LP: 100% biofuel mix ***Section: 7.1.6***	Estimates the economic flexibility potential of milling sewage sludge
LP: Hydrogen scenario ***Section: 7.1.7***	Estimates the economic flexibility potential of flexible hydrogen generation.

For all scenarios a non-flexible reference scenario was constructed where all processes occur at a fixed time. By comparing the non-flexible scenario with the flexible scenario the total cost savings were estimated. The following formula was used to estimate the cost savings:

$$c_{savings\ relative}[\%] = \frac{c_{no\ flex} - c_{flex}}{c_{no\ flex}}$$

The absolute costs savings were calculated as:

$$c_{savings\ absolute}[€] = c_{no\ flex} - c_{\ fex}$$

The amount of electricity load shifted was estimating by calculating the average difference in electricity consumption between the no flexibility scenario and the flexibility scenario for one day:

$$E_{average\ shifted\ daily}\left[\frac{MWh}{day}\right] = \sum_{t}^{T} |P_{no\ flex_t} - P_{flex_t}| \ * \frac{24\ hours}{T}$$

Where t indicates the timestep (in hours) and T is the total number of hours modelled.

7.1.1 Linear programming and limitations

7.1.1.1 Linear programming explanation

A linear program is a mathematical tool to find a minimum or a maximum of a function and is defined by Ferguson (n.d.) as:

“maximizing or minimizing a linear function subject to linear constraints”

In this thesis a linear program will be used to minimize the electricity cost while still create enough cement to satisfy the demand. The linear constraints are based on the characteristics of the production processes.

To illustrate the principle of a linear program a simple example provided by Ferguson (n.d.) is used. In this example the sum $x_1 + x_2$ will be maximized while subject to certain linear constraints. This example has no connection to a cement plant and is merely used to explain principles of a LP. The objective function is the function that will be minimized or maximized thus:

$$\max x_1 + x_2$$

While being subjected to the following constraints.

$$x_1 \geq 0$$

$$x_2 \geq 0$$

$$x_1 + 2x_2 \leq 4$$

$$4x_1 + 2x_2 \leq 12$$

$$-x_1 + x_2 \leq 1$$

This linear problem can be visualized in a 2d plane, the constraints are represented as lines and the area between those lines show the feasible solutions, see Figure 36. The maximized or minimized values are always present at a corner point. By comparing all corner points the maximum value can be determined while still satisfying the constraints. In the example the optimal point would be: 8/3 + 2/3 =10/3.

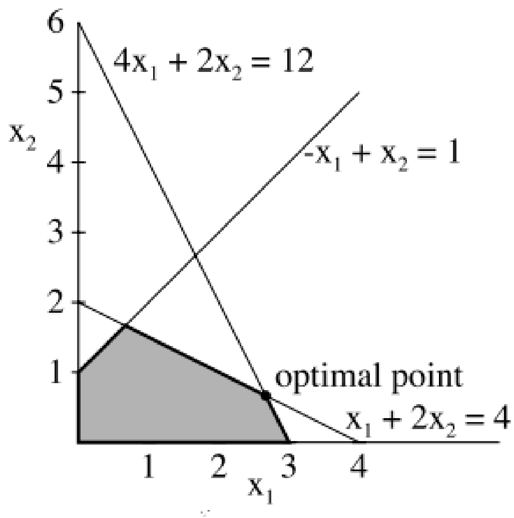

Figure 36: Visualisation of a simple Linear programming problem from Ferguson (n.d.).

The same method was used to find the minimum electricity costs for the cement plants in the different scenarios. In this thesis the variables used in the linear program are divided into the following categories:

- **Decision Variable (DV):** The variable which is the output of the linear program
- **Constant:** Variable which value remains constant (e.g. electricity needed to grind 1 tonne of limestone, Electricity prices, maximum storage size).
- **Variable derived from DV:** The result of a function that uses DV and a constant (e.g. mass of a material in storage based on the inflow and outflow of that storage)

7.1.1.2 Software used and limitations

To solve the linear problems the OpenSolver plug-in for Microsoft Excel was used. OpenSolver is an add-in that extends the conventional solver of excel which makes it possible to use other solvers and does not impose a variable size limit (Mason, 2012). The conventional solver of excel has a limit of 200 decision variables while the number of decision variable used in all models are much higher. Theoretically, OpenSolver supports infinite variables but by increasing the number of decision variables the time it takes to find a solution also increases. To decrease the processing time it was decided that instead of a whole year the prices of the winter and summer period were analysed. The winter month is defined as 1 February till 28 February and the summer period is defined as 1 Augustus till 28 Augustus.

7.1.2 Electricity price profile

To estimate the economic flexibility potential in 2050 multiple different price profiles were used. Different price profiles were used so the uncertainty of the development of electricity prices are included in the results. Because of time constraints it was not possible to analyse all countries in the EU and therefore one country of each for each subregion of Europe was chosen (North, East, South and West Europe). The chosen countries are: Germany, Greece, Poland and Sweden, see Figure 37. Other than the geographic locations the countries where also selected so each country represent a part of a different cluster defined their types of powerplant as described in (European Commission, 2018). The clusters described in European Commission (2018) are:

- The sunny cluster (BG, CY, ES, GR, MT, PT)
- The windy cluster (DE, FR, GB, IE, RO)
- The Nordic cluster (DK, EE, FI, LT, LV, NO, SE)
- The connected cluster (AT, BA, BE, CH, CZ, HR, HU, IT, LU, ME, MK, NL. PL, RS, SI, SK)

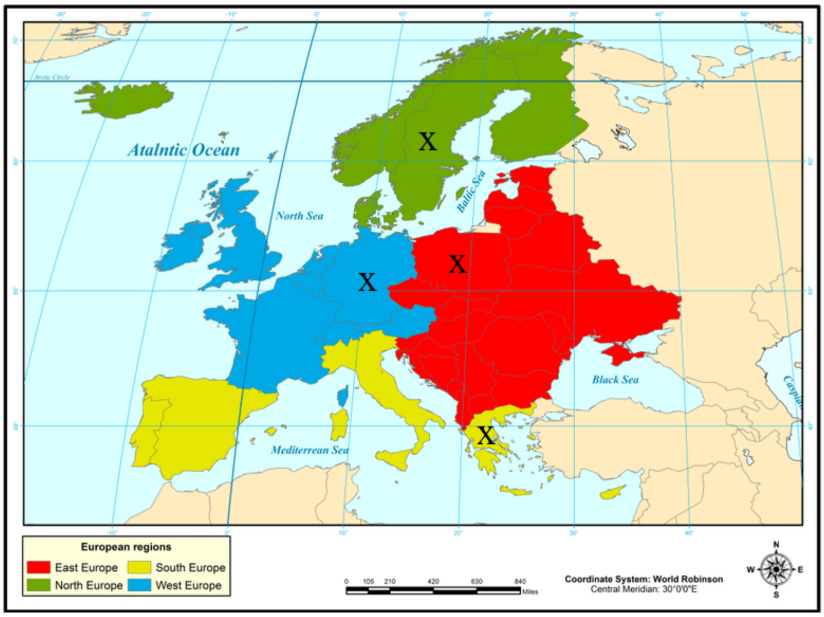

Figure 37: Subregions of Europe according to the United Nations Geoscheme where the X indicates that this country is analysed (Manic et al., 2017).

To get an indication of what the electricity prices could be in 2050 the results of energy models that calculate the electricity prices for 2050 or close to 2050 were used together with the historical electricity prices of 2019. The year 2019 was used instead of the most recent data to exclude the effect COVID-19 could have on the electricity prices. Table 40 shows which models are used for the price profiles of the selected countries.

Table 40: Country availability of the different datasets used for the electricity prices,

	Historical price profile of 2019 (ENTSO-E, 2021) ***Section: 7.1.2.1***	**Balmoral model FREE scenario in 2045 (Gea-bermúdez et al., 2021)** ***section 7.1.2.2 Section: 7.1.2.2***	**METIS S6 Price profiles of 2050 (Barberi et al., 2018)** ***Section: 7.1.2.3***
Germany (West Europe, Windy cluster)	X	X	X
Greece (southern Europe, Sunny cluster)	X		X
Poland (Eastern Europe, connected cluster)	X	X	X
Sweden (Northern Europe, the Nordic cluster)	X	X	X

7.1.2.1 Historical electricity prices

Even though the current electricity generation mix is are not carbon neutral, see Table 41, they do provide a realistic fluctuation of electricity prices throughout the day. Another benefit of using the current electricity prices is that this allows for comparison between the future scenarios and the current scenario.

Table 41: Electricity share from renewable energy for the countries used in this report in 2019 (Ritchie & Roser, 2020)

	Electricity share from renewable energy sources in 2019
Germany	17.48%
Greece	12.11%
Poland	6.18%
Sweden	42.24%

The electricity prices for the summer and winter period are shown in Figure 38 and are gathered from the European Network of Transmission System Operators (ENTSO-E). As shown in Figure 38 a high share of VRES does not necessary contribute to lower electricity prices. In all countries the electricity prices are lower in the winter but there is also more variance in the winter. Therefore, it is likely that the electricity savings will be higher in the winter when operating flexibly. The figure also shows that Germany sometimes has negative electricity prices. Negative prices can occur when there is a high supply of variable renewable energy and a low electricity demand. The higher prices in the winter are likely caused by the fact that there is less PV generation and more electricity demand than in the summer.

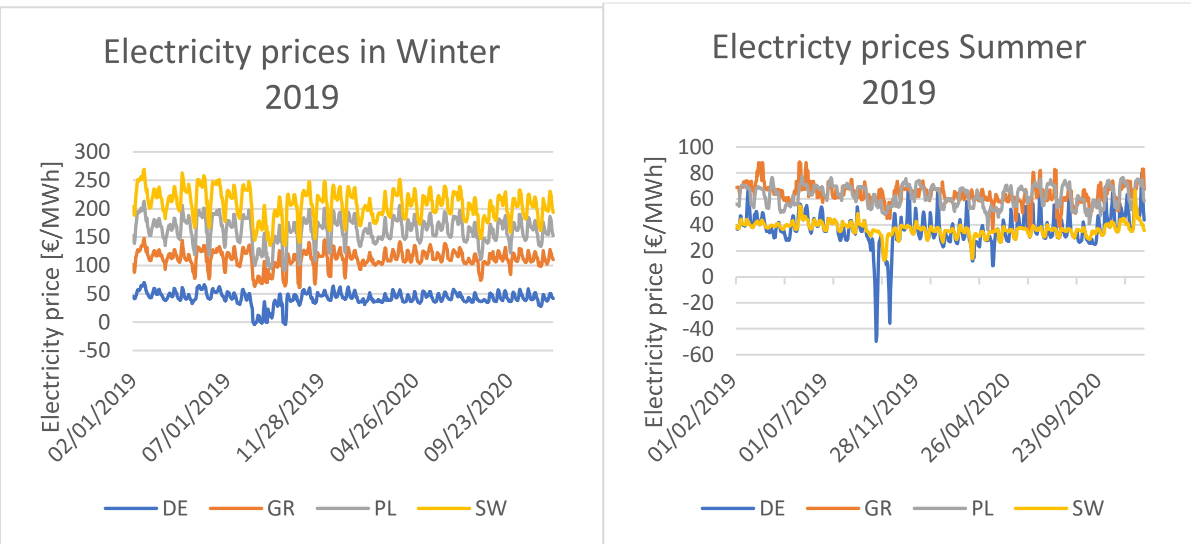

Figure 38: Actual electricity prices of 2019 (ENTSO-E, 2021)

7.1.2.2 Balmoral

Though personal communication (Gea-Bermúdez, Personal Communication, April 29, 2021) the hourly electricity prices calculated with the Balmoral software were acquired. The model is described in Gea-bermúdez et al. (2021) and features a flexible demand. The aim of the balmoral model was to minimize the total system costs (investment costs, fuel costs CO_2 tax, etc) while still satisfying the energy demand. The hourly electricity costs are determined by using the merit order. The balmoral model has a hourly time resolution.

Gea-Bermúdez offered multiple electricity price profiles but only the price profile for the scenario with the lowest emissions was used in this thesis (the FREE scenario). In the FREE scenario the CO_2 emissions are reduced to 76% compared to 1990 levels. Despite the fact that this scenario is not fully carbon neutral it could still provide valuable information because it is closer to a carbon neutral electricity mix than the current mix. The electricity prices of this model are shown in Figure 39.

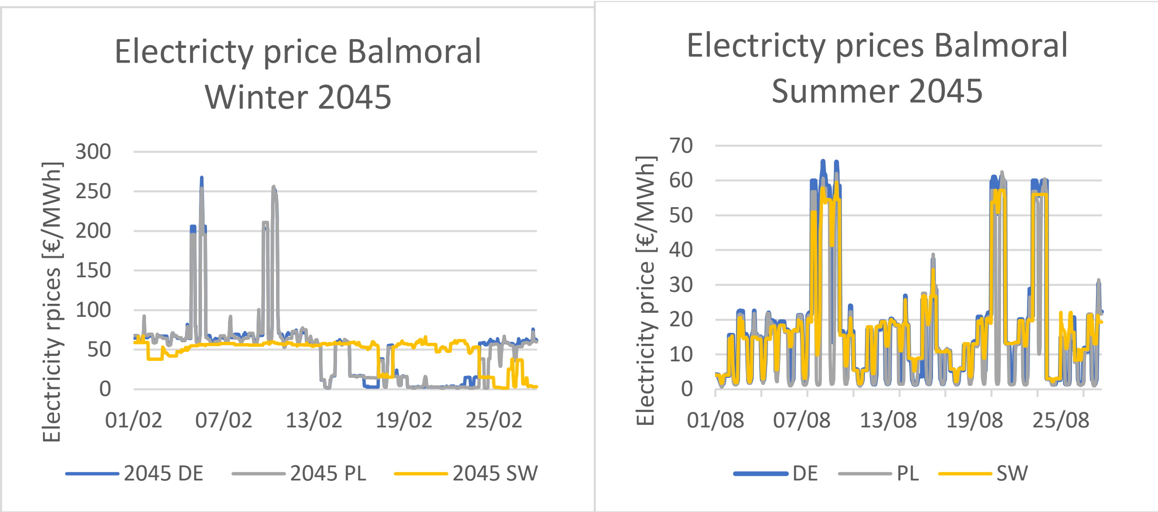

Figure 39: Wholesale electricity prices for 2045 calculated with the Balmoral software by Gea-bermúdez et al (2021)

As shown in Figure 39, just like the historical electricity prices the prices in the winter are higher than in the summer. The high spikes in electricity prices in the Winter are likely caused by the need to turn on expensive backup generators. Spikes also occur in the Summer period but here the spikes are much lower.

7.1.2.3 METIS model

METIS is an energy simulator used by the Joint Research Centre (JRC) (European Commission, 2016). The METIS model has an hourly time resolution. The electricity prices used in this thesis were the results of the S6 study from the European Commission which uses the METIS model. This scenario is based on the EUCO30-2050 scenario from the European commission where around 65% of the electricity is provided by renewable energy sources. Furthermore, in this scenario it was estimated that heat pumps could operate flexibly and thereby better matching the supply and the demand of electricity which lowers the electricity costs (Barberi et al., 2018).

Though personal communication with an employer from JRC (Boldrini, Personal Communication, June 16, 2021) the hourly electricity prices calculated for 2050 were acquired.

The electricity prices of the METIS model are shown in Figure 40.

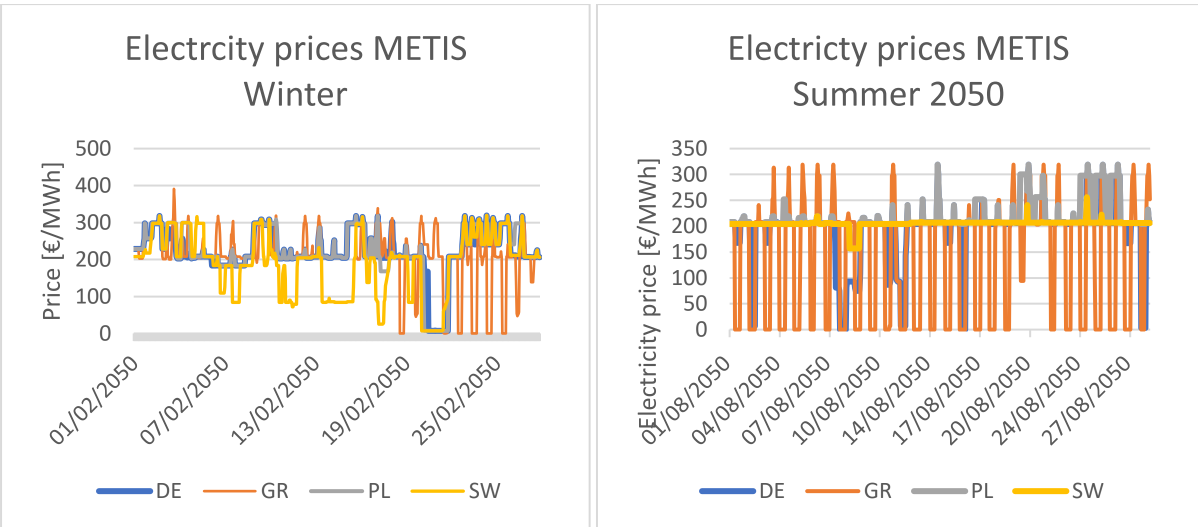

Figure 40: Wholesale electricity prices calculated by the METIS model.

7.1.2.4 Overview electricity prices

To show the difference between all electricity price profiles used, a boxplot was created, see Figure 41. According to the models the variance in electricity prices greatly increases in future scenarios. The reason for this variance are likely caused because of the implementation of VRES but also because of the static nature of this models. On average the electricity prices are lower in the summer than in the winter which is likely caused by the integration of PV into the mix and the higher electricity demand in the winter. The outliers of the future scenarios are likely caused by the use of expensive backup generators to supply electricity when the VRES are unable to. These high spikes show the need for flexible electricity demand because through load shifting some of these spikes could theoretically be prevented.

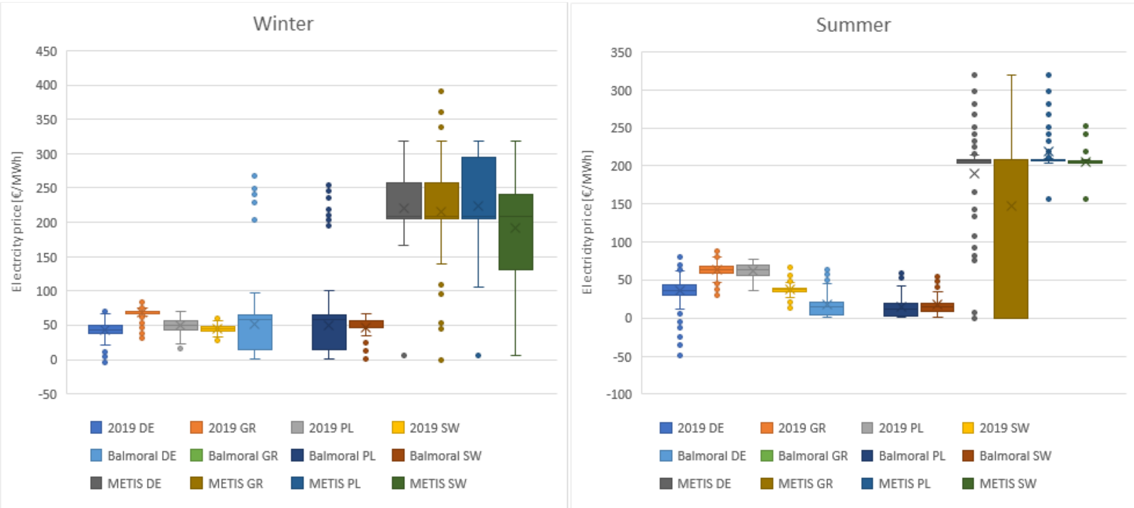

Figure 41: Boxplot of the different electricity price profiles in the summer and winter where the x shows the average value and the dots show the outliers.

7.1.3 Variables used in all LPs

All variables used in the LPs described in the next paragraphs are described in Table 42. As mention in *7.1.1* all variables are classified as constants (Remain constant), Decision variables (output of the LP) or variables derived from DV (The result of a function that uses DV and a constant). The constraints of each model will be described in *paragraphs 7.1.4 to 7.1.7*.

Table 42: All variables used the LPs to determine the economic load shift potential.

Decarbonization scenario and name of the model used	Type of variable (Given, decision Variable, Continuous)	Name	Description	Value of constant	Unit
Scenario: all scenarios	Constant	p_t	Electricity price per hour	See chapter 7.1.2	€/MWh
Model: used in all models	Variable derived from DV	E_t	Electricity consumption per time step		MWh
	Constant	T	Hours in the period	672	Hours
	Constant	t	Time step of one hour		
Scenario: all scenarios	Constant	$S_{\text{ginded limestone}}$	Storage capacity for crushed limestone	10,000	Tonne
Model: generic cement processes	Constant	$S_{\text{raw meal}}$	Storage capacity raw meal	80,000	Tonne

Constant	$S_{clinker}$	Storage capacity clinker	160,000	Tonne
Constant	S_{cement}	Storage capacity cement	70,000	Tonne
Variable derived from DV	$m_{grinded\ limestone,t}$	Mass grinded limestone in the grinded limestone storage at time t		Tonne
Variable derived from DV	$m_{raw\ meal,t}$	Mass raw meal in the raw meal storage at time t		Tonne
Variable derived from DV	$m_{clinker,t}$	Mass clinkers in the clinker storage at time t		Tonne
Variable derived from DV	$m_{cement,t}$	Mass cement in the cement storage at time t		Tonne
Constant	$m_{grinded\ limestone,\ 0}$	Initial value limestone storage	0	Tonne
Constant	$m_{raw\ meal,0}$	Initial value raw meal storage	12,784	Tonne, based on the buffer which was created when the kiln was offline
Constant	$m_{clinker,0}$	Initial value clinker storage	0	Tonne
Constant	$m_{cement,0}$	Initial value cement storage	0	Tonne
Constant	Q_{Cement}	Cement quota	140,622	Tonne , based on the annual production
Constant	$LH_{grinder}$	Load hours grinder	12	Hours/day, NOTE it is assumed that grinding does not take place on Sunday (every 7th day of the week)
Constant	$LH_{raw\ mill}$	Maximum load hours raw mill	20	Hours/day
Constant	$LH_{cement\ mill}$	Maximum load hours cement mill	20	Hours/day
Constant	$LH_{packaging}$	Maximum load hours packaging	18	Hours/day
Constant	$\dot{m}_{rrusher,\ max}$	Maximum production speed crusher	518	t/h
Constant	$\dot{m}_{ram\ mill,\ max}$	Maximum production speed ram mill	269	t/h
Constant	$\dot{m}_{cement\ mill}$	Maximum production speed cement mill	245	t/h
Constant	$\dot{m}_{packaging}$	Maximum production speed packaging	269	t/h
Constant	$\dot{m}_{kiln}$	Constant feed to the cement kiln	245	t/h
Constant	$ECV_{Crusher}$	Electric consumption value crusher	0.00056	MWh/t
Constant	$ECV_{raw\ mill}$	Electric consumption value raw mill	0.0090	MWh/t

Constant	ECV_{kiln}	Electric consumption value kiln	0.02200	MWh/t
Constant	$ECV_{cement\ mill}$	Electric consumption value cement mill	0.02750	MWh/t
Constant	$ECV_{packaging}$	Electric consumption value packaging	0.00150	MWh/t
DV	$OH_{grinder,\ t}$	Operating hours at timestep t of the grinder		h/h
DV	$OH_{raw\ mill,\ t}$	Operating hours at timestep t of the raw mill		h/h
Constant	$OH_{kiln,\ t}$	Operating hours at timestep t of the kiln	1	h/h
DV	$OH_{cement\ mill,\ t}$	Operating hours at timestep t of the cement mill		h/h
DV	$OH_{packaging,\ t}$	Operating hours at timestep t of the packaging unit		h/h
Variable derived from DV	$E_{grinder,t}$	Energy consumption grinder during timestep t		MWh
Variable derived from DV	$E_{ram\ mill,t}$	Energy consumption raw mill during timestep t		MWh
Variable derived from DV	$E_{kiln,\ t}$	Energy consumption kiln during timestep t		MWh
Variable derived from DV	$E_{cement\ mill,t}$	Energy consumption cement mill during timestep t		MWh
Variable derived from DV	$E_{packaging}$	Energy consumption packaging during timestep t		MWh
Variable derived from DV	$\dot{m}_{grinder,\ t}$	Amount of limestone processed at timestep t		t/h
Variable derived from DV	$\dot{m}_{Raw\ mill,\ t}$	Amount of limestone milled to raw meal at timestep t		t/h
Constant derived from another constant	$\dot{m}_{kiln,t}$	Amount of raw meal fed into the kiln	245	t/h
Variable derived from DV	$\dot{m}_{cement\ mill,\ t}$	Amount of clinkers milled at timestep t		t/h
Variable derived from DV	$\dot{m}_{packaging,\ t}$	Amount of cement being packaged and transported at timestep t		t/h
Variable derived from DV	Daily $OH_{grinder,\ i}$	Hours the grinder is in operation on day i		Hours
Variable derived from DV	Daily $OH_{Raw\ mill,\ i}$	Hours the Raw Mill is in operation at day i		Hours

	Variable derived from DV	Daily $OH_{Cement\ mill,\ i}$	Hours the Cement mill is in operation at day i		Hours
	Variable derived from DV	Daily $OH_{Packaging,i}$	Hours being packaged at day i		Hours
Scenario: reference fuel mix and 100% biofuel **Model: Reference fuel mix and 100% biofuel**	Constant	S_s	Storage sewage sludge	1,350	Tonne
	Constant	Q_s	Sewage sludge quota	3,935	Tonne
	Variable derived from DV	m_s	Amount of sewage sludge burned		Tonne
	Constant	$\dot{m}_{milling\ sewage\ sludge\ max}$	Maximum sewage sludge milling speed	9.2	Tonne/h
	Constant	$\dot{m}_{kiln\ feed\ max}$	Maximum sewage sludge kiln feed	8.0	Tonne/h
	DV	$m_{sewage\ sludge,\ t}$	Mass sewage sludge in the sewage sludge storage at time t		Tonne
	DV	$\dot{m}_{milling\ sewage\ sludge,\ t}$	Milling speed at time t		Tonne/h
	DV	$\dot{m}_{kiln\ feed,\ t}$	Sewage sludge kiln feed at time t		Tonne/h
	Constant	$S_{sewage\ sludge}$	Storage size of the sewage sludge	1350	
	Constant	$ECV_{sewage\ sludge\ mill}$	Electric consumption value sewage sludge mill	0.04	MWh/t
	Variable derived from DV	$E_{Sewage\ sludge\ mill,t}$	Electricity use of the sludge mill at time step t		MWh
	Variable derived from DV	$OH_{sewage\ sludge\ mill,\ t}$	Amount of time the sewage sludge mill is on in timestep t.		h/h
	Variable derived from DV	Daily $OH_{sewage\ sludge\ mill,\ max}$	The maximum amount of time the sewage sludge mill can be turned on	20	Hours/day
	Variable derived from DV	Daily $OH_{sewage\ sludge\ mill,\ i}$	Amount of hours the sewage sludge mill is in operation at day i		Hours/day
Scenario: reference fuel mix **Model: Reference fuel**	Constant	$Q_{CO2,scenario}$	Max bypassed CO_2	3,817	Tonne
	Constant	S_{CO2}	Storage size CO_2 in the buffer	170	
	DV	$\dot{m}_{scrubber,\ t}$	Amount of CO_2 fed into the scrubber at time t		
	DV	$\dot{m}_{stripper,\ t}$	Amount of CO_2 fed into the stripper at time t		
	Constant	$\dot{m}_{stripper\ max}$	Maximum of CO2 the stripper could process		t/h
	Constant	$ECV_{Scrubber}$	Electric consumption value scrubber	0.0972	MWh/tonne CO_2
	Constant	$ECV_{stripper}$	Electric consumption value stripper	0.875	MWh/tonne CO_2
	Variable derived from DV	$E_{scrubber,t}$	Electricity use of the scrubber at time step t		MWh

	Variable derived from DV/ constant	e_t	Emissions at timestep t	$\dot{m}_{kiln\ feed,\ t}$* - 0.0686 + 37.983 + 57.877	Emissions/ h
	DV	$e_{bypassed,\ t}$	Emissions bypassed at timestep t		Tonne / h
	Variable derived from DV	$m_{co2\ buffer,\ t}$	Mass CO_2 stored in the buffer at timestep t		Tonne
Scenario: 100% biofuel, hydrogen, Electrification **Model 100% biofuel, hydrogen**	Constant	$E_{compressor,t}$	Energy consumption of the CO_2 compressor at time step t	5.78	MWh/h
Scenario: hydrogen **Model: 100% hydrogen**	Constant	$S_{hydrogen,\ max}$	Storage capacity of the hydrogen storage	Moderate: 337.7 Medium: 675.3 High: 1,013.0	GJ
	Constant	$Feed_{kiln}$	Amount of energy needed for the operation of the kiln	337.7	GJ/h
	Constant	$H_{production,\ max}$	Maximum hydrogen production at timestep t	Moderate: 354.6 Medium: 393.9 High:422.1	GJ/hour
	DV	$H_{production,\ t}$	Hydrogen production at timestep t		GJ/Hour
	Variable derived from DV	HS_t	Hydrogen in the storage at time t		GJ
	Constant	HS_0	Initial amount of hydrogen in the storage	0	GJ
	Constant	$\eta_{electrolyzer}$	Efficiency of the electrolyser	60	%

7.1.4 Modelling generic cement production

In the next section the methodology used to construct the LP for the generic cement production processes is described. Before the LP is described a definition of a non-flexible cement plant is given so both scenarios could be compared. It is important to note that all values of semi-finished goods are expressed in tons of cement instead of their actual mass. The conversion values used are:

- 0.75 tonne limestone is needed for 1 tonne cement, as described in *5.2.2.*
- 0.5 tonne clinker is needed for 1 tonne cement, as described in *5.2.2.*

Expressing all values in tonne of cement has the benefit that the values are more easily compared (e.g. the raw mill has to process the same amount as the cement mill). Furthermore, expressing it in tonne of cement makes the formulas more comprehensive since the conversion factors do not need to be applied.

7.1.4.1 Definition no flexibility scenario

To estimate the cost savings the electricity costs of the flexible processes will be compared to the electricity costs of a scenario where the processes could not be shifted. In the non flexibility scenario it is assumed that the production is spread out over all available working hours of the equipment which results in a constant production speed.

Because a cement plant is in operation for 360 days a year but the kiln is only in operation for 330 days and the grinder for only 312 (6 days a week) days there need to be enough materials in stock to operate continuously. Table 43 shows the requirements for the different stocks of a cement plant.

Table 43: Stock requirements

Stock	Time it need to bridge
Grinded limestone	The grinding of limestone does not occur on Sunday. Therefore, 6 days of milling should provide enough for 1 day raw milling operation
Raw meal	Operates for 360 days a week to feed the kiln which is in operation for 330 days with two stops per year.
Clinker	165 days of clinker production should provide enough for 15 days of cement milling
Cement	

The two kilns stops are the reason that a large enough clinker stock should be maintained at the end of the week to supply enough clinkers to bridge this gap. For the models this has the effect that the hourly clinker production will increase. The daily clinker production is around 5478 tonne expressed in tonne cement while the raw mill produces 5022 tonne of potential cement[3]. For a 28 day period this gives a discrepancy of 12,784 tonne cement. It was assumed that this extra raw meal will be in the storage at the initial timestep from when it was milled when the kiln was in maintenance.

The assumed schedule and parameters for the processed of the non-flexible cement plant are shown in Table 44.

Table 44: key parameters and schedule non-flexible cement plant

Process	Maximum operating hours	Production speed [t cement/h]	Process starts	Process stops
Grinder	12h/day but no grinding on Sunday	488.27	06:00 except on every seventh day	18:00 except on every seventh day
Raw mill	20h/day	251.11	03:00	22:00
Kiln	24/day	244.79	00:00	00:00 next day
Cement mill	20h/day	251.11	03:00	20:00
Packaging	18h//day	279.01	Shift A: 03:00 Shift B: 17:00	Shift A: 14:00 Shift B: 23:00

Using the schedule presented in Table 44 the energy consumption of a cement plant will be calculated so it can be compared to a flexible cement plant. Figure 42 shows the stock levels of a non-flexible cement plant operating with the parameters presented in Table 44.

[3] Based on a cement quota of 1,808 kt and that the kiln operates for 330 days a year and the raw mill for 360 days a year.

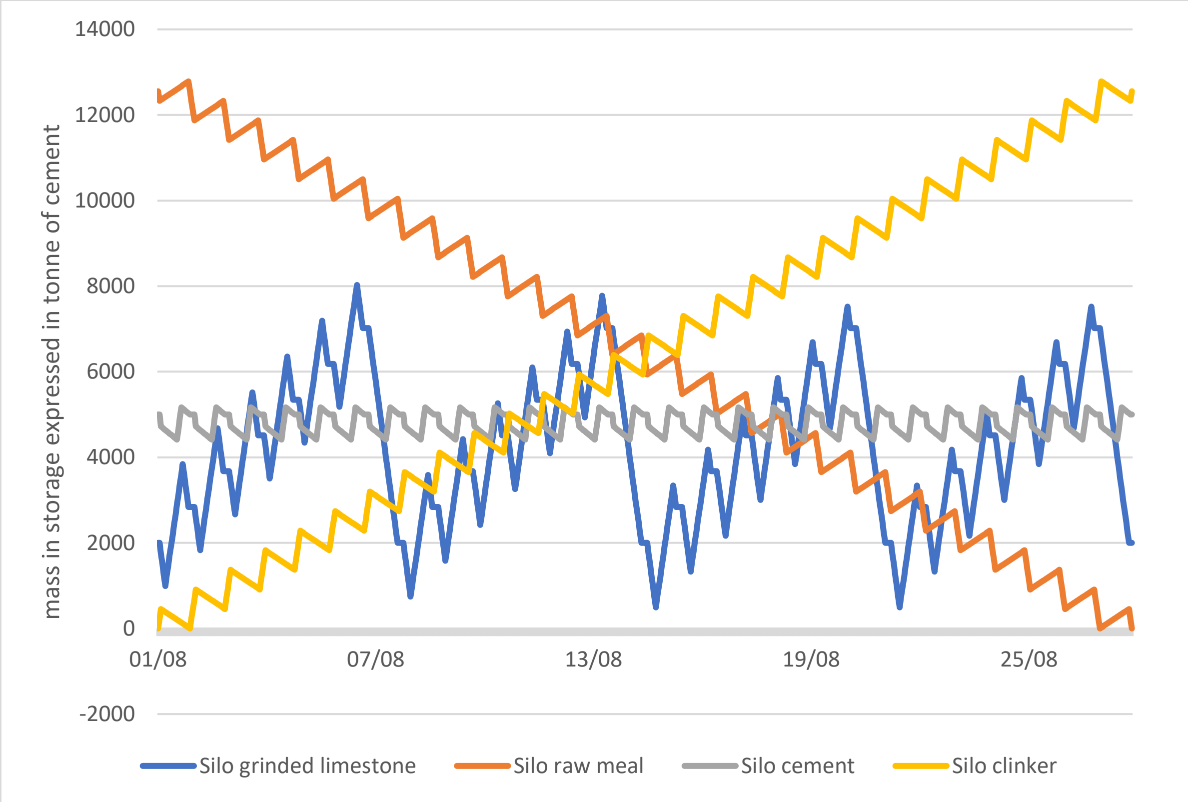

Figure 42: Stocks of a theoretical non-flexible cement plant during a 28 day period when 140.622 kt of cement is created. the clinker stock is increasing because the cement milling still needs to occur when the kiln in in maintenance. It was assumed that all other processes would occur when the kiln is in maintenance and therefore there are materials in the raw meal and cement storage at t=0.

7.1.4.2 Objective function

The linear program minimized the total electricity costs which is calculated with the decision variables about the operating hours of all equipment: $OH_{grinder,t}$, $OH_{Ram\ mill,t}$,$OH_{cement\ mill,t}$, and $OH_{packaging,\ t}$. The objective function is:

$$\min \sum_{t\in T} p_t E_t$$

Where the total electricity consumption is calculated as:

$$E_t = E_{grinder,t} + E_{raw\ mill,t} + E_{kiln,t} + E_{cement\ mill,t} + E_{packaging,t}\ \forall\ t$$

Where the electricity consumption of the different processes is calculated as:

$$E_{grinder,t} = \dot{m}_{grinder,t} * ECV_{grinder}\ \forall\ t$$

$$E_{Raw\ mill,t} = \dot{m}_{raw\ mill,t} * ECV_{Ram\ mill} \forall\ t$$

$$E_{kiln,} = \dot{m}_{kiln,t} * ECV_{kiln} \forall\ t$$

$$E_{cement\ mill,t} = \dot{m}_{cement\ mill,t} * ECV_{cement\ mill} \forall\ t$$

$$E_{Packaging,t} = \dot{m}_{packaging,t} * ECV_{packaging} \forall\ t$$

And the mass flowrate is calculated as:

$$\dot{m}_{grinder,t} = OH_{grinder,t} * \dot{m}_{grinder,max}\ \forall\ t$$

$$\dot{\mathrm{m}}_{raw\ mill,t} = OH_{raw\ mill,t} * \dot{\mathrm{m}}_{ram\ mill,max}\ \forall\ t$$

$$\dot{\mathrm{m}}_{kiln,t} = OH_{kiln,t} * \dot{\mathrm{m}}_{kiln,max}\ \forall\ t$$

$$\dot{\mathrm{m}}_{cement\ mill,t} = OH_{cement\ mill,t} * \dot{\mathrm{m}}_{mill,max}\ \forall\ t$$

$$\dot{\mathrm{m}}_{packaging,t} = OH_{packaging,t} * \dot{\mathrm{m}}_{packaging,max}\ \forall\ t$$

Because the clinker creation takes around 1 hour, the clinkers that are created in the kiln will be added to the next time step instead of directly to the storage (Schorcht et al., 2013). The amount of materials in the storages is calculated using the following formulas:

$$m_{grinded\ limestone,t} = \dot{\mathrm{m}}_{grinder,t} - \dot{\mathrm{m}}_{raw\ mill,t} + m_{grinded\ limestone,t-1}\ \forall\ t\ where\ t\ \neq 0$$

$$m_{ram\ meal,t} = \dot{\mathrm{m}}_{raw\ mill,t} - \dot{\mathrm{m}}_{kiln,t} + m_{raw\ mill,t-1}\ \forall\ t\ where\ t\ \neq 0$$

$$m_{clinker,t} = \dot{\mathrm{m}}_{kiln,t-1} - \dot{\mathrm{m}}_{cement\ mill,t} + m_{clinker,t-1}\ \forall\ t\ where\ t\ \neq 0$$

$$m_{cement,t} = \dot{\mathrm{m}}_{cement,t} - \dot{\mathrm{m}}_{packaging,t} + m_{cement,t-1}\ \forall\ t\ where\ t\ \neq 0$$

To make sure the daily maximum operating hours do not exceed the maximum daily operating hours a new matrix is created which holds the daily operating hours

$$Daily\ OH_{grinding,i} = \sum_{\substack{t=0 \\ i=0}}^{\frac{T}{24}} \sum_{t}^{24} OH_{grinding,t}$$

$$Daily\ OH_{raw\ mill,i} = \sum_{\substack{t=o \\ i=o}}^{\frac{T}{24}} \sum_{t}^{24} OH_{ram\ mill,t}$$

$$Daily\ OH_{cement\ mill,i} = \sum_{\substack{t=0 \\ i=0}}^{\frac{T}{24}} \sum_{t}^{24} OH_{cement\ mill,t}$$

$$Daily\ OH_{packaging,i} = \sum_{\substack{t=0 \\ i=0}}^{\frac{T}{24}} \sum_{t}^{24} OH_{cement\ mill,t}$$

7.1.4.3 Constraints

The objective function is subjected to the following constraints:

Storage

The materials stored at all timesteps should always be lower than maximum storage capacity but higher or equal to zero.

$$m_{grinded\ limestone,t} \geq S_{grinded\ limestone} \forall\ t$$

$$m_{raw\ meal,t} \geq S_{ram\ meal} \forall\ t$$

$$m_{clinkert,t} \geq S_{clinker} \forall\ t$$

$$m_{cement,t} \geq S_{cement} \forall\ t$$

$$m_{grinded\ limestone,t} \leq 0 \ \forall\ t$$

$$m_{raw\ meal,t} \leq 0 \ \forall\ t$$

$$m_{clinker,t} \leq 0 \ \forall\ t$$

$$m_{cement,t} \leq 0 \ \forall\ t$$

Production speed

All processes should have production speed lower than their maximum defined production speed

$$\dot{m}_{grinder,t} \leq \dot{m}_{grinder,max} \ \forall\ t$$

$$\dot{m}_{ram\ mill,t} \leq \dot{m}_{ram\ mill,max} \ \forall\ t$$

$$\dot{m}_{cement\ mill,t} \leq \dot{m}_{cement\ mill,max} \ \forall\ t$$

$$\dot{m}_{packaganing,t} \leq \dot{m}_{packaging,max} \ \forall\ t$$

And the production speed should be higher or equal to 0:

$$\dot{m}_{grinder,t} \geq 0 \ \forall\ t$$

$$\dot{m}_{ram\ mill,t} \geq 0 \ \forall\ t$$

$$\dot{m}_{cement\ mill,t} \geq 0 \ \forall\ t$$

$$\dot{m}_{packaganing,t} \geq 0 \ \forall\ t$$

Cement quota

At the end of the period the cement plant should have at least produced enough cement to satisfy the cement quota.

$$\sum_{t \in T} \dot{m}_{packaganing,t} \geq Q_{cement}$$

Operating hours

The operating hours of the all processes should be lower than their maximum specified operating hours and the grinder should be turned off on Sundays. That the grinder should be off on Sunday is implemented as no grinding on day 6, 13, 20 and 27.

$$Daily\ OH_{grinder,i} \leq LH_{grinder,i} \ \forall\ i\ where\ i \neq 6, i \neq 13, i \neq 20\ and\ i \neq 27$$

$$Daily\ OH_{grinder,6} = 0, Daily\ OH_{grinder,13} = 0, Daily\ OH_{grinder,20} = 0, Daily\ OH_{grinder,27} = 0$$

7.1.5 Modelling reference fuel mix

As described in *chapter 6* the sewage sludge processes are connected to the amine scrubbing CCS process because the amount of sewage sludge being co-fired changes the CO_2 emissions. This is relevant because for example when the electricity prices are low it is favourable to have much CO_2 in the flue gas so the CCS system can process more CO_2 at a lower price. In the 100% biofuel scenario fuel derived emissions are not captured and therefore the amount of sewage sludge co-fired has no effect on the total electricity consumption.

7.1.5.1 Definition no flexibility scenario

In the non-flexibility scenario it is assumed that sewage sludge milling will start each day at 03:00 and stops at 23:00 so the mill is turned on for 20 hours a day with a production speed of 7.77 t sewage sludge per hour (this results in 4,352 tonne sewage sludge being milled in a 28 day period). It was assumed that the sewage sludge being co-fired remains constant and therefore the CO_2 emissions will also remain constant.

7.1.5.2 Objective function

The electricity costs will be calculated by multiplying the energy consumption per time step by the electricity price of the given timestep. The aim of this program is to minimize the electricity cost.

$$\min \sum_{t \in T} p_t E_{total,t}$$

Where the electricity consumption is calculated using the following formula:

$$E_{total,t} = E_{sewage\ sludge\ mill,t} + E_{scrubber,t} + E_{stripper,t}\ \forall\ t$$

Where the variables derived from DVs are calculated with the following formulas

$$E_{sewage\ sludge\ mill,t} = \dot{\mathrm{m}}_{\mathrm{milling\ sewage\ sludge,t}} * \mathrm{ECV}_{\mathrm{milling\ sewage\ sludge,t}}\ \forall\ t$$

$$E_{scrubber,t} = \dot{\mathrm{m}}_{\mathrm{scrubber,t}} * ECV_{scrubber,t}\ \forall\ t$$

$$E_{stripper,t} = \dot{\mathrm{m}}_{\mathrm{stripper,t}} * ECV_{stripper,t}\ \forall\ t$$

The emissions which are not bypassed are directly fed into the scrubber. Therefore, the mass flowrate of the scrubber is defined as:

$$\dot{\mathrm{m}}_{\mathrm{scrubber,t}} = e_t - e_{bypassed,t} \forall\ t$$

The total emissions is dependent on the sewage sludge feed in rate and will be calculated with the linear formula constructed in pargraph *6.1.5.1*:

$$e_t = -0.0686 * \dot{\mathrm{m}}_{kiln\ feed,t} + 37.983 + 57.877$$

The amount of sewage sludge in the storage at every timestep is calculated with the following formula:

$$m_{sewage\ sludge,t} = m_{sewage\ sludge,t-1} + \dot{\mathrm{m}}_{\mathrm{milling\ sewage\ sludge,t}} - \dot{\mathrm{m}}_{kiln\ feed,t}\ \forall\ t\ where\ t\ \neq 0$$

At timestep 0 there is no sewage sludge in the storage.

$$m_{sewage\ sludge,0} = 0$$

The following formula is used to calculate how many hours per day the sewage sludge mill is on:

$$Daily\ OH_{Sewage\ sludge\ mill,i} = \sum_{\substack{t=0 \\ i=0}}^{\frac{T}{24}} \sum_{t}^{24} OH_{Sewage\ sludge\ mill,t}$$

7.1.5.3 Constraints reference fuel mix

Sewage sludge processes

The storage sludge can only be feed into the kiln when there is sludge in the storage and the feed-in speed is lower than the defined maximum. Burning sewage sludge cannot be reversed therefore the feed into the kiln must be positive.

$$\dot{m}_{kiln\ feed,t} \leq m_{sewage\ sludge,t}\ \forall\ t$$

$$\dot{m}_{kiln\ feed,t} \leq \dot{m}_{\text{kiln feed,max}}\ \forall\ t$$

$$\dot{m}_{kiln\ feed,t} \geq 0\ \forall\ t$$

All sewage sludge imported from a wastewater treatment plant should be co-fired at the end of the period.

$$\sum_{t\,\in\,T} \dot{m}_{kiln\ feed,t} = Q_s$$

Before the sewage sludge could be co-fired it first should be milled, this milling process is subjected to the following constraints:

$$\dot{m}_{\text{milling sewage sludge,t}} \leq \dot{m}_{\text{milling sewage sludge,max}}\ \forall\ t$$

$$\dot{m}_{\text{milling sewage sludge,t}} \geq 0\ \forall\ t$$

After the sludge is milled but before it can be co-fired it will be stored in a silo, the storage of sewage sludge is subjected to the following constraints:

$$m_{sewage\ sludge,t} \leq S_s \forall\ t$$

$$m_{sewage\ sludge,t}\ \geq 0\ \forall\ t$$

The sewage sludge mill cannot be on for more hours during the day than the specified maximum:

$$Daily\ OH_{Sewage\ sludge\ mill,i}\ \leq\ Daily\ OH_{Sewage\ sludge\ mill,max}\ \ \forall\ i$$

CCS processes

As mentioned previously the bypassing of the CCS system can only occur in reference fuel mix scenario. The total CO_2 bypassed should be lower or equal to the calculated maximum:

$$\sum_{t\,\in\,T} e_{bypassed,t}\ \leq Q_{CO_2,}scenario\ \forall\ t$$

The amount of CO_2 that is being bypassed should be lower or equal to the amount of CO_2 in the flue gas

$$e_{bypassed,t} \leq e_t\ \forall\ t$$

And is bound by a non-negativity constraint

$$e_{bypassed,t} \geq 0\ \forall\ t$$

In the reference fuel mix scenario amine scrubbing is used which could be flexible and therefore has additional constraints than other scenarios. The emissions that are not bypassed are fed into the scrubber and potentially could be stored in the solvent storage (buffer).

$$m_{CO_2\ buffer,t} = \dot{m}_{\text{scrubber,t}} - \dot{m}_{\text{stripper,t}} + m_{CO_2\ buffer,t-1}\ \forall\ t\ where\ t\ \neq 0\ and\ where\ t\ \neq T$$

In the beginning of the simulation the buffer should be empty and at the last timestep the buffer should also be emptied so all CO_2 is processed

$$m_{CO_2\ buffer,0} = 0$$

$$m_{CO_2\ buffer,T} = 0$$

The CO_2 in the buffer should always be lower than the max capacity of the storage.

$$m_{CO_2\,buffer,t} \leq S_{CO_2}\,\forall\,t$$

The buffer should not be emptied more quickly than the maximum operating speed of the stripper and should have a value higher than 0.

$$\dot{m}_{stripper,t} \leq \dot{m}_{stripper\,max}\,\forall\,t$$

$$\dot{m}_{stripper,t} \geq 0\,\forall\,t$$

7.1.6 Modelling 100% biofuel scenario

In the 100% biofuel scenario the only step that adds extra flexibility to the production process is the milling of sewage sludge. Because the fuel derived emissions are not captured in this scenario the amount of sewage sludge co-fired will not impact the energy consumption of the CCS system, as was the case in the reference fuel mix. Because the CO_2 streams are separated bypassing is not possible in this scenario.

7.1.6.1 Definition no flexibility scenario

In the non-flexibility scenario the sewage sludge will be milled at the same times as the non-flexibility scenario of the reference fuel mix, see *paragraph 7.1.5.1*.

7.1.6.2 Objective function

The electricity costs will be calculated by multiplying the energy consumption per time step by the electricity price of the given timestep. The aim of this program is to minimize the electricity cost.

$$\min \sum_{t\,\in\,T} p_t E_{total,t}$$

Where the electricity consumption is calculated using the following formula:

$$E_{total,t} = E_{sewage\,sludge\,mill,t} + E_{CCS,t}\;\forall\,t$$

Where the variables derived from DVs are calculated with the following formulas

$$E_{sewage\,sludge\,mill,t} = \dot{m}_{\text{milling sewage sludge,t}} * \text{ECV}_{\text{milling sewage sludge,t}}\;\forall\,t$$

The amount of sewage sludge in the storage at every timestep is calculated with the following formula:

$$m_{sewage\,sludge,t} = m_{sewage\,sludge,t-1} + \dot{m}_{\text{milling sewage sludge,t}} - \dot{m}_{kiln\,feed,t}\;\forall\,t\;where\;t\neq 0$$

At timestep 0 there is no sewage sludge in the storage.

$$m_{sewage\,sludge,0} = 0$$

The following formula is used to calculate how many hours per day the sewage sludge mill is on:

$$Daily\;OH_{Sewage\,sludge\,mill,i} = \sum_{\substack{t=0\\i=0}}^{\frac{T}{24}} \sum_{t}^{24} OH_{Sewage\,sludge\,mill,t}$$

7.1.6.3 Constraints 100% biofuel scenario

All sewage sludge imported from a wastewater treatment plant should be co-fired at the end of the period.

$$\sum_{t\,\in\,T} \dot{m}_{kiln\,feed,t} = Q_s$$

Before the sewage sludge could be co-fired it first should be milled, this milling process is subjected to the following constraints:

$$\dot{\mathrm{m}}_{\mathrm{milling\ sewage\ sludge,t}} \leq \dot{\mathrm{m}}_{\mathrm{milling\ sewage\ sludge,max}}\ \forall\ t$$

$$\dot{\mathrm{m}}_{\mathrm{milling\ sewage\ sludge,t}} \geq 0\ \forall\ t$$

After the sludge is milled but before it can be co-fired it will be stored in a silo, the storage of sewage sludge is subjected to the following constraints:

$$m_{sewage\ sludge,t} \leq S_s \forall\ t$$

$$m_{sewage\ sludge,t}\ \geq 0\ \forall\ t$$

The sewage sludge mill cannot be on for more hours during the day than the specified maximum:

$$Daily\ OH_{Sewage\ sludge\ mill,i}\ \leq\ Daily\ OH_{Sewage\ sludge\ mill,max}\ \ \forall\ i$$

7.1.7 Modelling hydrogen processes

In this section the LP used to determine the minimal electricity costs for the production of hydrogen is described.

7.1.7.1 Definition no flexibility scenario

In the no flexibility scenario there will be no storage for hydrogen and no overcapacity of the electrolysers, the electrolyser will constantly provide enough fuel for the kiln (337.7 GJ/h)

7.1.7.2 Objective function

The electricity costs will be calculated by multiplying the energy consumption per time step by the electricity price of the given timestep. The aim of this program is to minimize the electricity cost.

$$\min \sum_{t\, \in\, T} p_t E_t$$

Where the electricity consumption is calculated by the energy consumption of the electrolyser and of the compressor. Due to the constant clinker production the CO_2 are also constant and thus also the energy consumption of the compressor.

$$E_t = \frac{H_{production,t}}{\eta_{electrolyzer}} + E_{compressor,t} \forall\ t$$

And amount of hydrogen in the storage is calculated as:

$$HS_t = HS_{t-1} + H_{production,t} - Feed_{kiln}\ where\ i\ \neq 0$$

Where $H_{production}$ is the decision variable.

7.1.7.3 Constraints Hydrogen feed kiln

For the kiln to operate 24 hours a day there need to be a constant amount of hydrogen being feed into the kiln from the hydrogen storage.

To always satisfy this hydrogen demand a constraint is added which makes it impossible for the tank to be empty. This constraint has two purposes:

1. Create a realistic storage because it cannot hold a negative amount of hydrogen.
2. Because of the constant flow of hydrogen to the kiln (constant outflow from the storages) this constraint makes sure that there will always be enough hydrogen generated to meet the hydrogen demand.

$$S_{hydrogen,t} \geq 0 \; \forall \; t$$

Hydrogen generation

The production process is limited by the maximum capacity of the storage and the maximum production speed.

$$H_{Production,t} \leq H_{Production,max} \forall \; t$$

The storage should be limited to the maximum amount of hydrogen it can hold.

$$S_{hydrogen,t} = \; S_{hydrogen,t} \leq S_{hydrogen\,,max} \forall \; t$$

7.2 RESULTS

In this paragraph the behaviour of the LP was analysed so the results could be verified. By checking the variables of each different model it was determined that the constraints described in previous paragraph were successfully implemented. After the behaviour was verified the results of all different scenarios are presented. Al models are checked with the German price profile of summer 2019 because this dataset has smooth fluctuations which makes the results easier to interpret.

7.2.1 Generic cement processes

In *paragraph 7.2.2.1* the model is verified and in *paragraph 7.2.2.2* the results are shown. As mentioned previously to simplify the model the mass of all semi-finished goods is expressed in tonne of cement rather than the actual mass.

7.2.1.1 Validation results

As mentioned in the description of the LP the operating hours of all equipment should not exceed the maximum operating hours. Table 45 shows the operating hours of a flexible European cement plant while subjected to the German electricity prices of the summer of 2019.

Table 45: operating hours of the different cement processes

Day	Grinder	Raw mill	Cement mill	Packaging
1	12.00	19.00	16.45	13.91
2	12.00	17.00	17.78	15.00
3	12.00	20.00	20.00	18.00
4	12.00	20.00	20.00	18.00
5	7.01	13.33	14.00	10.00
6	12.00	19.00	19.00	18.00
7	0.00	20.00	20.00	18.00
8	12.00	20.00	20.00	18.00
9	12.00	20.00	20.00	18.00
10	12.00	20.00	20.00	18.00
11	12.00	20.00	20.00	18.00
12	12.00	20.00	20.00	18.00
13	12.00	20.00	20.00	18.00
14	0.00	19.00	19.00	18.00
15	12.00	20.00	20.00	18.00
16	12.00	20.00	20.00	18.00
17	12.00	20.00	20.00	18.00
18	12.00	20.00	20.00	18.00

19	12.00	20.00	20.00	18.00
20	12.00	19.00	19.00	16.21
21	0.00	18.00	18.00	18.00
22	12.00	20.00	20.00	18.00
23	12.00	20.00	20.00	18.00
24	12.00	20.00	20.00	18.00
25	12.00	20.00	20.00	18.00
26	6.55	14.00	15.00	14.00
27	6.00	13.00	13.00	12.40
28	0.00	10.91	11.00	10.50

As shown in Figure 43 the operating hours are determined by the electricity prices, when the electricity prices are low enough the processes will turn on to minimize the electricity costs. The LP shifts all processes to time periods where the electricity prices are the lowest.

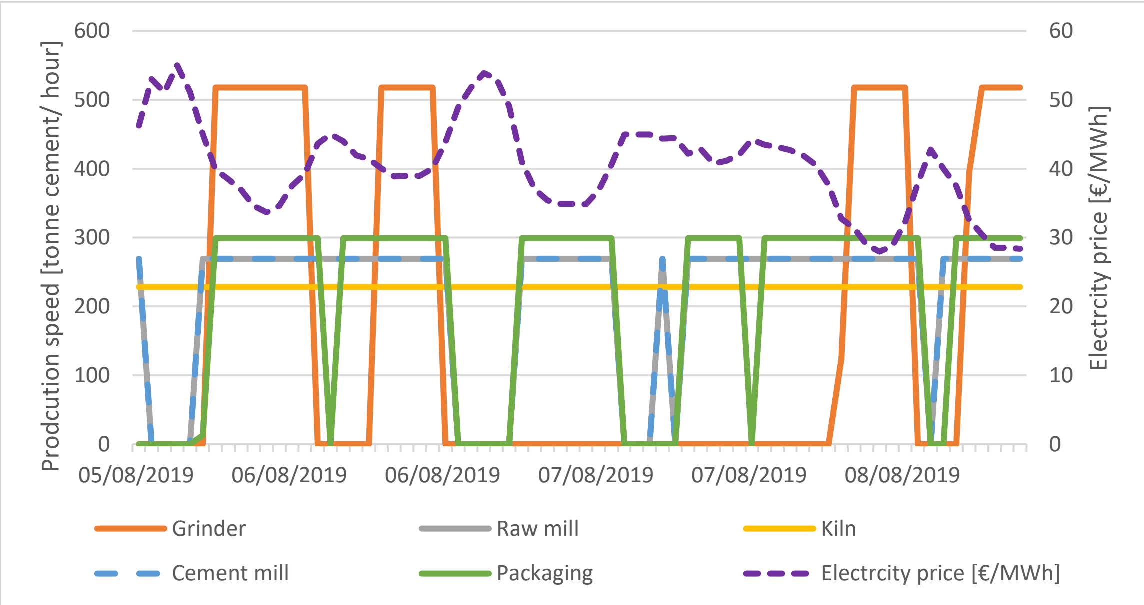

Figure 43: Production speed of all the generic cement production process while subjected to the German electricity prices of August 2019. As shown all processes only operate when the electricity prices are relatively low. The grinder will not operate on august the 7th because it was limited by 6 working days a week.

A constraint of the model was that the grinder will not be operated on Sundays. Therefore, enough stock must be build up on Monday to Saturday so all the other processes can continue on Sunday. This behaviour is shown in Figure 43 and Figure 44. At the end of the month the kiln needs to produce enough clinkers so that the cement milling can still continue when the kiln is in maintenance, this means that more clinkers are created than needed to satisfy the cement quota. When the kiln is in maintenance a large enough stock of raw meal is created to compensate for these extra clinkers. Figure 44 shows this behaviour. At the end of the 28 days period enough clinkers are packaged to satisfy the cement quota of 140,622 tonne cement.

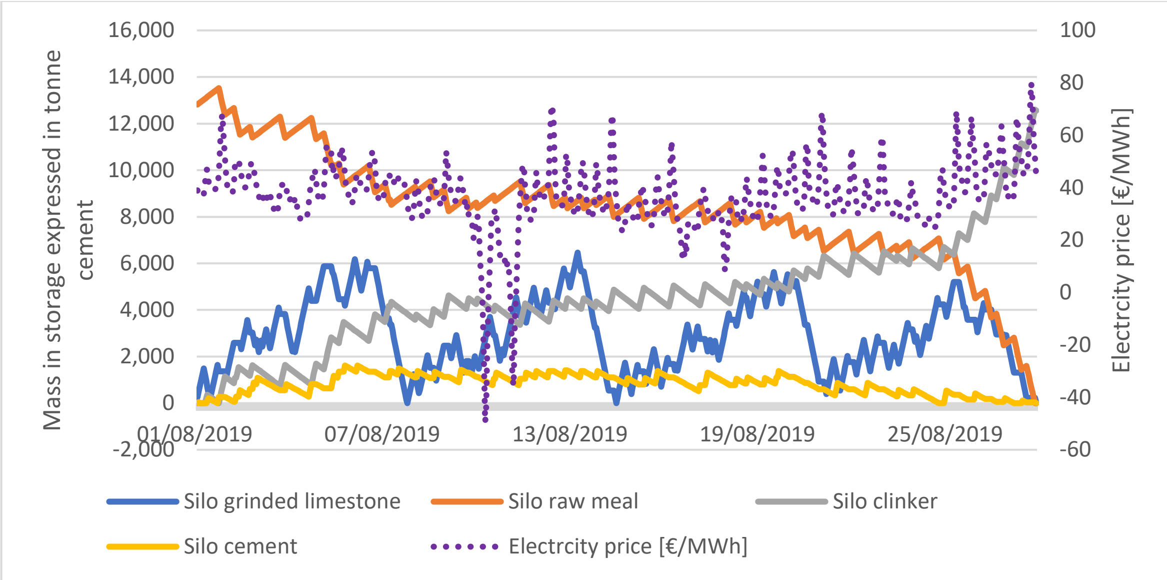

Figure 44: Grinded limestone, Raw meal, clinker and cement storage of a European cement plant subjected to the German electricity prices of August 2019

7.2.1.2 Overview economic potential for different price scenarios

By using all different electricity price profiles the economic flexibility potential of the generic cement processes was calculated, see Figure 45. Because the electricity prices are higher in the METIS scenario the absolute economic savings are much higher in this scenario compared to the other scenarios. In the Balmoral scenarios the electricity costs are generally lower than the historic electricity prices but because of their increased fluctuations the relative saving potential (expressed in %) is higher.

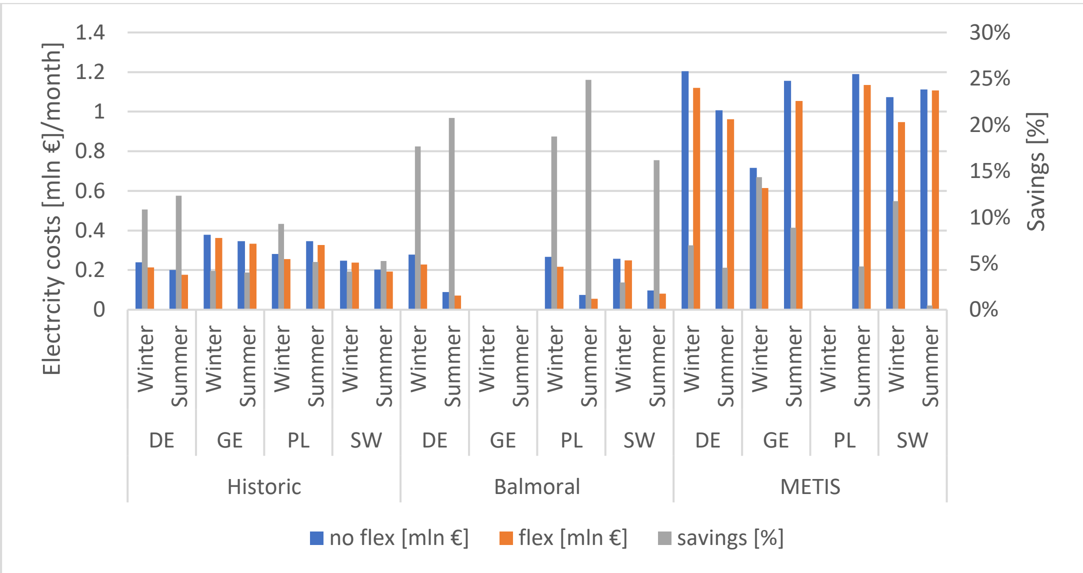

Figure 45: Monthly electricity costs and relative savings for the generic cement production processes

Because of the high electricity consumption of the cement mill this process contributes the most to the saving potential followed by the raw mill, see Figure 46.

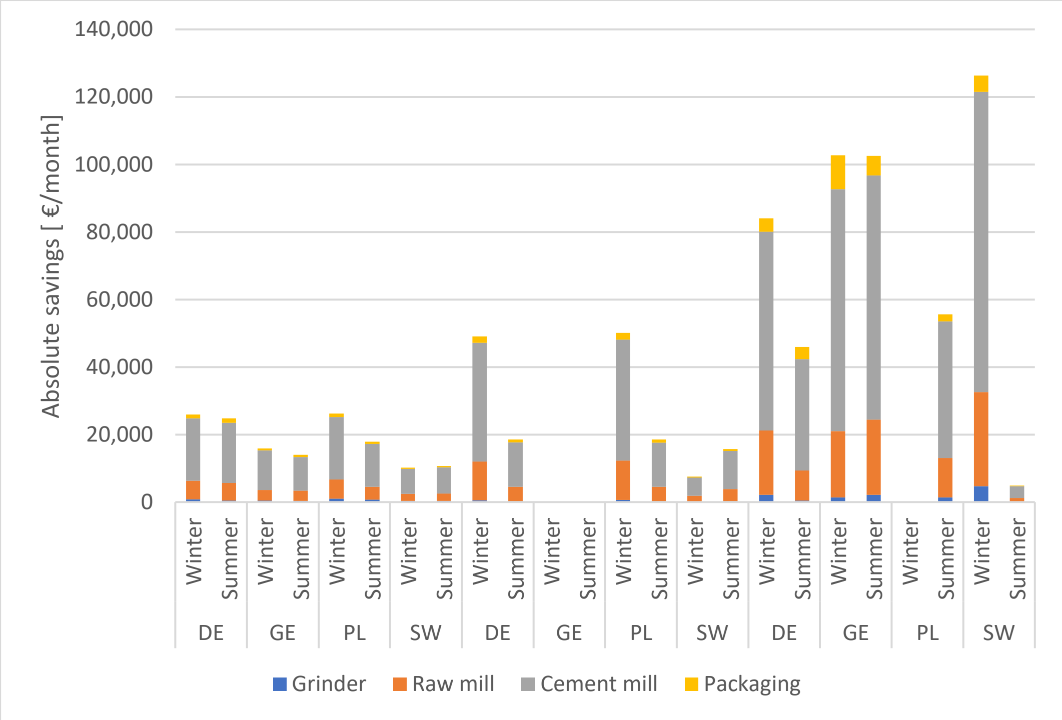

Figure 46: absolute saving potential of the different cement production processes

How much energy is load shifted with respect to the scenario with fixed operating hours is shown in Figure 47.

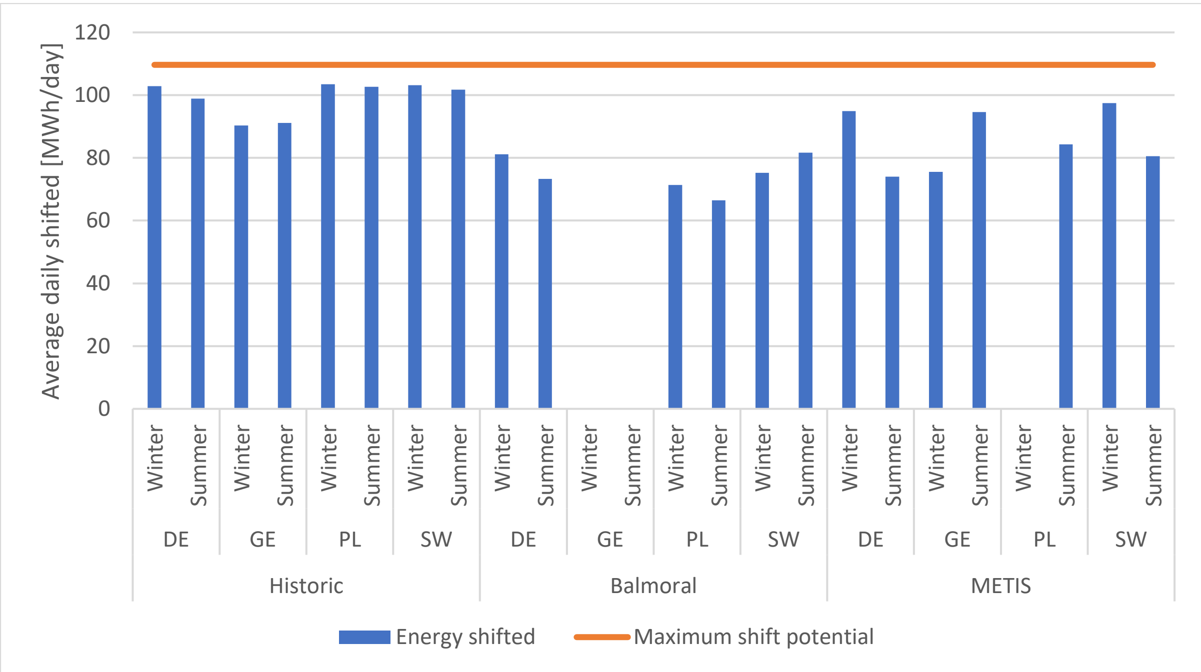

Figure 47: The average daily shifted load of the generic cement production processes for the flexible scenarios in respect to the no flexibility scenario. The maximum load shift potential was the value calculated in 6.2

7.2.2 Reference fuel mix

There are three processes in the reference scenario which introduce extra flexibility. These processes are the milling of sewage sludge, the co-firing of sewage sludge so the CO_2 concentration in the flue gas changes and the usage of a flexible amine scrubbing CCS system.

The CCS process and co-firing sewage sludge is validated in *paragraph 897.2.2.3* and the cost savings are shown in *paragraph 7.2.2.4*.

7.2.2.1 Validation results: Sewage sludge milling

To minimize the electricity costs milling should only occur when the electricity prices are at their lowest. This behaviour is especially noticeable at August the tenth when the electricity prices are negative, see Figure 48.

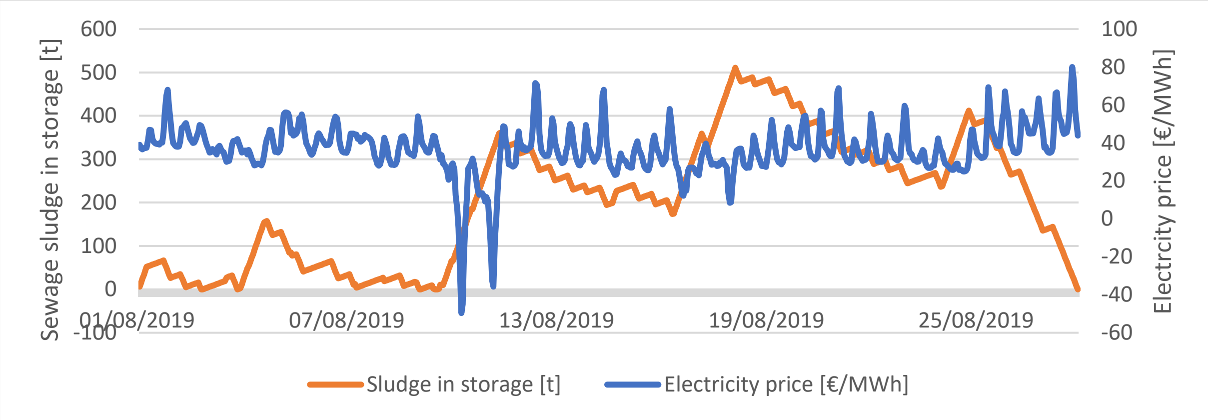

Figure 48: The amount of sewage sludge in the storage throughout Augustus of a European cement plant subjected to the German electricity prices of 2019

In the reference fuel mix where co-firing sewage sludge decreases the CO_2 emissions it is beneficial to co-fire sewage sludge when the electricity prices are high so the CCS costs decrease. This behaviour is shown in Figure 49.

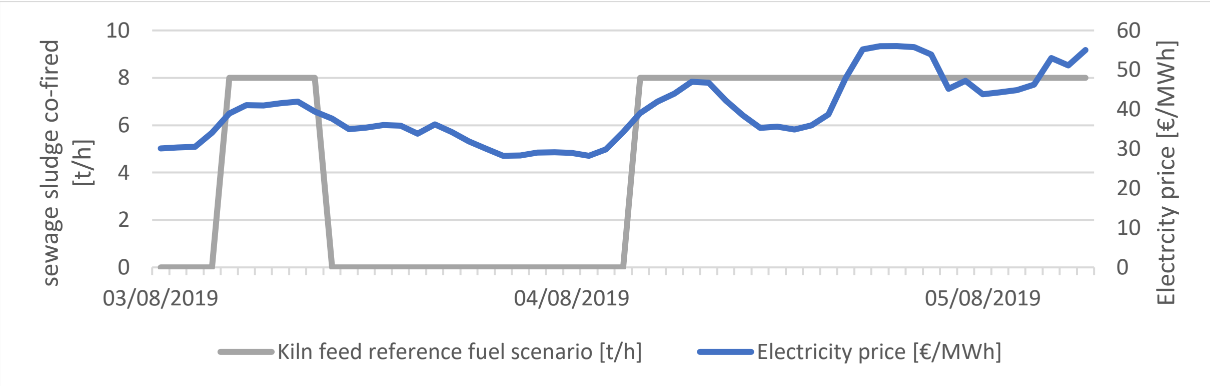

Figure 49: Sewage sludge kiln-feed for reference fuel mix scenario.

7.2.2.2 Results sewage sludge

As described in *paragraph 7.1.5* the electricity costs for a non-flexible and a flexible sewage sludge mill are calculated for all electricity prices mentioned in *paragraph 7.1.2*. The results are shown in Figure 50. In all scenarios the electricity costs are lower in the summer which is explained by the lower electricity prices. The relative savings are not always higher/lower in a specific season, see Figure 51. One interesting phenomenon occurs in when the sewage sludge mill is subjected to the electricity prices of the Balmoral model of Sweden in the winter. Here, flexible operation increases the electricity cost. This behaviour allows for more sewage sludge being fed to the kiln at desired times so the CCS cost, and thus the total electricity cost can decrease.

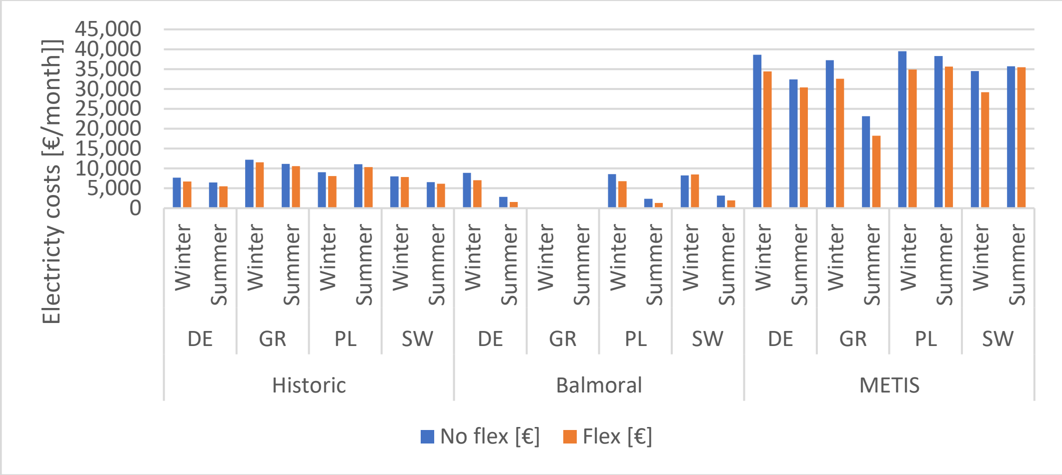

Figure 50: Electricity costs for the milling of sewage sludge

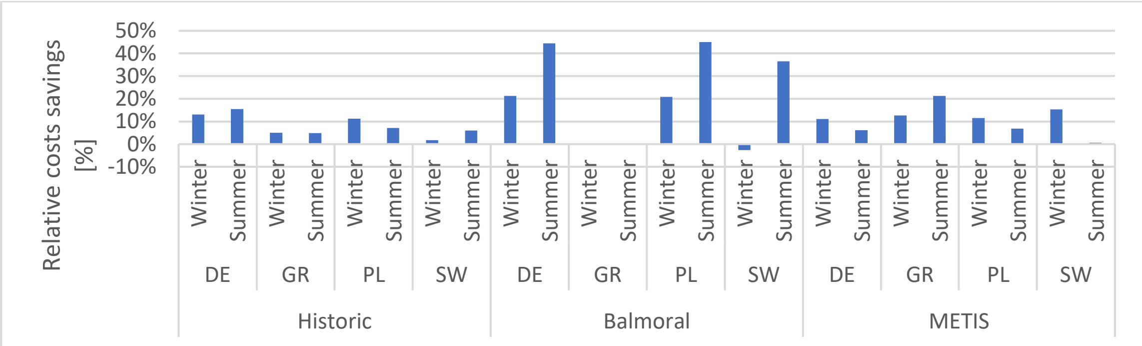

Figure 51: Relative electricity costs savings for the milling of sewage sludge in the reference fuel mix scenario

Surprisingly, the average electricity load shifted per day is in some scenarios almost the same as the calculated maximum potential in RQ3, see Figure 52. This behaviour could be explained by the high milling speed.

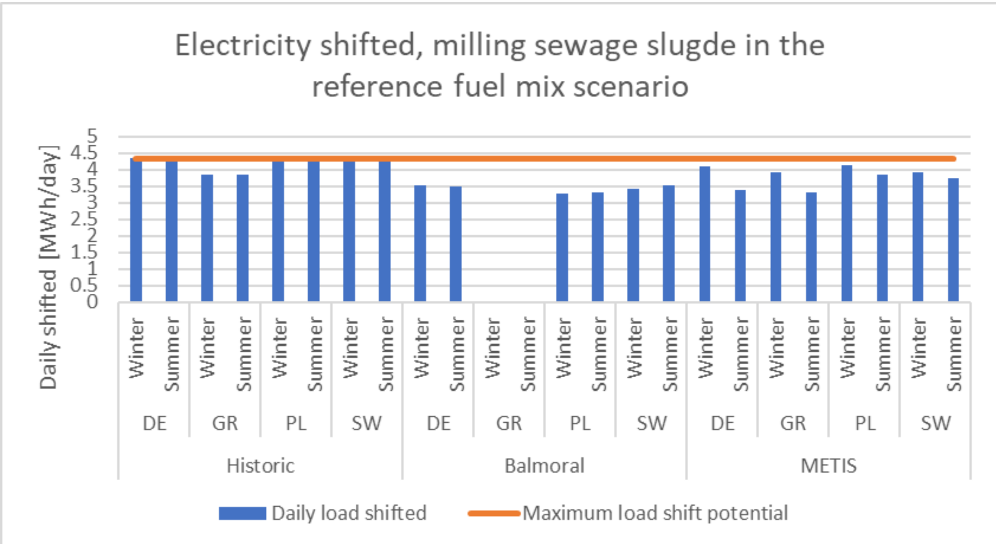

Figure 52: the average amount of electricity shifted per day for the milling of sewage sludge and the maximum load shift potential as calculated in RQ3.

7.2.2.3 Validation results: CCS in the reference fuel mix

The CCS uses a buffer system which could hold up to 170 tonne CO_2, when the electricity prices are high this buffer will be filled so the CO_2 can be processed when the electricity prices are low. Bypassing the CCS is reserved for moments when the electricity prices are the highest and this can only happen a limited amount of times. This behaviour is shown in Figure 53, at around august 1, 16:00 the electricity prices are considered too high and therefore CO_2 emissions will be vented. During lower price spikes the CO_2 will be stored in the buffer so it can be processes at a later moment in time.

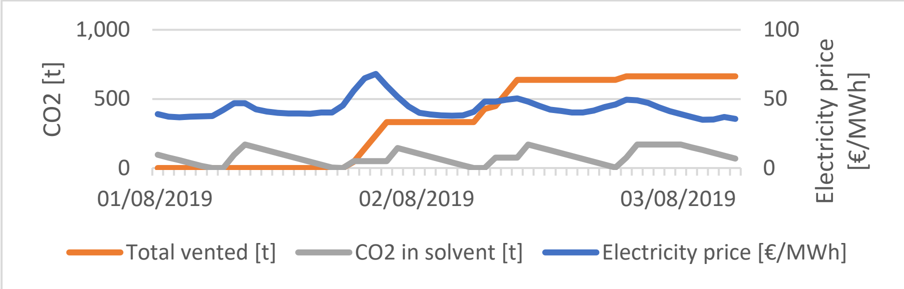

Figure 53: CO_2 stored in the buffer and the cumulative vented CO_2 emissions of a European cement plant subjected to the German electricity prices of 2019 when the reference fuel mix is used.

7.2.2.4 Overview economic potential for different scenarios

The flexible use of co-firing the sewage sludge in combination with a buffer for the CCS system could lower the electricity costs, see Figure 54.

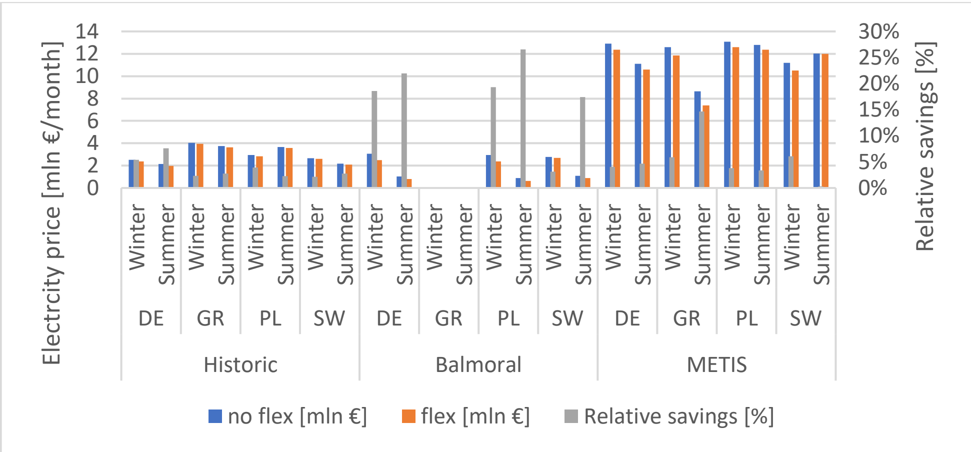

Figure 54: The economic potential of a flexible CCS system in the reference fuel mix scenario.

Despite that the relative costs savings is different in in all scenarios the amount of electricity is fairly similar in all scenarios (Range from 500 MWh/ day to 565 MWh/ day), see Figure 55

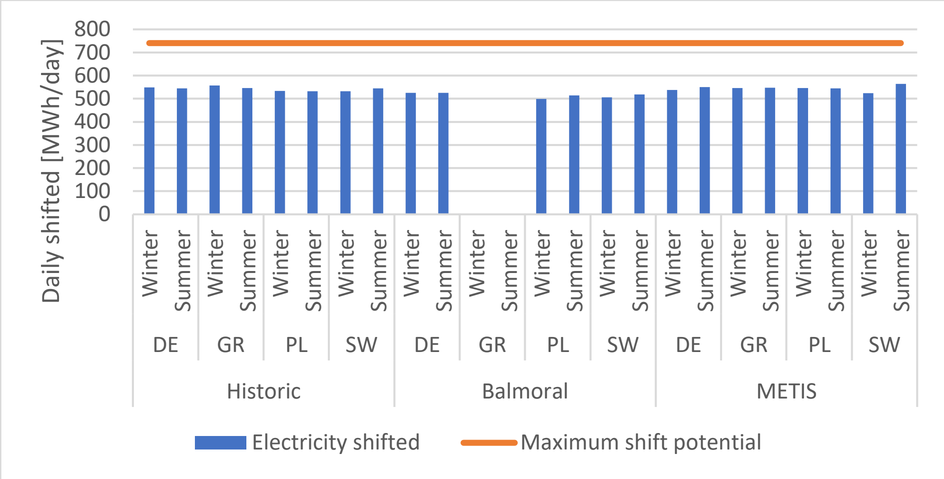

Figure 55: Average daily electricity shifted for the CCS system in the reference fuel scenario.

7.2.3 100% biofuel mix

7.2.3.1 Validation

As shown in Figure 56 the milling of sewage sludge only occurs when the electricity prices are at their lowest. The amount of sewage sludge in storage throughout the period is shown in Figure 57.

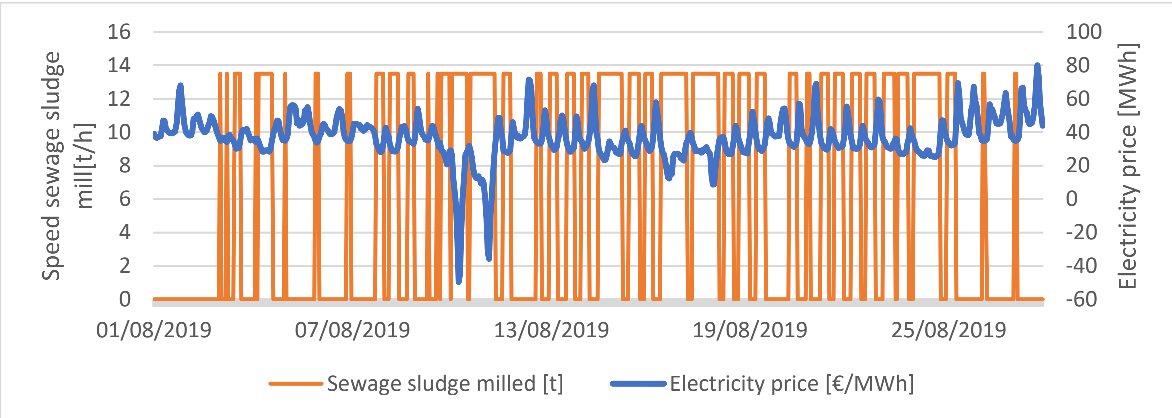

Figure 56: Milling of sewage sludge in the 100% biofuel scenario

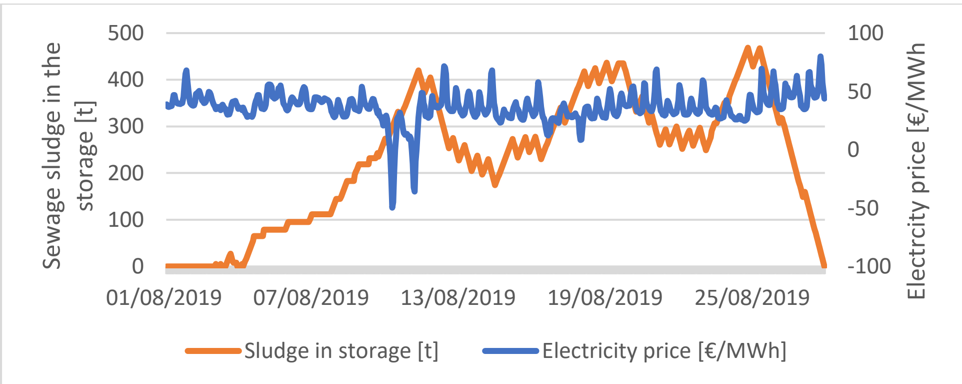

Figure 57: Stock fluctuations of the milled sewage sludge storage of the 100% biofuel scenario

7.2.3.2 Results

Similar to the reference fuel mix scenario but because it is not connected to the consumption of the CCS system the savings of the milling process are higher but the overall savings are lower. The difference is clearly shown when the model was subjected to the electricity prices of the balmoral model for Sweden in the winter. In the reference fuel mix the costs savings were negative because the sewage sludge processes were combined with the CCS system. In the 100% biofuel scenario the relative costs savings are positive.

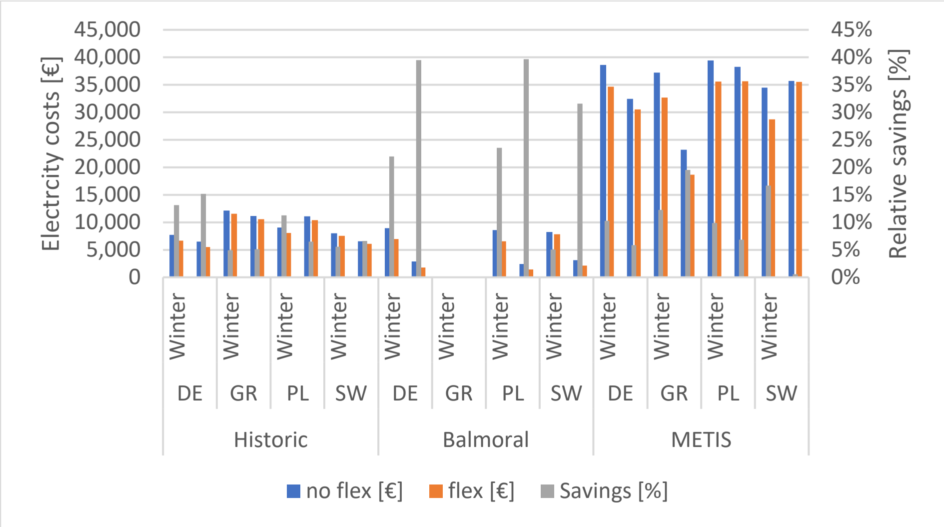

Figure 58: Electricity costs and relative savings of milling sewage sludge in the 100% biofuel scenario

The average amount of electricity shifted per day is shown in Figure 59. The electricity that is shifted ranges from arround 3 MWh/day to 4.2 MWh/day

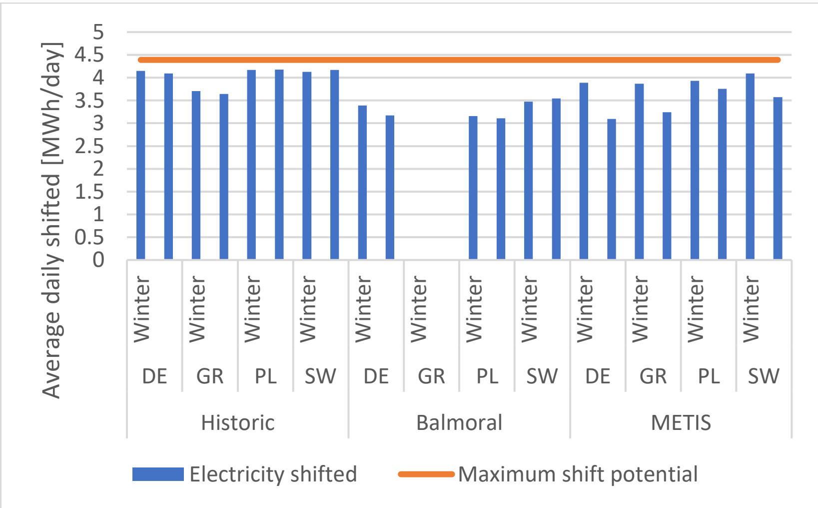

Figure 59: Average amount of electricity shifted per day when sewage sludge is milled flexibly in the 100% biofuel scenario. the maximum potential was calculated in RQ3.

7.2.4 Hydrogen processes

The LP used to minimize the electricity cost for the production of hydrogen is validated in *paragraph 7.2.4.1* and the results are shown in *paragraph 7.2.4.2.*

7.2.4.1 Validation

Throughout the whole month the electrolyser provides enough hydrogen for the kiln, this is seen in Figure 60 because the hydrogen storage never has a negative amount of hydrogen stored. Figure 60 also shows that hydrogen is being produced and stored when the electricity prices are low and the hydrogen is used from this storage when the electricity prices are high.

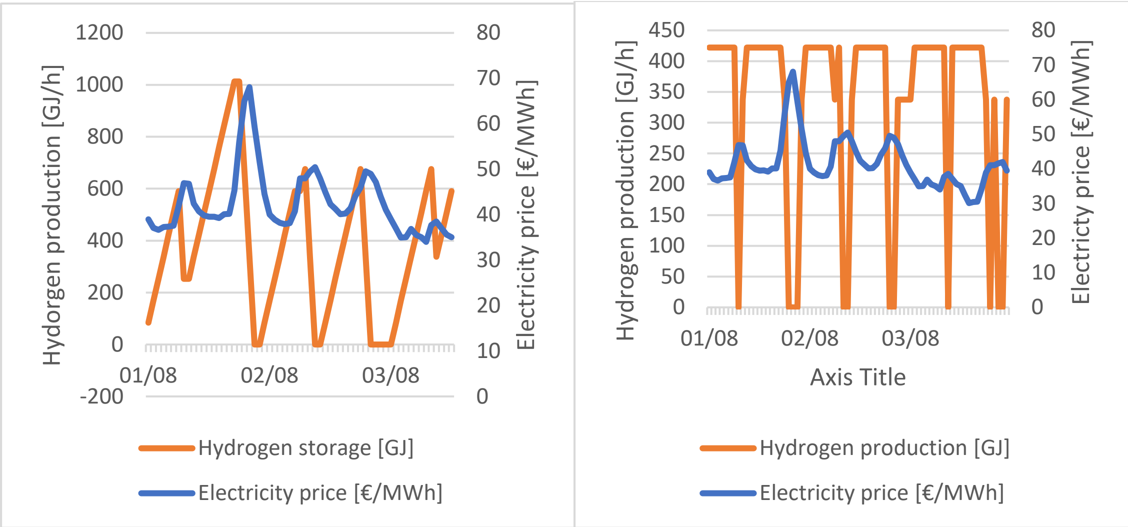

Figure 60: Behaviour electrolyzer in the summer.

7.2.4.2 Overview economic potential for different scenarios

Using the LP the minimal electricity costs for the different price profiles were calculated, see Figure 61. The scenarios with where the variance in electricity costs the highest also has the highest electricity saving potential.

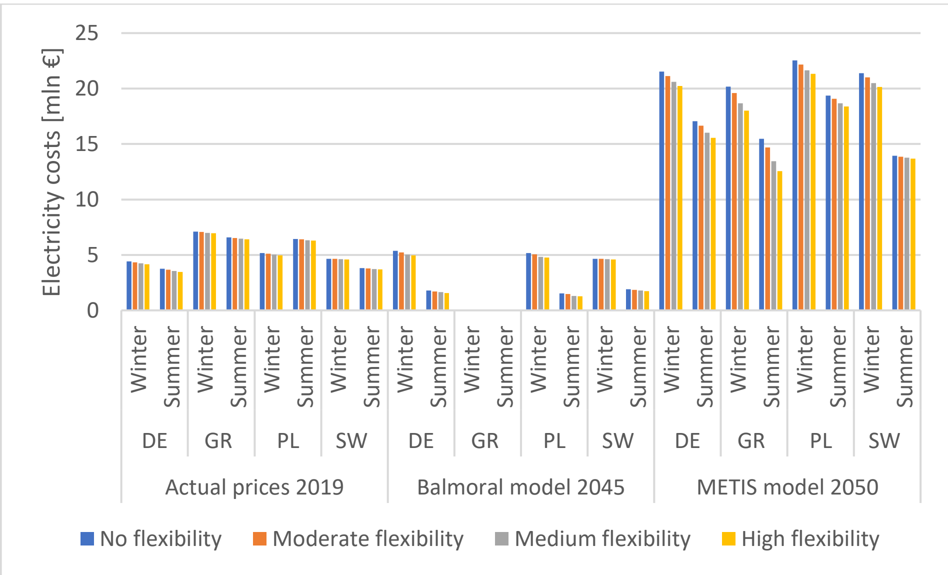

Figure 61: Electricity costs for the production of hydrogen of a European cement.

The total average amount of electricity which is shifted throughout the days is shown in Figure 62.

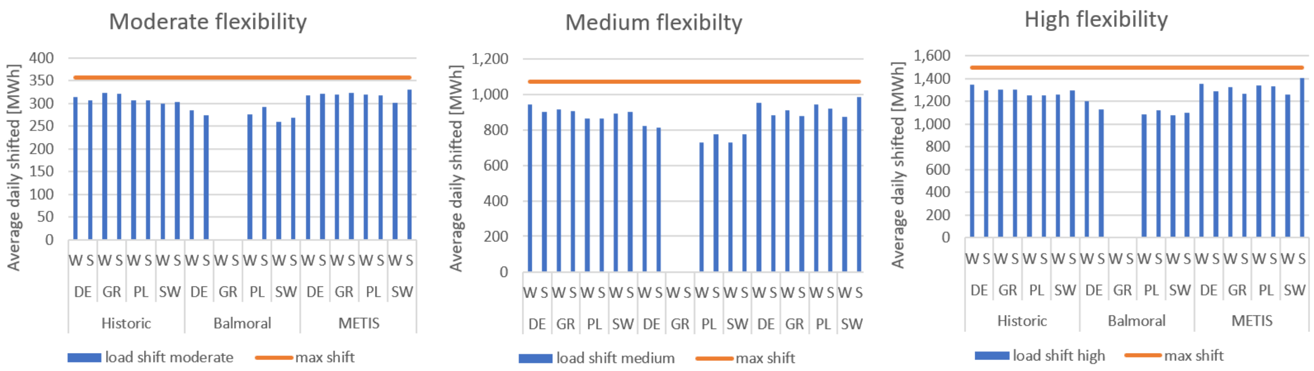

Figure 62: Daily electricity shifted when the electrolyser is used flexibly

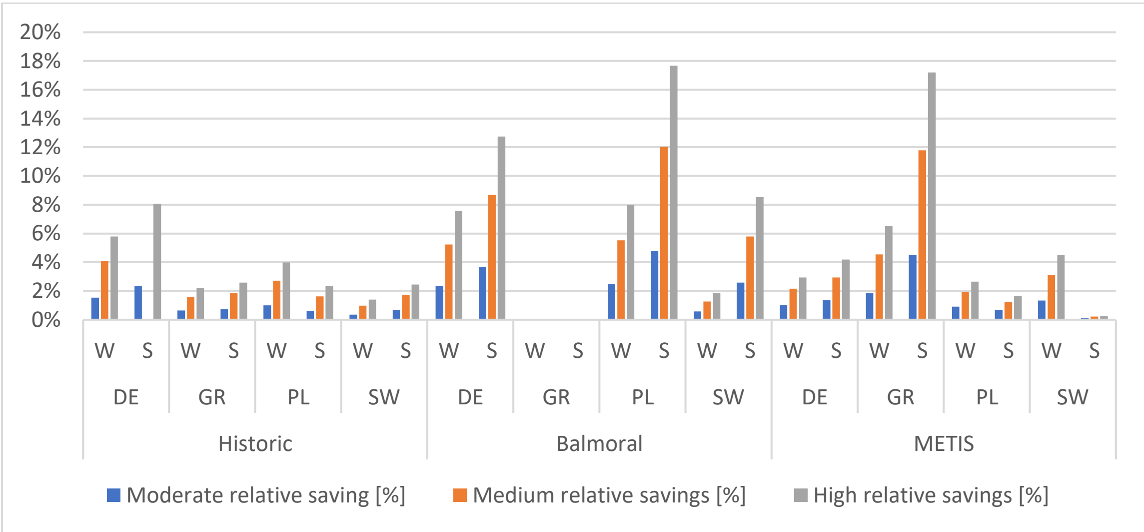

Figure 63: Relative costs savings of the hydrogen scenario.

7.2.5 Overview relative costs savings

The relative costs savings for all flexible technologies are added together to estimate the total absolute cost savings, for each scenario see Figure 64, Figure 65, Figure 66 and Figure 67. The Reference fuel mix scenario and the hydrogen scenario both have the highest economic flexibility potential which can be explained by their high electricity demand, See *paragraph 5.3* and high load shift potential see *paragraph 6.2.5*. These figures also shows that the Reference fuel mix scenario has similar economic potential than the hydrogen scenario when subjected to the historic and Balmoral prices. However, when subjected to the METIS prices the high flexible hydrogen scenario can achieve more total savings. This is likely due to the high price fluctuations of this model and because the hydrogen scenario has a large storage and overcapacity installed so it can better handle these fluctuations than the CCS system. The electrification and 100% biofuel scenario has the lowest economic saving potential because compared to the other scenarios not much processes could be made flexible.

It should however be stressed that the absolute savings are the savings of the flexible operation compared to the not flexible scenario. This has the effect that all scenarios are compared to another reference. The absolute saving potential does not necessarily provide information about which scenario has the lowest electricity costs. For example, the savings of the hydrogen scenario are higher than the savings of the electrification scenario. But because the electrification scenario uses almost 50% less electricity than the hydrogen scenario, the total electricity costs of the electrification scenario would almost always be lower.

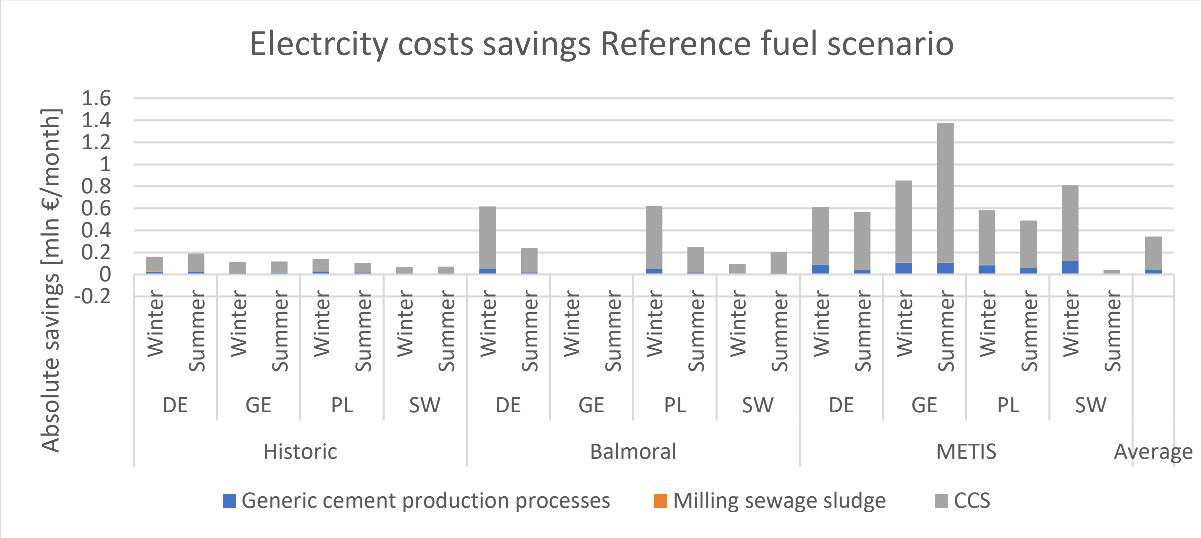

Figure 64: Total electricity costs savings of the reference fuel scenario

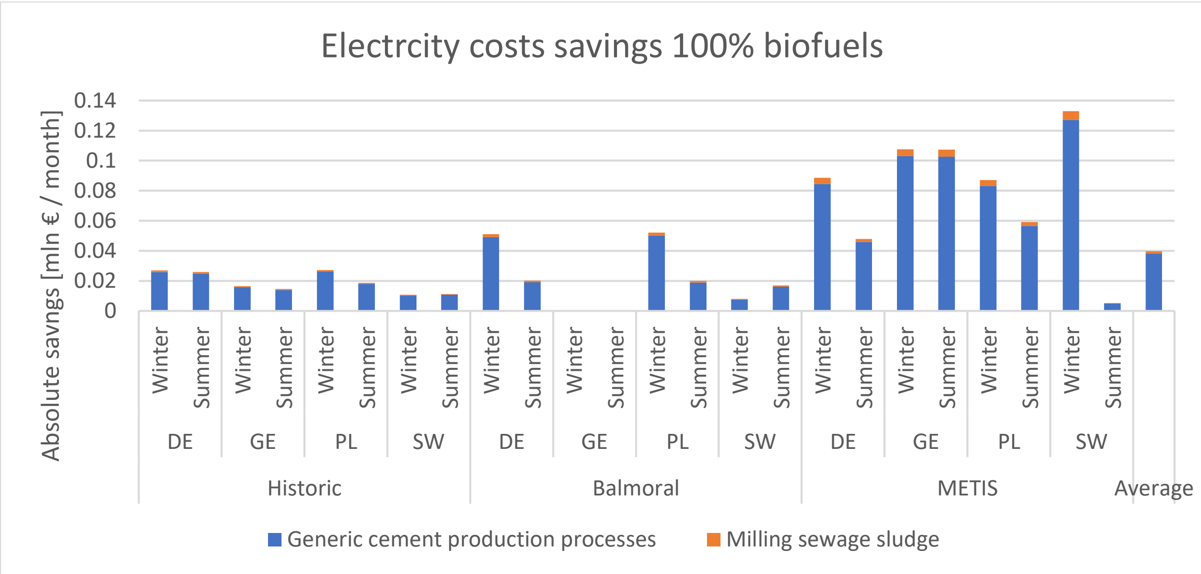

Figure 65: Total electricity costs savings of the 100% biofuel scenario

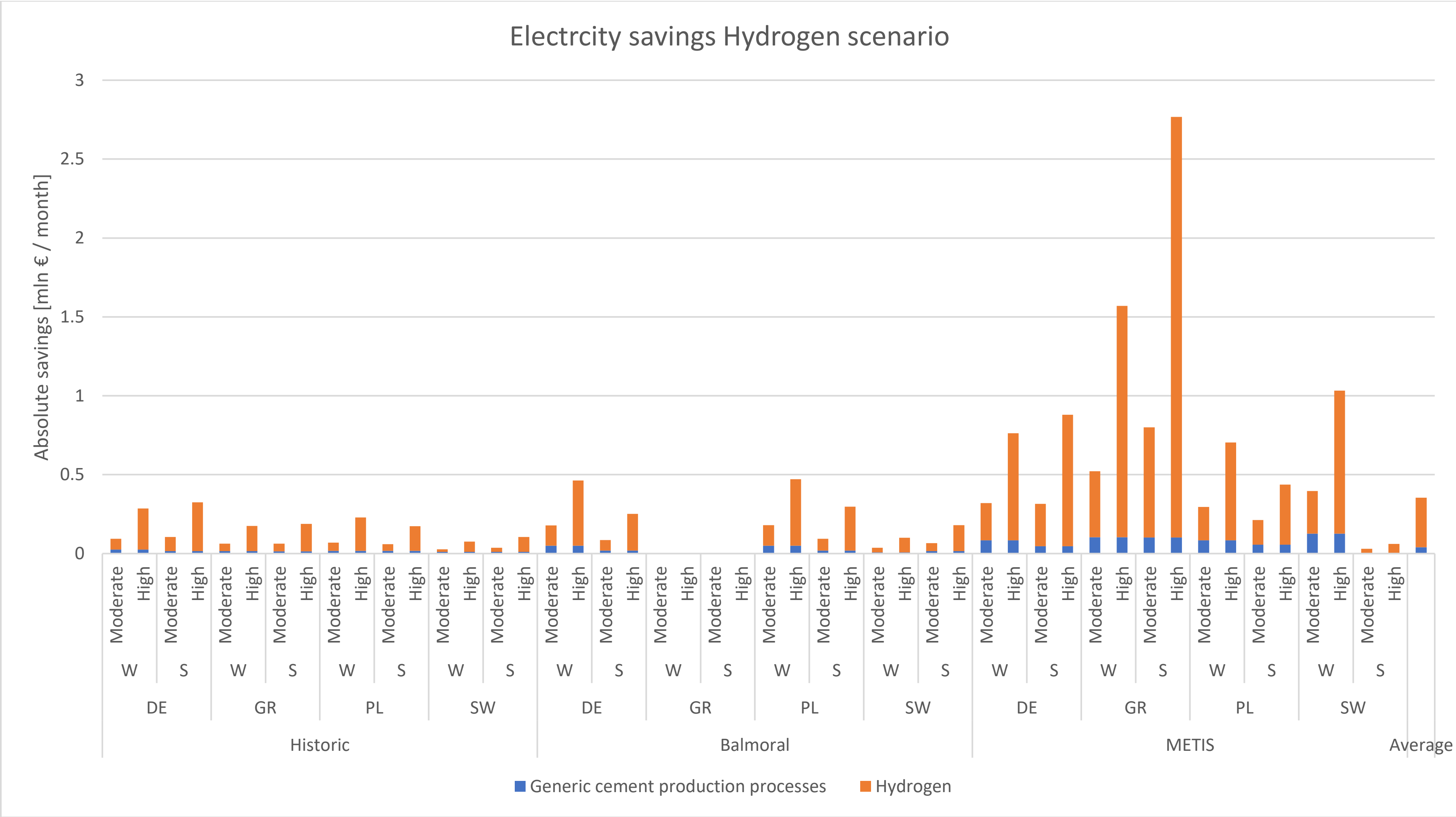

Figure 66 : Total electricity costs savings of the hydrogen scenario

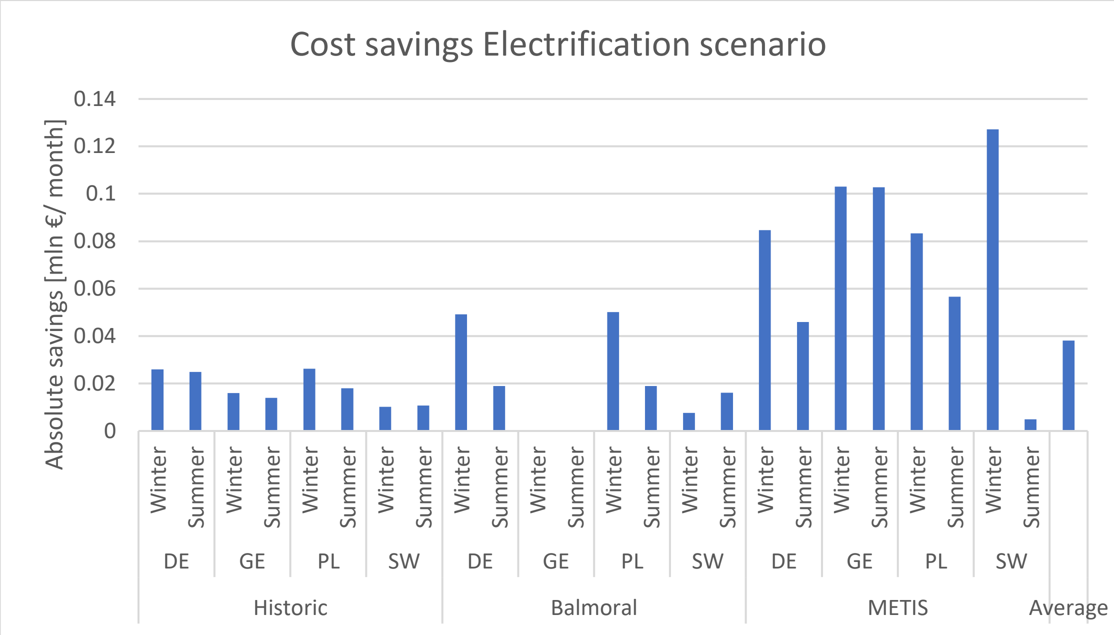

Figure 67: Cost savings of the electrification scenario, in this scenario the only identified flexible processes were the generic cement production processes.

7.2.6 Overview total costs savings

Previously this chapter only mentions the savings per process and not the total electricity costs. By adding the electricity costs of all flexible processes (described in this chapter) and the non-flexible processes using the key assumptions from *paragraph 5.2.7*. Due to time constraints it was assumed in this thesis that the drying of BFS and the compression of CO_2 could not be flexible.

The total electricity costs and relative savings are compared for each scenario and shown in Table 46. In this table the total flexible electricity costs are compared to the electricity costs of the non-flexibile scenario. The total electricity costs were calculated using the electricity costs of the flexible processes (as calculated in this chapter) and the costs for the non-flexible processes using the different price profiles. The electricity consumption of the non-flexible processes was proved in *chapter 5.*

The reader should be aware that this table only shows the electricity costs and not the total fuel costs. For example the 100% biofuel scenario may have the lowest electricity costs but a study should be conducted about the costs of importing biofuels. The hydrogen and electrification scenario however can be compared because in those scenarios no fuels are imported and only electricity is used. Even though the electrification scenario has lower relative and absolute savings it has a lower overall electricity costs compared to the hydrogen scenario because of its high efficiency.

Table 46: Total electricity costs savings of all scenarios

	Savings achieved with operating flexible [%]			Total electricity costs when operating flexible [mln € / month]			Processes	
	Lowest found	average	Highest found	Lowest found	Average	Highest found	Flexible	Non flexible
Reference fuel mix	0.27%	7.04%	22.44%	0.87	3.43	16.28	Generic cement production processes, Milling sewage sludge , CCS	Drying BFS
100% biofuel	0.07%	1.05%	2.55%	0.80	5.20	12.01	Generic cement production processes, Milling sewage sludge.	CO_2 compression, Drying BFS
Hydrogen moderate	0.09%	1.12%	1.24%	2.23	15.10	34.01	Generic cement production processes, Electrolyzer	CO_2 compression, Drying BFS
Hydrogen medium	0.00%	2.51%	8.18%	2.12	14.91	33.77	Generic cement production processes, Electrolyzer	CO_2 compression, Drying BFS
Hydrogen high	0.20%	3.88%	12.03%	2.03	14.76	33.60	Generic cement production processes, Electrolyzer	CO_2 compression, Drying BFS
Electrification	0.03%	0.51%	1.24%	1.51	9.73	22.51	Generic cement production processes,	CO_2 compression, Drying BFS

7.2.7 Overview electricity shifted

The total amount of electricity shifted per scenario is calculated by adding all electricity shifted per process together. The lowest, average and highest amount of electricity shifted found is shown in Table 47.

Table 47: Overview of the total amount of electricity shifted per scenario.

	Lowest found	**Average**	**Highest found**	**Maximum potential (See RQ3, *Chapter 6*)**	**Processes involved**
Reference fuel mix [MWh/day]	573	628	656	859	Generic cement processes, Milling sewage sludge, CCS
100% biofuel [MWh/day]	70	92	108	114	Generic cement processes, Milling sewage
Hydrogen moderate [MWh/day]	334	392	416	466	Generic cement processes, electrolyser
Hydrogen medium [MWh/day]	799	960	1,067	1,182	Generic cement processes, electrolyser
Hydrogen high [MWh/day]	1,153	1,343	1,485	1,501	Generic cement processes, electrolyser
Electrification [MWh/day]	67	88	103	110	Generic cement processes

If we compare the average amount of electricity shifted per day with the actual electricity consumption as calculated in RQ1 and RQ2 we see that the hydrogen scenarios with medium and high flexibility will shift the most electricity relative to their electricity consumption.

	Average electricity use per day [MWh] *(see RQ1 and RQ2, chapter 4 and 5)*[4]	**Average load shifted [MWh][5]**	**percentage load shifted [%]**
Reference plant (current plant)	322	0	0%
Reference fuel mix + CCS	2,625	628	24%
100% biofuel scenario + CCS	789	108	14%
Hydrogen, flex moderate + CCS	4,596	466	10%
Hydrogen, flex medium + CCS	4,596	1,182	26%
Hydrogen, flex high + CCS	4,596	1,501	33%
Electrification + CCS	2,569	110	4%

[4] Values are based on the annual energy consumption shown in Figure 18, the daily electricity consumption was calculated by using 330 operating days per year for the kiln and 360 days per year for all other processes.
[5] The reader should be aware that the amount of electricity load shifted is the electricity shifted both up and down.

7.3 CONCLUSION

Based on the results of previous chapters a linear program was constructed which could with help of different electricity price profiles estimate the electricity costs savings for a European cement plant in 2050. The results of this model were used to answer the research question:

"What is the economic flexibility potential of a carbon neutral cement plant in 2050?"

How the electricity prices would develop in 2050 will be highly uncertain and to incorporate this uncertainty into the results multiple electricity profiles were used. Electricity prices calculated with models for 2050 and actual electricity prices from 2019 were used as data sources. A total of 11 price profiles for 4 different European countries where used where each country represented a specific part of Europe. Two of the data sources (The historic data and the Balmoral model) provides prices in the similar range but the average electricity price of the METIS model lies around 5 times higher. Moreover, the METIS model has larger outliers which greatly increases the economic flexibility potential. The economic flexibility potential was calculated for all proposed decarbonization pathways of a cement plant.

The processes: grinding, raw meal milling, cement milling and packaging are processes shared in each decarbonization scenario and therefore their economic potentials are the same for all decarbonization scenarios. Based on different electricity prices the monthly savings for these processes range from €5,000 to almost €130,000 per month. The large difference between these two values clearly shows that different electricity price profiles have a big impact on the total savings. On average is was calculated that 10% of the electricity costs for grinding, milling, and packaging could be saved by operating flexibly and around 90 MWh will be shifted per day.

In both the reference fuel mix scenario and the biofuel scenario sewage sludge will be milled, when this process is made flexible another €400 to €5,000 could be saved monthly depending on the electricity price profiles. Because the milling of sewage sludge is connected to the CCS system of the reference fuel mix scenario there was found the be a slight discrepancy between the milling in the 100% biofuel scenario and the reference fuel mix scenario. This difference was in most scenarios relatively small and could therefore be neglected. On average around 14% of the electricity cost for milling could be saved when the mill is operated flexibly. When the sewage sludge mill is operated flexible around 3.7 MWh will be shifted per day.

In the reference fuel mix an Amine scrubbing CCS system was used. As mentioned in RQ3 a buffer will be added to this CCS system so the CO_2 from the flue gas can be temporary stored before it is processed. Assuming electricity is used to supply heat for the CCS system a buffer could greatly reduce the electricity costs. Because the emissions from biomass are captured in the reference fuel mix scenario there is also the possibility to let some of the emissions bypass the CCS system. Bypassing introduces flexibility since the emissions could bypass the whole CCS system when the electricity prices are high and make up for these emissions by capturing the CO_2 from the biofuels when the electricity prices are low. Depending on the price profiles used a flexible CCS system could save between 0.03 and 1.3 million euro per month with an average of 0.3 million euro. The average relative savings of all price profiles of a CCS system are around 8% of the electricity costs for a CCS system. When operating the CCS system flexibly around 536 MWh will be shifted throughout the day which is around 73% of the maximum load shift potential found in *Chapter 6.*

In the hydrogen scenario an electrolyser will be used which could generate hydrogen when the electricity prices are low and store it so it can be used when the prices are high. Because of the uncertainty related to the storage size and the installed capacity of the electrolyser three different flexibility potential scenarios were constructed. The average amount of electricity load shifted in the moderate, medium and high flexibility scenarios was 304 MWh, 871 MWh and 1,255 MWh respectively which in all scenarios is around 83% of their maximum load shift potential. The average savings of the electricity costs of a electrolyser in the moderate, medium and high flexible scenarios were calculated to be 2%, 4% and 6% respectively.

Comparing the calculated load shifted electricity with the total electricity consumption for each scenario the relative load shifting was calculated. The High hydrogen, Medium hydrogen, and reference fuel mix scenario have the highest relative load shifting of 33%, 26% and 24% respectively. In the 100% biofuel, moderate hydrogen and electrification scenarios the relative load shifting is lower and around 14%, 10% and 4% of the total electricity consumption, respectively.

Looking at the total electricity costs (flexible and non-flexible processes combined) it was estimated that the reference fuel mix, 100% biofuel, hydrogen and electrification scenario could save 7.04%, 1.05%, 1.12% and 0.5% on the total electricity costs respectively. If future research concludes that the drying of BFS and the compression of CO_2 could be made flexible these savings could increase.

8 DISCUSSION

This study has shown the extent to which a cement plant could apply demand response strategies that would favour the integration of variable renewable energy sources. Meanwhile, it highlighted the large uncertainties related to the scope of the study. In the first part (8.1) of this chapter these uncertainties are discussed, in the second part (8.2) the connection to other studies is highlighted.

8.1 UNCERTAINTIES RELATED TO THIS STUDY

The uncertainties related to this study can be categorized as (I) the pathway of decarbonisation of the cement industry, (II) the development of electricity prices in 2050, (III) the modelling performed, (IV) the data used to estimate the flexibility potential, and (V) the definition of a carbon neutral cement plant.

(I) How the cement industry achieves carbon neutrality in 2050 is highly uncertain, and this uncertainty is incorporated into this thesis by analysing multiple scenarios. For all scenarios, key assumptions about the used technologies were made to define each scenario. However, it is possible that a cement plant in 2050 will use different technologies than assumed and thereby changing the result of this thesis. Probable changes of key parameters and assumptions are listed below

CCS technology

The Amine scrubbing CCS of the reference fuel mix scenario could utilize an energy source different from electricity. In that case, the flexibility potential would decrease together with the electricity consumption. It was also assumed that the amine scrubbing CCS system has a capture rate of 100% but the electricity consumption was based on systems with a lower capture rate (90%). Increasing the capture rate greatly increases the electricity consumption. Therefore, it is likely that if amine scrubbing would be used in 2050 the capture rate would remain around 90%. Using a lower capture rate has the effect that less emissions from the bio-fuels can be bypassed which makes the CCS system less flexible. A less flexible CCS system would lead to higher electricity costs. However, not all emission have to be captured to become carbon neutral. Biofuels emissions are considered carbon neutral and some of the calcination emissions are reabsorbed during the lifecycle of cement, point (V) addresses the effect of reabsorption more in depth. A brief analysis showed that if more than 6% of the calcination emissions are absorbed into the cement throughout its lifecycle, the reference fuel mix scenario will still remain carbon neutral, even though the CCS system only captures 90% of the total emissions[6]. If 6% of the calcination emissions are reabsorbed with a capture rate of 90% there is no possibility for the flue gas to bypass the CCS system and thereby decreasing the flexibility potential.

Oxyfuel CCS technology could be a promising technology too. However, due to time constraints this was not researched. In an oxyfuel kiln pure O_2 is used for combustion which lowers the energy demand and makes CO_2 easier to capture. One study showed that using oxyfuel could make the fuels 54% more efficient (Han et al., 2018) and theoretically, the creation of pure oxygen could be made flexible (Nimtz & Krautz, 2013).

[6] By using the CO_2 emissions shown in Figure 17 of *chapter 5* and using a capture rate of 90% it was calculated that only 644 kt of the 715 kt CO_2 emitted annually would be captured. Because of the use of biofuels only 670kt CO_2 needs to be captured per year to become carbon neutral. The total calcination emissions were 458 kt of CO_2 per year so if 6% of these emissions are reabsorbed into the cement, the plant would still remain carbon neutral.

Hydrogen technology

Hydrogen could be imported and thereby the load shift potential would be allocated to the producer of hydrogen instead of the cement plant.

The usage of BFS as clinker substitute

Because of time constraints it was assumed that the drying of BFS uses electricity and could not be made flexible. If future research concludes that the drying of BFS could be made flexible than the flexibility potential could greatly increase. Especially because the drying of BFS contribute to around 10% to 19% of the total electricity demand for all decarbonization scenarios.

The assumed clinker to cement ratio of 50% will likely be higher due to the scarcity of additives. In fact, a study showed that it is likely that there will be a supply problem of fly-ash and BFS if all cement plants use this clinker cement ratio (Kermeli et al., 2019; Worrell & Kermeli, 2017). Especially because the availability of these substitution materials is linked to the steel industry and amount of coal-fired powerplants available. To decarbonize all industries in 2050 it is likely that most coal-fired power plants will close and that the size of the steel industry will decrease. Alternative clinker substitutes are available but they are either expensive, cannot offer the same replacement ratios or are unavailable in some countries (Kermeli et al., 2019; Worrell & Kermeli, 2017). CEMBUREAU (2020b) stated that they target for an average clinker cement ratio of 65% in Europe 2050. Clinker production is a highly energy intensive process and therefore the energy consumption would increase. Moreover, creating more clinkers also increases the calcination emissions and therefore more electricity will be needed for the CCS systems. A higher clinker ratio could have one of the following effects on the flexibility.

(1) If the installed capacity would remain similar, producing more clinkers results in less flexibility for the processes grinding and raw milling. This decrease in flexibility is caused by the increased need for raw meal which is used to create clinker. The flexibility potential of the cement mill and packaging unit would remain similar because the same amount of cement is produced. (2) If the installed capacity increases to match the increased need of raw meal, the absolute savings and amount of electricity shifted of the grinder and raw mill would increase while the relative savings would remain similar. However, the electricity consumption of the raw mill and packaging unit would remain similar.

Electrification scenario

In this thesis no flexibility potential was identified for the electrification scenario. Theoretically, it should be possible to use a hybrid system where bio-gas or hydrogen could be used to lower the electricity demand (D. Rennie, personal communication, July 22, 2021). The use of a hybrid system was researched but no scientific sources were found and therefore it was chosen to exclude it from this thesis. If the costs of installing a hybrid system are relatively low, a hybrid system could be a good way of adding flexibility to an electric cement plant, but more research is needed to determine this.

(II) The economic flexibility potential is largely influenced by the development of electricity prices in 2050. A larger variance in electricity prices throughout the day increases the potential savings on electricity costs. The electricity prices time series are outputs of models that apply multiple and different assumptions on the highly uncertain future energy system and climate. All these assumptions introduce uncertainties which makes the results of these models highly uncertain. To incorporate these uncertainties, multiple price profiles were used. These assumptions get more certain the closer we get to 2050. Therefore, it is suggested that both flexibility potential and electricity price projections studies keep getting conducted so benefits of flexible industries could better be estimated.

(III) The aim of the model was to minimize the electricity costs for a month of operations based on perfect future knowledge. Realistically, a cement plant only has knowledge of the day-ahead prices of electricity. For more realistic results the cement plant should be modelled per day while using prediction software to predict the electricity prices for the coming days. Because of the minimization of electricity costs, the model will never build up stock for the next months because this would require more energy. Realistically, it could be beneficial to build up stock before the next month especially if it is expected that the electricity prices would rise. Because of these limitations, it is likely that the actual costs savings would be lower than calculated.

(IV) Uncertainties concerning the data used to estimate the flexibility potential arise from the fact that almost no large scale projects were yet conducted to test the feasibility of the decarbonization technologies. The electricity consumption of these new technologies is estimated using the efficiency of relatively small pilot projects or estimations found in literature. To decrease these uncertainties, more research should be conducted on the performances of these decarbonization technologies.

The load shift potential is mainly determined by the capacity factor of the cement plant. Lowering the capacity factor while still supplying the same amount of cement requires a larger installed capacity which increases investment costs, not taken into account in this study. More in depth studies should be conducted to estimate the capacity factor of each production step and storage sizes where the profit is maximized.

(V) In this thesis, a carbon neutral cement plant is described as a cement plant that does not emit CO_2, excluding emissions from bio-fuels. According to literature CO_2 is also being absorbed into the cement (CEMBUREAU, 2020b; Gartner & Sui, 2017; GCCA, 2020; Xi et al., 2016) but is not considered in emission inventories nor in this thesis. In 2050, when a carbon neutral cement industry is envisioned, the amount of possible CO_2 uptake should be included in the definition of a carbon neutral cement plant. The actual amount of uptake varies in the literature from 23% (CEMBUREAU, 2020b) to 100% (GCCA, 2020) of the calcination emissions.

8.2 COMPARISON WITH LITERATURE

No studies where found regarding the flexibility of a carbon neutral cement plant. However, studies about the economic flexibility potential of current cement plants state that it is possible to achieve electricity savings between 3.7 % and 10% (Lidbetter & Liebenberg, 2014; Summerbell et al., 2017; Swanepoel, 2012). If we only look at the generic processes of the cement plant (so the same processes as in a current cement plant) in 2050 and only the historic price profiles this study concludes that between 1% and 21% with an average of 9% could be saved. Therefore, it is concluded that at least the costs for the generic cement production processes lie between a feasible range. The difference could be explained by the use of other price profiles and that this study uses more electricity saving measures.

The results of research question 2, the energy consumption of carbon neutral cement plant, is compared to similar literature. In the factsheet from the JRC (European Union, 2020) it was found that only using CCS in combination with fossil fuels slightly lowers the energy consumption of a cement plant. The same factsheet state that a fully electrified cement plant uses around 60 % energy of that of the reference plant. Both findings are in line with the results present in this thesis, see *chapter 5, Figure 18.*

9 CONCLUSION

The aim of this research was to estimate the technical and (partially) economical flexibility potential of a carbon neutral cement plant in 2050. These results are valuable for estimating the role the cement industry could play in integrating VRES into the mix, but also for helping to map out the costs and benefits associated with creating a carbon neutral cement plant. The research question this thesis aimed to answer is:

"What is the flexibility potential of a carbon neutral cement plant in 2050?"

The research was structured into two parts. Part A of the thesis estimated the energy consumption of a carbon neutral cement plant (RQ1) and how this would develop for four different decarbonization scenarios (RQ2). Part B of this thesis uses the results of part A to model the technical flexibility potential (RQ3) and the electricity costs savings of all scenarios (RQ4).

(RQ1) "What are the CO_2 *emissions and energy consumptions for every production step of a European cement plant?"*

The cement industry is a highly carbon intensive industry and it is responsible for around 4% of the total global CO_2 emissions. Depending on the fuel source, around 40% of the emissions originate from the combustions of fuels and 60% of the CO_2 emissions are released when the semi-finished product clinker is created. The burning of fuels to create clinker consumes the most energy and it occurs in the calciner and kiln. Nowadays, electricity accounts for only 8% of the energy consumption and it is mainly used for milling and to operate the kiln.

(RQ2) "Based on different decarbonization pathways, how does the energy consumption of a European cement plant change?

To create a carbon neutral cement plant it was assumed that (I) efficiency measures would be implemented, (II) carbon neutral heating technologies could supply heat to create clinkers, and (III) that CCS would be implemented to capture the clinker related emissions and, if needed, the CO_2 emissions from fossil fuel combustion. It was assumed that the electricity in 2050 would be supplied by a carbon neutral power system.

(I) In this study, energy consumption is lowered by decreasing the clinker-to-cement ratio to 50%. By-products from the steel industry (BFS) are used as clinker replacements in this thesis. By using a lower clinker to cement ratio and more efficient equipment, the electricity consumption of generic cement production processes could decrease by 40%. Furthermore, it was assumed that in 2050 the current cement kilns are replaced by more efficient ones decreasing the energy consumption by 20%.

(II) To become fully carbon neutral a cement plant is likely to decarbonize in 2050 by one of the following decarbonization pathways:

- Keep using the same fuel mix but install a CCS system to capture the fuel combustion – and calcination emissions.
- Use biofuels for process heat so only the calcination emissions need to be captured with CCS.
- Use hydrogen that is generated onsite so only the calcination emissions need to be captured with CCS. Conventional kilns need to be modified to fire hydrogen but it was assumed that the efficiency would remain the same.
- Use an electric kiln and CCS to capture the calcination emissions. It was assumed that an electric kiln has a higher efficiency compared to a conventional kiln.

(III) Only using carbon neutral energy sources does not fully decarbonize the cement industry because of the CO_2 emissions released when clinkers are created. Therefore, in all scenarios CCS is needed.

When the CO_2 that needs to be captured is mixed with other gasses the CO_2 needs to be separated before it can be stored. This separation process greatly increases the electricity consumption and is the case in the reference fuel mix scenario. Moreover, it was assumed that in the reference fuel mix scenario there was almost no technological advancements related to CCS technologies. Therefore it was assumed that the current benchmark technology was used, which is inefficient compared to promising future technologies. In all other scenarios it was estimated that there were more technological advancements so that the calcination emissions could be separated from the fuel emissions with help of a direct capturing unit, creating a pure CO_2 stream which is easier to handle. It is estimated that because of the carbon neutral fuels and pure CO_2 emissions the only electricity consumption in these scenario are from the compression of CO_2. The compression of CO_2 only consumed 7% of the electricity compared to the CCS system of the reference fuel mix scenario.

In all decarbonization scenarios the energy consumption of the kiln and the generic cement production processes decrease due to energy saving measures. However, due to the CCS used in the reference fuel mix scenario the total energy consumption is similar to the energy consumption of the reference plant. In the hydrogen scenario the energy consumption is also similar to that of the reference plant due to the energy loss associated with generating hydrogen. In the 100% biofuel and electrification scenario the same savings measures were implemented. Because the usages of CCS in the 100% biofuel and electrification scenario only slightly increases the electricity consumption the overall energy consumption decreases by as much as 40% compared to the reference cement plant.

With the estimated energy consumption estimated in part A (RQ1 & RQ2) the flexibility potential was modelled in part B (RQ3 & RQ4).

(RQ3) "What is the technical flexibility potential of a European carbon neutral cement plant in 2050?"

To answer this research question the flexibility of all processes is defined by the maximum amount of electricity that can be shifted throughout the day.

It is possible for a cement plant to operate flexible mainly because:

- A typical cement plant does not operate at full capacity
- There is enough storage capacity between production steps
- Except for the kiln not all processes happen 24 hours a day and could therefore be shifted

In all scenarios the production of cement could be made flexible but depending on the decarbonization pathway additional technologies could add to this flexibility. The amine scrubbing CCS system in the reference fuel mix scenario greatly increases the energy consumption. By implementing a buffer into the amine scrubbing system load shifting becomes possible. The combination of biofuels and a CCS systems allows for load shedding by bypassing the CCS system. Moreover, despite that this scenario uses the most energy only 60% of the energy in this scenario comes from electricity, which lowers the strain on the electricity grid. Using hydrogen also has a high flexibility potential but because in this scenario all energy comes from electricity this scenario would put the most stress on the electricity grid. In the electrification scenario all energy is also provided in the form of electricity, but because of the higher efficiency there is less electricity needed compared to the hydrogen scenario. No extra flexibility potential was identified when using an electric kiln. The biofuel scenario has a low flexibility potential compared to the reference fuel mix and hydrogen scenario, but because of its low energy consumption and use of fuels it is expected that this scenario has the lowest impact on the electricity grid.

Load shifting can be incentivised by price signals. High electricity prices at certain times could stimulate to shift processes to times when the electricity prices are low. In RQ4 the economic potential of shifting these processes will be estimated for all scenarios.

(RQ4) "What is the economic flexibility potential of a European carbon neutral cement plant in 2050?"

A linear program was constructed for all decarbonization scenarios to estimate their potential electricity costs savings. To incorporate the uncertainty of the development of price signals, multiple electricity price projections were used. By applying these different price signals it was found that on average the actual amount of electricity shifted ranges from 73% to 90% of the theoretical calculated load shift potential at RQ3.

By comparing the total electricity costs of a flexible cement plant with the electricity costs of a cement plant with fixed operating hours the relative and absolute electricity cost savings were calculated for all decarbonization scenarios.

It was estimated that in the *reference fuel mix scenario* the relative electricity cost savings is the highest ranging from 0.27% to 22.44%, with an average of 7.04%. It was calculated that the absolute savings in this scenario range from €40,000 to €1,375,000 per month with an average of €380,000 per month. Comparing the electricity shifted to the total electricity consumption shows that around 24% of the electricity consumption could be shifted.

The *hydrogen scenario* has the second largest relative electricity costs savings range from 0.09% to 12.03% with an average of 3.88%. This large difference is caused by the uncertainties related to the installed capacity of the electrolyser and the storage capacity. It was found that the absolute electricity costs savings in this scenario range from €27,000 to €2,800,000 per month with an average of €350,000 per month. Compared to the total electricity consumption to the electricity shifted it was found that around 33% for the high flexibility, 26% for the medium flexibility and 14% for the moderate flexibility scenario could be shifted.

The *100% biofuel scenario* has the second lowest relative electricity cost savings ranging from 0.07% to 2.55% with an average of 1.05%. The absolute savings in this scenario range from €5,000 to €139,000 per month with an average of €45,000 per month. By comparing the amount of electricity shifted it was calculated that 14% of the total electricity consumption could be shifted.

The *electrification scenario* has the lowest relative electricity cost savings ranging from 0.03% to 1.24% with an average of 0.51%. The absolute electricity costs savings of this scenario range from €4,900 to €127,000 per month with an average of €42,000 per month. Comparing the total electricity consumption of this scenario to the amount of electricity shifted shows that only 4% of the consumed electricity could be shifted.

It should be noted that due to time constraints the flexibility of drying BFS was not researched and therefore the impact of drying BFS lies outside the scope of this thesis. The higher the flexibility potential the better the cement plant could help integrating VRES into the electricity mix. However, the reference fuel mix and 100% biofuel scenario uses less total electricity compared to the other scenarios and therefore it could prevent the need for new power plants.

It was estimated that despite the energy savings measures, the electricity consumption of a carbon neutral cement plant would increase mainly because of the need for CCS. By flexible operating the cement plant electricity costs could be saved while simultaneously favour the integration of VRES. However, plant operators would only operate flexibly if it is profitable and therefore more research is needed on the costs associated to conclude if this strategy is profitable.

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