Graduate thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Solveig Heggvoll

Life-Cycle Assessment of alternative bio-fuelled cement plants for negative emissions

Graduate thesis in Energi og miljø
Supervisor: Francesco Cherubini
July 2020

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PROJECT WORK

for

student Solveig Heggvoll

Spring 2020

Life-Cycle Assessment of alternative bio-fuelled cement plants for negative emissions

Norwegian title

Background and objective

The continuing increase in emissions will present a major challenge for meeting the international goal of limiting warming to <2 °C relative to the preindustrial era, particularly if stringent climate change mitigation strategies are not introduced rapidly. To avoid warming of more than 2 °C with a >50% chance, the joint large-scale deployment of renewable energy options and carbon capture and storage (CCS) solutions is required. The application of CCS technology to biomass-based combustion plants delivers negative emissions, which are essential for climate stabilization. As society must decide which mitigation pathways are desirable to tackle climate change, information on the technical opportunities and sustainability profile afforded by alternative negative emission options is important, especially if they can be integrated within existing industrial systems.

Global production of cement has grown very rapidly in recent years, and after fossil fuels and land-use change, it is the third-largest source of anthropogenic emissions of carbon dioxide. Global process emissions in 2018 were 1.50 ± 0.12 Gt CO2, equivalent to about 4 % of emissions from fossil fuels. Cumulative emissions from 1928 to 2018 were 38.3 ± 2.4 Gt CO2, 71 % of which have occurred since 1990. Global cement production has increased more than 30-fold since 1950, and almost four-fold since 1990, with much more rapid growth than global fossil energy production in the last two decades. There are two aspects of cement production that result in emissions of CO2. First is the chemical reaction involved in the production of the main component of cement, clinker, as carbonates (largely CaCO3, found in limestone) are decomposed into oxides (largely lime, CaO) and CO2 by the addition of heat. They are called process emissions and contribute about 5% of total anthropogenic CO2 emissions. The second source of emissions is from the combustion of fossil fuels to generate the significant energy required to heat the raw ingredients to well over 1000°C, and these ‘energy’ emissions could add a further 60% on top of the process emissions. Total emissions from the cement industry could therefore contribute as much as 8% of global CO2 emissions.

Despite the relevant role played by the cement industry, there is a lack of environmental studies assessing the potential for negative emissions from cement plants. The latter can be realized by replacing coal as energy source with fuel mixes based on bio-based products. However, because of the lower heating value of biomass, it is unclear the fraction that it can represent in the alternative fuel mixes or co-firing with coal. Further sequestration of CO2 requires integrating oxyfuel technology in the cement industry for cost-effective carbon capture solutions. This can happen by adapting an existing plant (retrofitting).

This thesis work will build on the review analysis performed in the previous semester and perform a Life-Cycle Assessment of a retrofitted cement plant where traditional coal is replaced by an alternative, bio-based, fuel mix. Proper modelling tools (e.g., ASPEN) will be used to simulate the amount of biomass that can be used in co-firing with coal, or in a refuse-derived fuel mix, to provide the heat required for the calcination process, and the associated emission factors. Alternative scenarios of fuels can be considered. The cement production chain should reflect best available technologies in terms of reported conversion efficiencies and the most promising options for future market potentials. An understanding and process flow diagrams of the main steps of the system will be developed. Specific data on input and emission inventories, mass balances, and energy efficiencies will be compiled for each individual step of the system. The LCA will be performed to shed light on the major environmental benefits and tradeoffs of alternative fuels and oxyfuel technology. A breakdown of the impact per individual step of the value chain will be performed, and results interpreted and discussed within the context of the recent literature in the field.

The following tasks are to be considered:

1) Provide a short review of the environmental impacts of cement systems and the main challenges for improving the climate performances,
2) Identify the potentially most relevant options for alternative fuel mixes (and share of biomass) and possibility of integration of oxyfuel technology.
3) Compile a process and flow-sheet diagram for the specific system(s) identified in task n. 2, with the specific emission factors from combustion
4) Gather process and emission data for the specific system(s) designed in task n. 3. Different options of fuel mixes can be chosen and compared to each other.
5) Perform an LCA of the cement system (and possible alternative options). Breakdown of the results to show individual contributions from each step and main energy and material input.
6) Interpret and discuss the results, with identifications of areas of concerns and possible improvement options.

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The project work comprises 15 ECTS credits.

The work shall be edited as a scientific report, including a table of contents, a summary in Norwegian, conclusion, an index of literature etc. When writing the report, the candidate must emphasise a clearly arranged and well-written text. To facilitate the reading of the report, it is important that references for corresponding text, tables and figures are clearly stated both places.
By the evaluation of the work the following will be greatly emphasised: The results should be thoroughly treated, presented in clearly arranged tables and/or graphics and discussed in detail.

The candidate is responsible for keeping contact with the subject teacher and teaching supervisors.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

According to “Utfyllende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU” § 20, the Department of Energy and Process Engineering reserves all rights to use the results and data for lectures, research and future publications.

Submission deadline: June 5th 2020
Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department for Energy and Process Engineering, *Januar 2020*

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Francesco Cherubini
Supervisor

Co-Supervisor(s):

Dr. Marjorie Morales

Preface

This master thesis finalizes the work of the M.Sc. programme Energy and Environmental Engineering at the Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU). I have chosen to specialise in Energy- and Environmental Analysis and the thesis is written in collaboration with the Industrial Ecology Programme at NTNU. This thesis continues the work of my project thesis from fall 2019, "Exploring the possibilities of emission reductions in cement manufacturing". The project thesis was based on a literature review of cement manufacturing with focus on possible mitigation options in the cement industry. The mitigation options fuel substitution and inclusion of oxy-fuel CCS technology is further studied in this thesis by simulating the combustion process of a cement plant and conducting a life cycle assessment.

Thank you to my supervisor Francesco Cherubini and my co-supervisor Marjorie Morales for valuable guidance and help with the thesis, it has been greatly appreciated. I also want to thank my family for their support.

Solveig Heggvoll
19.07.2020

Summary

The cement industry contributes to large amounts of CO_2 emissions yearly and is today responsible for around 8% of global anthropogenic CO_2 emissions. With a predicted increase in cement demand in the coming years it is important to find ways to lower the emissions associated to cement production. This thesis studies the environmental benefits and possible negative impacts of using alternative fuels and oxy-fuel carbon capture and storage (CCS) in cement manufacturing. The study looks into how much biofuel can be used in the fuel mix and if it is possible to achieve negative CO_2 emissions for production of clinker, the main constituent of cement. Three different biofuels were chosen to obtain more comprehensive results; municipal solid waste, sewage sludge and forest residues.

A simplified model of the cement kiln system is made in Aspen Plus to simulate the combustion of various fuel mixes for both combustion in air and for oxy-fuel combustion. These simulations provided emission information from the combustion process and showed which fuel mixes that could work for cement production. Life cycle assessment (LCA) was used to analyse the environmental impacts associated to using alternative fuels and oxy-fuel CCS.

Results from the Aspen Plus simulations showed that the share of biofuels in the fuel mix could be increased from around 25-50% to around 100% when oxy-fuel combustion was used instead of traditional combustion in air. The results from the LCA show that combined use of biofuels and oxy-fuel CCS has a large CO_2 mitigation potential, making neutral emissions from clinker production possible. Achieving negative emissions does however appear to be difficult. The use of both oxy-fuel CCS and biofuels have some environmental trade-offs, but based on this study the environmental benefits appear to outweigh the negative effects.

Sammendrag

Sementindustrien står for store mengder CO_2-utslipp årlig, og er i dag ansvarlig for om lag 8% av de globale menneskeskapte CO_2-utslippene. Ettersom behovet for sement er antatt å øke i årene fremover er det viktig å finne gode løsninger som kan minske utslippene fra sementproduksjon. Denne oppgaven studerer de miljømessige fordelene og ulempene som følger med bruken av bio-baserte brenselsstoffer og oxy-fuel karbonfangstteknologi (CCS) i produksjonen av klinker, hovedbestanddelen i sement. Oppgaven undersøker hvor høy andel biobrensel som kan brukes og om det er mulig å oppnå negative CO_2 utslipp i klinkerproduksjon. Tre forskjellige biobrensler er undersøkt; husholdningsavfall, kloakkslam og skogsavfall.

En forenklet modell av forbrenningsystemet til sementproduksjon er laget i Aspen Plus for å simulere forbrenningen av forskjellige sammensetninger av biobrensler og kull. Simuleringer er kjørt både for forbrenning i luft og for oxy-fuel-forbrenning. Disse simuleringene ga informasjon om utslippene fra forbrenningsprosessen i tillegg til å vise hvor høy andelen med biobrensel kunne være. Livssyklusanalyse (LCA) er brukt for å analysere miljøpåvirkningene man kan få av å bruke biobrensler og oxy-fuel CCS i sementproduksjon.

Resultater fra Aspen Plus simuleringene viser at andelen biobrensel som kan brukes til sementproduksjon kan økes fra rundt 25-50% til nærmere 100% når oxy-fuel-forbrenning er brukt i stedet for vanlig forbrenning i luft. Resultatene fra livssyklusanalysen viser at det kan være mulig å oppnå nøytrale CO_2-utslipp for produksjonen av klinker ved å kombinere bruken av oxy-fuel CCS og biobrensler. Det virker derimot usannsynlig at det er mulig å oppnå negative CO_2-utslipp. Både bruken av oxy-fuel CCS og biobrensler medfører noen miljømessige ulemper, men ut ifra resultatene i denne studien virker det som at de store miljøfordelene veier opp for ulempene.

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Abbreviations

ASU = Air Separation Unit
BAT = Best Available Technology
CCS = Carbon Capture and Storage
CPU = Cryogenic Purification System
DOC = Degree of calcination
FET = Freshwater ecotoxicity
FE = Freshwater eutrophication
FGR = Flue gas re-circulation
FL = Free lime
FU = Functional unit
FRP = Fossil resource scarcity
FR = Forest residues
GHG = Greenhouse Gas
GWP = Global warming potential
HT-carcinogenic = Human carcinogenic toxicity
HT-non carcinogenic = Human non-carcinogenic toxicity
IR = Ionizing radiation
LCA = Life cycle assessment
LCI = Life cycle inventory
LCIA = Life cycle impact assessment
LU = Land use
ME = Marine eutrophication
MET = Marine ecotoxicity
MR = Mineral resource scarcity
MSW = Municipal solid waste
OD = Stratospheric ozone depletion
ODSs = Ozone depleting substances
PM = Particulate matter formation
SS = Sewage sludge
TA = Terrestrial acidification
TET = Terrestrial ecotoxicity
WC = Water consumption

1 Introduction

High emissions of greenhouse gases (GHGs) is an issue that requires substantial mitigation efforts in the years to come in order to meet the 2 °C target by year 2100. According to the fifth assessment report by the Intergovernmental Panel on Climate Change (2014) the industry sector is the biggest emitter of global GHGs, accounting for 32% of the total emissions when both direct and indirect emissions are accounted for. GHG emissions from industries have increased by 45% since 2000 (Intergovernmental Panel on Climate Change, 2014). Addressing emissions from the industry sector will therefore be important in the coming years in order to tackle the issue before emissions increase further and the 2 °C target gets more difficult to reach. Upgrading to best available technology (BAT), technology innovation, shift to low-carbon electricity and -fuel and use of carbon capture and storage (CCS) are highlighted by the Intergovernmental Panel on Climate Change (2014) as good mitigation options for the industry sector.

The cement industry is one of the biggest emitters of greenhouse gases of the industry sector and is estimated to be responsible for up to 8% of the global anthropogenic CO_2 emissions (Andrew, 2019). Cement is widely used for construction purposes around the world due to its strong physical properties and the abundance of limestone (the main constituent of cement), which makes cement a strong, durable and relatively cheap construction material. With an average annual growth rate for cement of 6% between 2005 and 2012 (Intergovernmental Panel on Climate Change, 2014) and an estimated increase in cement demand between 12-23% (International Energy Agency, 2017), the industry needs to find a way to lower the industry related emissions while the demand for cement continues to increase.

Emissions from cement manufacturing mainly comes from combustion of fuels and from the calcination process necessary to form cement clinker (IEA, 2018). Large amounts of fuel are needed for cement manufacturing as a temperature of around 1450 °C is required to create clinker (Fischedick et al., 2014). Fossil fuels with high carbon intensities have typically been used for this purpose, which have resulted in high emissions of CO_2. The combustion of fossil fuels have been responsible for around 40% of the direct CO_2 emissions from cement production, while the remaining 60% are mainly caused by the chemical calcination process ($CaCO_3 \longrightarrow CaO + CO_2$) (IEAGHG, 2013). This calcination process is necessary so that the cement gets the required strength and physical properties that are needed. The main challenges for improving the climate performance of cement is therefore that CO_2 emissions has to be lowered without having the possibility to lower the combustion temperature or getting away from the calcination process.

The literature review conducted in the project thesis identified the following mitigation options as both possible and good: lowering the clinker ratio in the cement, substituting fossil fuels for cleaner alternatives, implementing efficiency measures and coupling of CCS technologies to cement production. The amount of clinker in the cement, the clinker ratio, can only be decreased to a certain degree before it affects the cement quality, but there is still a large potential of lowering the clinker ratios in many cement plants. Reducing the clinker ratio means less CO_2 emissions from calcination per kg cement as well as less fuel demand per kg cement. Substitution of fossil fuels for cleaner alternatives like biofuels can decrease the CO_2 emissions from fuel combustion, but will only work as long as the new fuel can provide a high enough combustion temperature. Many places already uses a mix of fossil fuels and alternative fuels for cement productiion. The EU, for example, has an alternative fuel share of 41% for its cement production. Improving the efficiencies of the equipment in cement plants can possibly lead to some emission reductions due to lowered energy demand, but there is a limit to how much CO_2 that can be abated by efficiency measures alone. The project thesis found that lowering the clinker ratio and using CCS technology were the best mitigation options, as they could tackle emissions from both the combustion and the calcination, and the limit to how much CO_2 that could be abated was much higher than for the other options.

The project thesis looked into which CCS technologies were best suited for coupling to the cement industry. Pre-combustion CCS was found to be a poor choice for capturing emissions from cement production as it is unable to capture the high emissions from the calcination process (IEAGHG, 2013). Post-combustion and oxy-fuel CCS technologies were found to be good options for use in the cement industry in the project work. Both post-combustion CCS and oxy-fuel CCS captures the CO_2 from the combustion flue gas, which includes CO_2 from both the fuel combustion and calcination process. Post-combustion CCS is more researched and is easier to retrofit to existing plants than oxy-fuel CCS, and is therefore the best CCS option for short term implementation. Oxy fuel CCS has a simple carbon capture method, lower abatement costs than post-combustion CCS (IEAGHG, 2013) and oxy-fuel combustion gives a higher combustion temperature than combustion in air. With more research regarding implementation, oxy-fuel CCS appears to be a good CCS option for the cement industry in the long run.

This thesis continues the work of the project thesis and looks further into coupling of oxy-fuel CCS to cement production and the potential of using biofuels and refuse derived fuels in the combustion process. The two main advantages of oxy-fuel combustion technology are (1) CO_2 can be separated relatively easy by condensation as the flue gas consists of mainly CO_2 and water, and (2) combustion in almost pure oxygen increases the combustion temperature compared to combustion in air. This can lower the amount of fuel necessary to obtain the desired temperature in the kiln or allow for higher percentages of bio-based fuels in the fuel mix, which typically have lower heats of combustion compared to fossil fuels. The goal of this thesis is to research coupling of oxy-fuel CCS technology and the use of biofuels in cement production, to find the major environmental benefits and possible trade-offs and to see if negative emissions from the cement industry is possible with the use of oxy-fuel CCS and biofuel.

A simplified model of the cement kiln system will be made in Aspen Plus to simulate the combustion process for different fuels and combustion conditions. These simulations will provide the achieved combustion temperature and associated emissions for the scenarios that are run. Combustion in air using 100% coal as fuel will be used as a reference scenario, representing modern cement manufacturing. Various mixes of alternative fuels and coal will be simulated for both combustion in air and for combustion in oxygen enriched air (oxy-fuel combustion). Municipal solid waste (MSW), sewage sludge (SS) and forest residues (FR) are chosen as alternative fuels for the simulations, and are referred to as "biofuels" in this thesis. Three alternative fuels are chosen in order to get a more comprehensive result, as the properties of alternative fuels can vary widely. Life Cycle Assessments will then be conducted for the various scenarios in order to get an overall insight of the environmental benefits and trade-offs associated to using different fuel mixes and implementing oxy-fuel CCS in cement production.

2 Methodology

2.1 Research of cement systems

2.1.1 Best available technology cement production

Existing best available technology (BAT) for cement production uses a dry manufacturing process (uses raw materials with a low moisture content), has a 5-stage cyclone pre-heater and a pre-calciner, uses a rotary kiln and has a modern grate clinker cooler (IEAGHG, 2013; IEA, 2018).

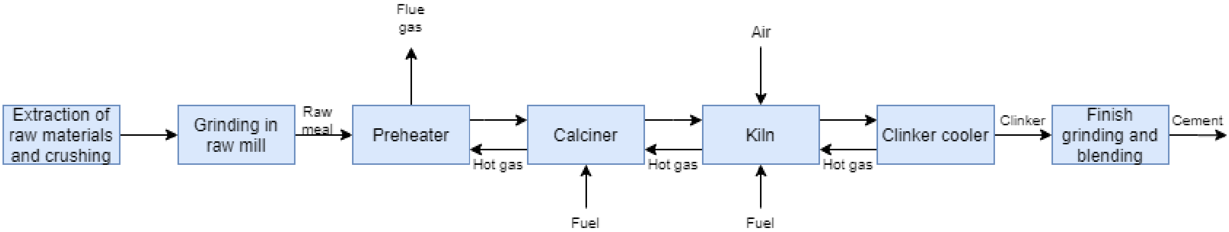

Figure 2.1: Overview of BAT cement production system. Adapted from IEA (2018).

Figure 2.1 shows an overview of how modern cement production following BAT is manufactured. Cement manufacturing begins with the extraction of the necessary raw materials (mainly limestone, iron ore and clay). The raw materials are ground and mixed to obtain the required chemical composition and then milled into a fine powder called “raw meal”. This raw meal is led into the kiln system, starting with a pre-heater which heats the raw meal to over 900°C as hot exhaust gases from the rotary kiln are sent through the pre-heater. The raw meal is next led into the pre-calciner, which is a combustion chamber positioned at the bottom of the pre-calciner and partly in the rotary kiln. The pre-calciner starts the chemical decomposition of limestone, known as the calcination process. As the raw meal is led into the rotary kiln the combustion temperature is increased to about 1450 °C. The high temperature causes more chemical and physical reactions, including completion of the calcination process, that melts the raw meal into clinker. The clinker is then cooled by a grate cooler that blows cold air over the clinker. This cold air gets heated as it passes over the hot clinker, and this heated air is used as inlet air into the kiln, lowering the amount of fuel needed to achieve the necessary combustion temperature of 1450°C. After the clinker is cooled it is blended with gypsum and other constituents before it is ground into the fine powdered cement. (IEAGHG, 2013; IEA, 2018; Hewlett and Liska, 2019)

2.1.2 Cement production coupled to oxy-fuel CCS

In order to retrofit an existing cement plant to an oxy-fuel combustion cement plant with carbon capture and storage an air separation unit (ASU) and a CO_2 compression and purification unit (CPU) has to be added to the production system. An overview of a cement system with oxy-fuel CCS is displayed in figure 2.2. Whether or not existing cement kilns can handle the switch from combustion in air to oxy-fuel combustion may be dependent on the kiln technology used. Carrasco et al. (2019) investigated modern cement kilns' suitability for oxy-fuel combustion, and found that modern kiln burners with single jet arrangements could be suitable for oxy-fuel combustion without any additional modifications to the kiln. It is also important that there is free space available in the cement plant for installation of the ASU and the CPU. This study assumes that the existing cement plant used for retrofitting has a kiln that is compatible with oxy-fuel combustion and enough available area for the ASU and the CPU.

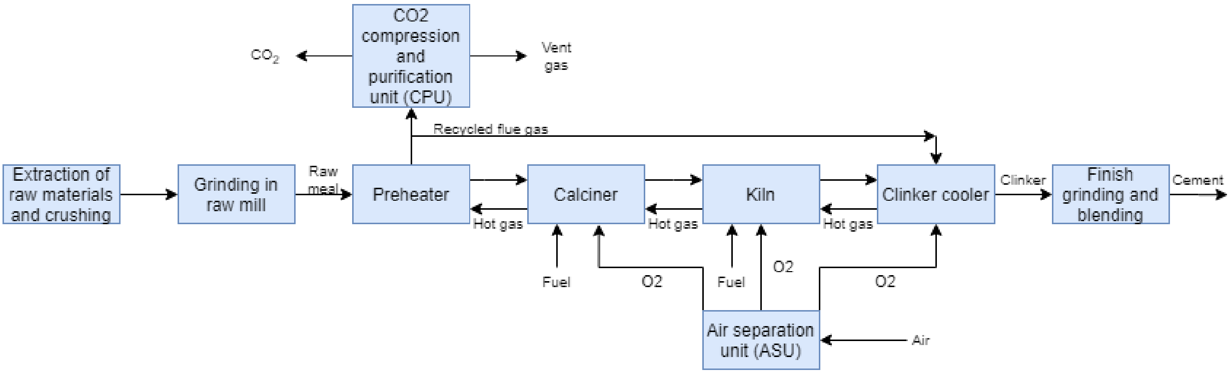

Figure 2.2: Overview of cement production system with oxy-fuel CCS. Adapted from Carrasco-Maldonado et al. (2016).

The air separation unit is needed to produce the high amounts of oxygen needed by the kiln system for combustion in oxygen instead of air. The oxygen delivered by the ASU should have a high purity of 95% (Carrasco-Maldonado et al., 2016; Ditaranto and Bakken, 2019).

Combustion in almost pure oxygen instead of air leads to a higher percentage of CO_2 in the flue gas, as diluents like N_2 are minimized. Flue gas from oxy-fuel combustion typically consists of up to 80% CO_2, water vapour, diluents (N_2, O_2, Ar) and trace contaminants $(SO_2, SO_3, NO, NO_2, CO$ +++) (Besong et al., 2013). The high CO_2 concentration of the flue gas simplifies the CO_2 capturing process as less filtering of the flue gas is needed to obtain a high purity CO_2 stream.

The CPU uses condensation to separate out the water, which in some cases is all that is necessary to do before the CO_2 can be compressed and transported for storage. Whether or not the diluents and trace contaminants needs to be removed from the CO_2 stream depends on requirements of CO_2 purity, pipeline requirements and geological requirements. When needed the diluents and trace contaminants can be filtered out through further processing (Besong et al., 2013).

The CPU capture rate can vary between 85-99% depending on the efficiency of the CPU, air leakages into the kiln system and the CO_2 purity of the flue gas (IEAGHG, 2013; Besong et al., 2013). Air leakages into the system should be kept below 2% to ensure a high purity CO_2 product and a capture rate above 90% (Besong et al., 2013). A capture rate of 96% is assumed for this study based on literature review of Singh et al. (2011); Besong et al. (2013) and IEAGHG (2013).

2.1.3 Choice of alternative fuels

Several studies have been investigating the use of alternative fuels for cement production, and many cement plants already use fuel mixes that include various alternative fuels. The EU currently uses 41% alternative fuels for its cement production (Chatterjee and Sui, 2019). Some of the alternative fuels that can be used for cement production are scrap tyres, municipal solid waste, sewage sludge, forest residues (wood waste), food waste, meat and bone meal and packaging waste (Chatterjee and Sui, 2019; Stafford et al., 2016).

For this study it is of interest to see if the use of bio-based fuels and CCS potentially can lead to a negative global warming potential of cement production. Alternative fuels with high biogenic percentages are therefore chosen. Three different bio-based fuels are chosen to see if any of them are better suited for cement production. The chosen fuels are municipal solid waste, sewage sludge and forest residues. All of them are refuse-derived fuels that are easily available in most places. Sewage sludge and forest residues are assumed to consist of 100% biogenic material, and municipal solid waste is assumed to have a fossil share of 47% based on data of Norwegian municipal solid waste from AvfallNorge (2010).

2.2 Scenarios

Combustion in air using only coal as fuel is chosen as a reference case scenario that represents how cement is commonly made today when the best available technology is used. It is of interest to study the effect of both fuel substitution and integration of oxy-fuel CCS. For each fuel substitution option (MSW, SS and FR) scenarios are studied for four different mixing ratios with coal, for both combustion in air and for combustion in an oxy-fuel environment with CCS implemented. Table 2.1 shows an overview of all the different scenarios, 26 in total.

Table 2.1: Overview of scenarios

Air combustion	**100% Coal, air (base case)**			
Oxy combustion	**100% Coal, oxy**			
Biofuel %	0			
Coal %	100			
Air combustion	**100% MSW, air**	**75% MSW, air**	**50% MSW, air**	**25% MSW, air**
Oxy combustion	**100% MSW, oxy**	**75% MSW, oxy**	**50% MSW, oxy**	**25% MSW, oxy**
Biofuel %	100	75	50	25
Coal %	0	25	50	75
Air combustion	**100% SS, air**	**75% SS, air**	**50% SS, air**	**25% SS, air**
Oxy combustion	**100% SS, oxy**	**75% SS, oxy**	**50% SS, oxy**	**25% SS, oxy**
Biofuel %	100	75	50	25
Coal %	0	25	50	75
Air combustion	**100% FR, air**	**75% FR, air**	**50% FR, air**	**25% FR, air**
Oxy combustion	**100% FR, oxy**	**75% FR, oxy**	**50% FR, oxy**	**25% FR, oxy**
Biofuel %	100	75	50	25
Coal %	0	25	50	75

2.3 Creating a model for the combustion system

Aspen Plus is used to create a simplified model of the cement kiln system that can be used to model the combustion of various fuel mixes under different operating conditions. The model is used to get the achieved combustion temperature and the emissions to air from the fuel combustion for the different scenarios. The clinker calcination process (i.e. how much clinker is produced) is calculated in Microsoft Excel due to the complexity of the chemical compounds needed to model the calcination.

Two different variations of the model are created in order to simulate each of the different scenarios. One model is used for combustion using 100% coal or 100% biofuel. The other model is used for the scenarios where coal and biofuels are mixed in different ratios. The same model is used for combustion in air as for combustion under oxy-fuel conditions, only with varying input parameters.

2.3.1 Model setup

Figure 2.3 shows an overview of how the fuel combustion is modeled for the scenarios using 100% of one fuel type. Figure 2.3 shows two separate combustion lines, one for biofuels, that includes a drying process, and one for coal, without a drying process.

In the biofuel combustion line biofuel at 25°C is led into a two-stream heat exchanger, DRYER HeatX, alongside a stream of steam at 300°C. The hot steam will start heating the fuel so that the separator, DRY-SEP, can separate out parts of the moisture from the biofuel. The moisture content in biofuels is assumed to be reduced when the fuels are heated to 120°C. The dried fuel leaves the separator with an assumed moisture content of 10%. The amount of water removed by the separator is calculated by equation based on the 10% moisture content. The fuel is then led into two reactors, RYield and RGibbs. The Gibbs reactor models chemical equilibrium of the combustion process by minimizing the Gibbs free energy. As fuel is a non-conventional component, the Gibbs free energy cannot be calculated directly. The RYield reactor is included before the Gibbs reactor as it can be used to decompose the fuel into its constituent elements, which the Gibbs reactor can then use. The fuel is therefore led into RYield first, where the fuel is decomposed and the heat of the combustion reaction is determined. Air and fuel is then mixed together in a mixer before entering the Gibbs reactor, which then simulates the combustion process. The stream leaving the Gibbs reactor is led into a separator, SSplit, that separates the gaseous and solid emissions into two different streams. The emissions from the combustion process (modeled in RYield) are related to the ultimate composition of the fuels at wet basis.

The only difference between the biofuel combustion line and the coal combustion line is the absence of the fuel drying process. The coal is assumed to already be dry, which removes the need of a drying process. The coal is therefore led directly into the RYield reactor, with the remainder of the process being the same as for the biofuel line.

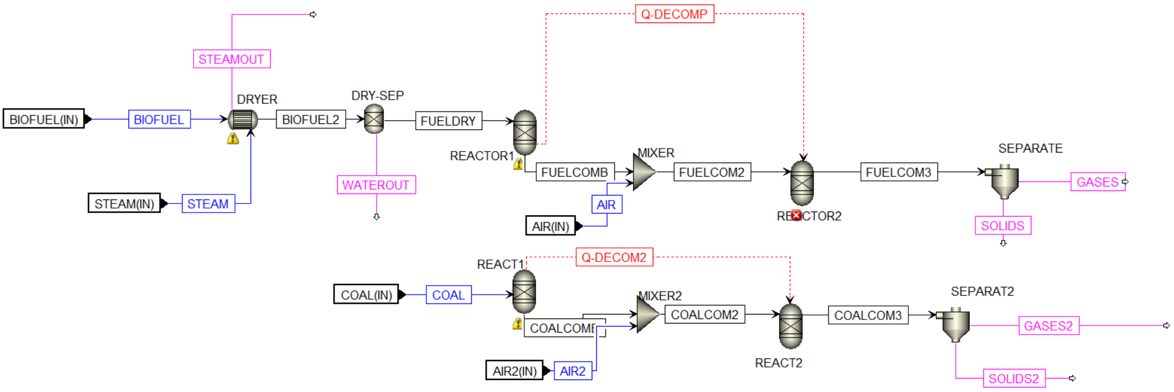

Figure 2.3: Flowsheet for Aspen model for combustion using only coal or biofuels

Figure 2.4 shows how the combustion process is modeled for combustion using a mix of coal and biofuel. The process is similar to the model for 100% biofuel and 100% coal but differs as the outputs from the biofuel combustion line and the outputs from the coal combustion line are mixed together before the gaseous and solid emissions are separated. This setup is practical for simulating a mix of different fuels as it makes it easy to vary the input ratio of coal and biofuels by changing the fuel fluxes while at the same time providing a combined result of the emissions and the combustion temperature.

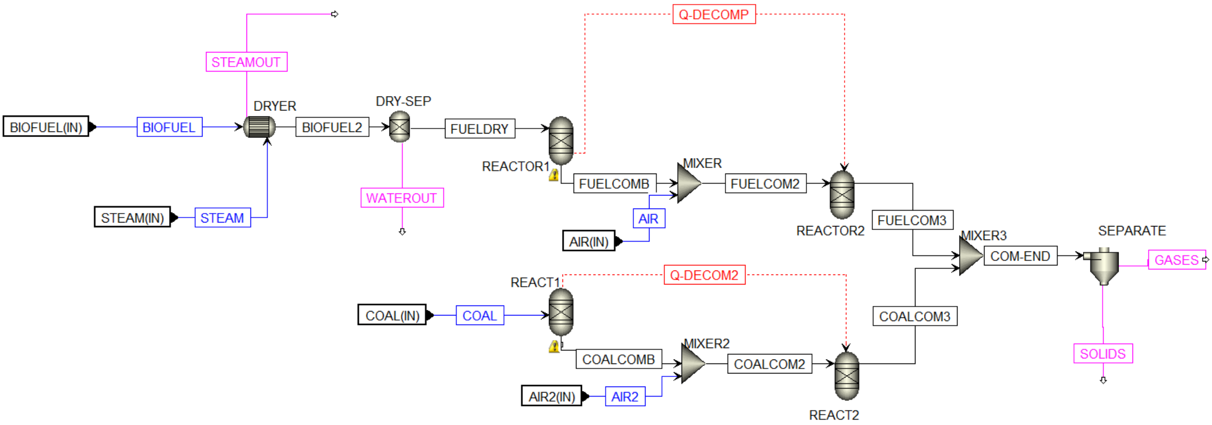

Figure 2.4: Flow sheet for Aspen model for combustion using a mix of coal and biofuels

2.3.2 Input parameters

Fuel properties

10 000 kg fuel/h is used as input for all scenarios, and this is used to determine the other flows of the system. Fuel properties for the various fuels are collected from literature and databases. Coal and forest residue properties are collected from the Phyllis2 database, respectively the properties for Bituminous coal #2928 (Phyllis2, a) and Wood, forest residues #846 (Phyllis2, b). The properties for MSW are collected from Hla and Roberts (2015), under the assumption that the chemical characteristics of the Australian MSW analysed by Hla and Roberts (2015) are comparable to those of Norwegian MSW. The report "Fornybar andel i avfall til norske forbrenningsanlegg i 2009" by AvfallNorge (2010) reported a similar combustion heat for MSW in Norway as the one reported for the Australian MSW by Hla and Roberts (2015), which makes it reasonable to assume that the chemical properties of Norwegian and Australian MSW are similar. The chemical properties for sewage sludge are collected from He et al. (2013), which analysed different pre-treatment options to improve the fuel properties of sewage sludge. Sewage sludge has a naturally high moisture content, which is why pre-treatment before combustion is wanted. The chemical compositions of the different sewage sludges analysed by He et al. (2013) are very similar. The chosen sewage sludge type from He et al. (2013) is "HC-6". An overview of the fuel properties can be found in table A.1 in the appendix.

Air inlet

For combustion in air, air is assumed to be in excess, and is modeled with a 9:1 ratio in Aspen (9kg air:1kg fuel). The chemical composition for air used in the simulations is 79% nitrogen and 21% oxygen.

For the scenarios using oxy-fuel combustion the air inlet consists of 5% nitrogen and varying percentages of oxygen and CO_2. CO_2 is included in the air inlet as a way to simulate re-circulation of CO_2 from the flue gas, a process known as flue gas re-circulation (FGR). The combustion temperature can increase significantly for oxy-fuel combustion compared to air combustion and re-circulating the CO_2 is a mechanism used to lower the temperature to a safe and wanted level for the kiln system.

As oxygen is energy intensive to separate out from air, an optimal air inlet to fuel ratio is found for each fuel. This is done by running the Aspen model simulation for various air/fuel ratios for each fuel type. For these simulations the air inlet is set to consist of 95% O_2 and 5% N_2, which simulates the air inlet before CO_2 re-circulation is included. The goal is to find the air/fuel ratio that can provide the highest CO_2 percentage in the flue gas. A high CO_2 percentage is wanted in the flue gas in order to make the CO_2 capturing process simpler. Results from these simulations are gathered in table A.2 and visualised graphically in figure A.1 to find the optimal air/fuel ratio for each fuel. Figure A.1 is included to make it easier to see what amount of air per kg fuel gives the maximum share of CO_2 in the flue gas. These maximum air/fuel ratios are also highlighted with colours in table A.2. The total air inlet flux is calculated by multiplying the optimal air/fuel ratio for each scenario with the fuel flux.

The CO_2 percentage used in the air inlet to simulate FGR is decided individually for each fuel mix scenario. The combustion temperature should be in the range 1450-2000°C for the clinker to be made without damage to the production equipment (Fischedick et al., 2014; Carrasco-Maldonado et al., 2016). Simulations are run in Aspen for various CO_2 percentages in the inlet air in order to find the highest possible CO_2 percentage that give a combustion temperature above 1450°C. The O_2 percentage in the inlet air is decided by subtracting the percentages for CO_2 and N_2 from 100%.

The oxygen needed to be produced by the ASU is calculated for each oxy-fuel scenario by multiplying the decided O_2 percentage in the inlet air with the total air inlet flux.

2.3.3 Calculation of clinker compounds and produced clinker mass flux

The mass flux of produced clinker and the calcination CO_2 emissions are calculated in Microsoft Excel. These calculations are based on the chemical reactions that take place in the kiln system (Hewlett and Liska, 2019):

(1) $CaCO_3 \longrightarrow CaO + CO_2$
(2) $2\,CaO + SiO_2 \longrightarrow (CaO)_2 \cdot SiO_2$
(3) $4\,CaO + Al_2O_3 + Fe_2O_3 \longrightarrow (CaO)_4 \cdot Al_2O_3 \cdot Fe_2O_3$
(4) $3\,CaO + Al_2O_3 \longrightarrow (CaO)_3 \cdot Al_2O_3$
(5) $CaO + (CaO)_2 \cdot SiO_2 \longrightarrow (CaO)_3 \cdot SiO_2$

Bogue's formula is often used to calculate the mass flux of each clinker compound in the finished clinker (Hewlett and Liska, 2019).

Bogue's Formula
$(CaO)_4 \cdot Al_2O_3 \cdot Fe_2O_3 = 3.043 \cdot Fe_2O_3$
$(CaO)_3 \cdot Al_2O_3 = 2.650 \cdot Al_2O_3 - 1.692 \cdot Fe_2O_3$
$(CaO)_2 \cdot SiO_2 = -3.071 \cdot (CaO - FL \cdot -0.7 \cdot SO_3) + 8.602 \cdot SiO_2 + 5.068 \cdot Al_2O_3 + 1.079 \cdot Fe_2O_3$
$(CaO)_3 \cdot SiO_2 = 4.071 \cdot (CaO - FL \cdot -0.7 \cdot SO_3) - 7.602 \cdot SiO_2 - 6.719 \cdot Al_2O_3 - 1.430 \cdot Fe_2O_3$

**FL = free lime (amount of unreacted CaO in the finished clinker).*

The chemical composition of the raw meal is taken from Hewlett and Liska (2019), with minor adjustments made to get the total equal to 100%.

Table 2.2: Raw meal composition (Hewlett and Liska, 2019)

$CaCO_3$	79.34%
SiO_2	13.96%
Al_2O_3	2.89%
Fe_2O_3	1.93%
MgO	0.67%
SO_3	0.72%
K_2O	0.49%
TOTAL	100.00%

The Excel calculations are conducted as follows:

1) The raw meal consumed per hour is calculated first. The consumed raw meal per MJ of deliverd energy (kg raw meal/MJ) is assumed the same as in Rolfe et al. (2018), 0.4545 kg raw meal/MJ. The energy released per kg of fuel (MJ/kg fuel) is calculated for each fuel mix scenario based on the individual fuel's heat of combustion and the percentage of each fuel in the mix. This number is multiplied with the fuel flux per hour, 10 000 kg fuel, to obtain the total energy released per hour (MJ/h). The total energy per hour (MJ/h) is then multiplied with the consumed raw meal per MJ of energy (kg raw meal/MJ) to obtain the consumed raw meal per hour (kg raw meal/h).

2) The mass flux of each chemical compound in the raw meal is calculated by multiplying the total amount of raw meal consumed per hour with the percentage of each compound in table 2.2.

3) Free Lime per hour (FL) is calculated as 2% of the total consumed raw meal per hour. (1-3% FL is normal according to Hewlett and Liska (2019))

4) Bogue's formula is then used to calculate mass flux of the remainder of the clinker components, using the mass flux of raw meal components calculated in step (2).

5) The total produced clinker per hour (kg clinker/h) is calculated by taking the sum of all clinker components' mass fluxes calculated in step (3) and (4).

6) The calcination CO_2 emissions are calculated by using eq. 1 and the mass flux of $CaCO_3$ in table 2.3. The molar mass of $CaCO_3$ is first calculated and then used to calculate the mass flux of CaO and CO_2, assuming a 98% degree of calcination (DOC). According to Hewlett and Liska (2019), DOC is normally in the range 94-98%.

Table 2.3: Molecular weights

	kg/mol
$CaCO_3$	0.10009
CaO	0.05608
CO_2	0.04401

Detailed calculation results from the Excel calculations are listed in table A.3, A.4, A.5 and A.6 in the appendices.

2.4 Life Cycle Assessment

Life Cycle Assessment is an analysing tool used for assessing the environmental impacts accumulated by a product over its lifetime.

2.4.1 Goal and scope definition

The goal of the study is to find the major environmental benefits and possible trade-offs of implementing biofuels and oxy-fuel CCS technology in cement production. 1 kg of produced clinker is chosen as the functional unit (FU). 1 kg of clinker is chosen as the functional unit instead of 1 kg cement in order to reduce uncertainties by limiting possible production variations. There are many different types of cement, which can vary greatly in clinker ratio (kg clinker/kg cement) and have different additional constituents that affect the impact per kg cement. As the focus of this study is the combustion process and possible integration of CCS, including cement blending in the scope is not considered necessary.

Cradle-to-gate methodology is chosen instead of the traditional cradle-to-grave methodology because the focus of the study is to analyse the impacts of changing the production system. Including the use and end-of-life phases would greatly increase uncertainties as cement and concrete can be utilised in many different ways and have variable lifetimes and end-of-life handling. Cradle-to-gate methodology appears to be standard for LCA of cement production, and is used in e.g. García-Gusano et al. (2013); Feiz et al. (2015); Josa et al. (2007) and Huntzinger and Eatmon (2009).

Figure 2.5 shows the system boundary for the scenarios with combustion in air without CO_2 capture. The clinker production is simplified into two main processes:

- Subsystem 1: Raw material processing. Includes crushing, grinding and blending of the raw materials.
- Subsystem 2: Kiln system. Includes the preheater, precalciner, rotary kiln operation and clinker cooler.

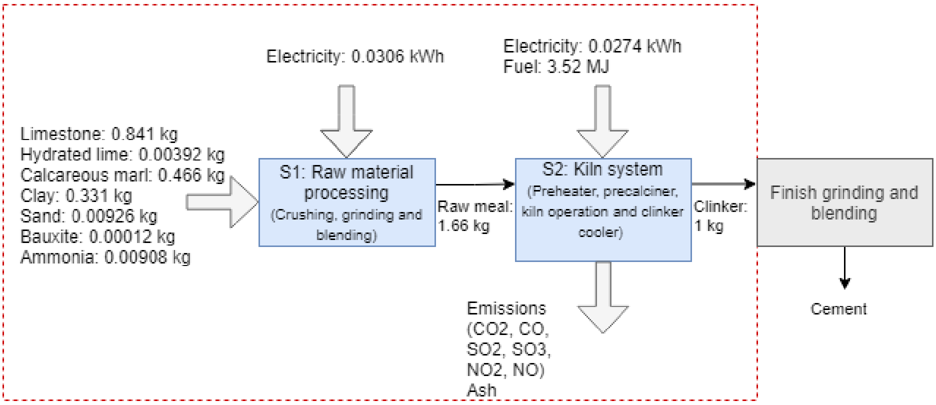

Figure 2.5: System boundary for system with combustion in air, no CCS. Input values are per kg produced clinker.

Figure 2.6 shows the system boundary for the scenarios with combustion in oxy-fuel conditions with CO_2 capture. An additional subsystem is added to the system in figure 2.5 to include the machinery needed to produce oxygen and capture CO_2, S3: Oxy-fuel retrofit machinery operation. Subsystem 3 accounts for the operation of the ASU and CPU and the capture of CO_2 from the flue gas. Figure 2.6 shows the input of oxygen and re-circulation of flue gas into the kiln system, S2.

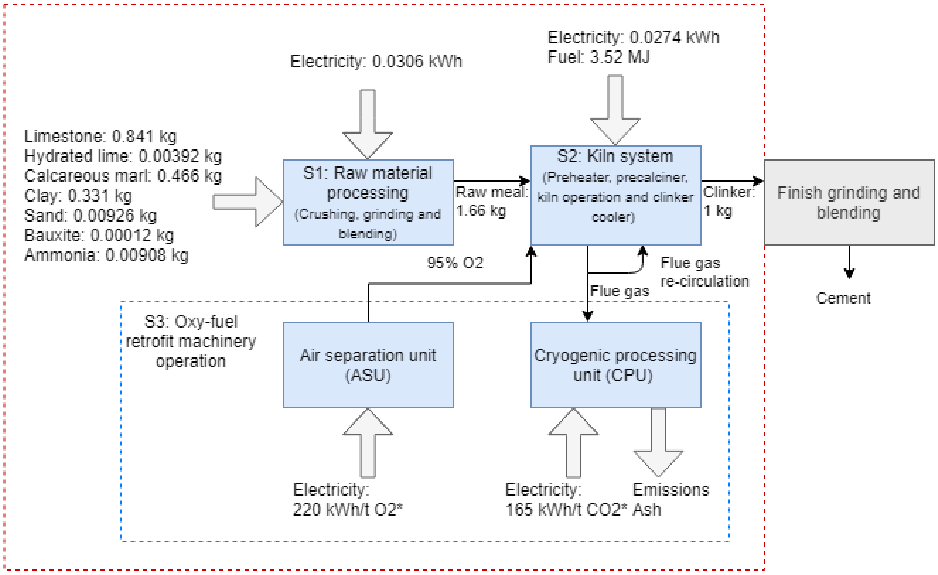

Figure 2.6: System boundary for system with oxy-fuel combustion and CCS. Input values are per kg produced clinker.
* Variable input per kg clinker depending on each scenario

2.4.2 Inventory analysis

For the inventory analysis input and output information for each subsystem is collected. All inputs and outputs are calculated on a per functional unit basis, i.e. per kg of clinker produced. Machinery input is not included in the inventory. Simapro and the LCI database "Ecoinvent 3.5 - allocation, cut-off by classification - unit" is used to create inventory lists for each scenario. Inventory lists for each scenario can be seen in appendix B.

Raw material input

The raw materials used to create the clinker's raw meal is the same for all the scenarios. This information is collected from the Ecoinvent 3.6 database. The dataset chosen is "Clinker production - Europe without Switzerland", valid from 1998-01-01 to 2019-12-31 and representative for the current technology level. This dataset also uses 1 kg of clinker as the functional unit, so no further calculations were necessary for the raw material input. Transport of the raw materials are included in the raw material processes selected from the Ecoinvent 3.5 database.

Fuel input

Fuel input per kg clinker is calculated for each scenario based on the input of coal and biofuel per hour and how much clinker is produced per hour in the given scenario.

Electricity input

Electricity input is necessary to all three subsystems. Norwegian electricity mix, medium voltage is chosen as a way to represent Norwegian clinker production. The Ecoinvent dataset used for the raw material input is used to determine the electricity demand for subsystem 1 and 2. The dataset reported a total demand of 0.058 kWh per kg clinker. In order to distribute this el. demand between S1 and S2 information from Afkhami et al. (2015) on the electrical energy consumption breakdown in a cement plant is utilised. In this breakdown the clinker cooler is considered as a part of the kiln system and its individual el. demand is not known. For simplicity's sake, the clinker cooler is therefore included in S2 in this study. Raw material processing was found to be responsible for 53% of the el. demand for clinker production, and the kiln system for 47%.

The oxy-fuel scenarios also have considerable electricity demands associated to the operation of the ASU and the CPU. How much energy they use depend on the amount of O_2 produced and the amount of CO_2 captured, which will differ for each oxy-fuel scenario. Reviewed literature lists energy consumption for an ASU to be in the range 180-245 kWh/t O_2 produced (IEAGHG, 2013; Borgert and Rubin, 2017; Hong et al., 2009; Rolfe et al., 2018; Zheng, 2011). 200-220 kWh/t O_2 appears to be the most common energy demand for an ASU based on the reviewed literature. The energy demand of the CPU ranges between 90-192 kWh/t CO_2 in the reviewed literature (Borgert and Rubin (2017); Mathisen et al. (2014); Rolfe et al. (2018); Romano et al. (2014); Zheng (2011); Besong et al. (2013)). Four of six sources have listed energy demands for the CPU between 155-166 kWh/t CO_2. An energy demand of 220 kWh/kg O_2 for the ASU and an energy demand of 165 kWh/t CO_2 for the CPU are chosen for this study since they are in the range of the most common energy demands and choosing from the upper end of the common energy demands will lower the risk of underestimating the environmental impact of the ASU and the CPU. Table 2.4 shows an overview of the calculated electricity demand for the ASU. Total oxygen demand per hour (kg O_2/h) is multiplied with 220 kWh/kg O_2 to get the total electricity demand per hour. The total el. demand is then divided by the produced clinker per hour in order to get the el. demand per kg clinker.

Table 2.4: Oxygen and ASU electricity demand for oxy-fuel scenarios

	Clinker (kg/h)	**O2% in air inlet**	**O2 demand (kg/h)**	**El. demand ASU (kWh/h)**	**El. demand ASU (kWh/ kg clinker)**
100% Coal	85698.90	30%	15000	3300	0.039
100% MSW	32415.17	87.00%	6960	1531.2	0.047
75% MSW	45735.94	60.00%	11100	2442	0.053
50% MSW	59056.71	35.00%	10150	2233	0.038
25% MSW	72377.47	32.00%	12640	2780.8	0.038
100% SS	41954.49	38.00%	2660	585.2	0.014
75% SS	52890.43	34.00%	6035	1327.7	0.025
50% SS	63826.37	31.50%	8977.5	1975.05	0.031
25% SS	74762.31	30.00%	11775	2590.5	0.035
100% FR	57369.19	32.00%	3840	844.8	0.015
75% FR	64451.46	30.00%	6450	1419	0.022
50% FR	71533.72	30.50%	9455	2080.1	0.029
25%FR	78615.99	30.00%	12150	2673	0.034

Table 2.5 show an overview of the CO_2 produced from the calcination reaction and the combustion process and the associated electricity demand for capturing this CO_2. The CPU is assumed to have a capturing rate of 96% based on literature review (Singh et al., 2011; IEAGHG, 2013). The electricity demand per hour is calculated based on the captured CO_2 per hour and the el. demand of the CPU, which is then divided by the clinker produced per hour to get the CPU's el. demand per kg clinker.

Table 2.5: Overview of captured CO2 and CPU electricity demand

	Clinker (kg/h)	CO2 from calcination (kg/h)	CO2 from combustion (kg/h)	Total CO2 (kg/h)	Captured CO2 (kg/h)	El. demand CPU (kWh/h)	El. demand CPU (kWh/kg clinker)
100% Coal	85698.90	46822.94	38134.90	84957.84	81559.53	13457.32	0.16
100% MSW	32415.17	17710.54	7781.83	25492.37	24472.67	4037.99	0.12
75% MSW	45735.94	24988.55	15606.88	40595.43	38971.61	6430.32	0.14
50% MSW	59056.71	32266.56	24239.39	56505.95	54245.71	8950.54	0.15
25% MSW	72377.47	39544.57	31305.20	70849.77	68015.78	11222.60	0.16
100% SS	41954.49	22922.50	4057.72	26980.22	25901.01	4273.67	0.10
75% SS	52890.43	28897.52	13234.60	42132.12	40446.84	6673.73	0.13
50% SS	63826.37	34872.54	21596.03	56468.57	54209.83	8944.62	0.14
25% SS	74762.31	40847.56	29629.59	70477.16	67658.07	11163.58	0.15
100% FR	57369.19	31344.56	9371.17	40715.73	39087.10	6449.37	0.11
75% FR	64451.46	35214.07	17416.40	52630.46	50525.24	8336.67	0.13
50% FR	71533.72	39083.57	24566.28	63649.85	61103.86	10082.14	0.14
25% FR	78615.99	42953.08	31235.69	74188.77	71221.22	11751.50	0.15

Emissions to air

The emissions to air from the kiln system are gathered from the Aspen process simulations for each scenario and calculated per kg produced clinker. CO_2 emissions from the combustion process come from both biogenic and fossil sources based on the fuel used in each scenario. CO_2 from biogenic sources are assumed to be carbon neutral, and has no impact on global warming potential (GWP). The amount of fossil and biogenic CO_2 is calculated for each scenario by assuming a constant amount of biogenic and fossil CO_2 for each fuel, which is calculated based on the emitted CO_2 for combustion of 100% coal, MSW, SS and FR. CO_2 from coal is assumed to be 100% fossil, CO_2 from MSW is assumed to be 47% fossil and 53% biogenic (AvfallNorge, 2010) and CO_2 from SS and FR are assumed to be

100% biogenic. The calculated biogenic and fossil CO_2 emitted per hour is displayed in table A.7. Calcination CO_2 emissions calculated in Excel are summed with the fossil CO_2 emissions from the combustion process to get the total fossil CO_2 emissions to air.

For the oxy-fuel CCS scenarios the CPU captures 96% of the CO_2 leaving the kiln system. Calculation of the captured CO_2 is displayed in table 2.5. The captured CO_2 per hour is divided by the clinker produced per hour in order to get the captured CO_2 per kg clinker. As this is a negative emission, the captured CO_2 is denoted with a minus sign in the inventory list.

2.4.3 Impact assessment

Simapro and Excel has been used to calculate the environmental impacts of each scenario and subsystem. The environmental impact of 1 kg or 1 kWh of the inputs to the system was calculated in Simapro using the ReCiPe 2016 v1.1 midpoint method, Hierarchist version.

ReCiPe 2016 has three different perspectives; Individualist, Hierarchist and Egalitarian. The hierarchist perspective is chosen for this study as it is based on scientific consensus regarding the time frame and the plausibility of impact mechanisms (Huijbregts et al., 2017). It is considered to be the default ReCiPe 2016 model. Midpoint characterisation is chosen over endpoint characterisation because it has a relatively low uncertainty and it has a stronger relation to the environmental flows (Huijbregts et al., 2017).

Global warming potential is the main characterisation factor/impact category of interest but impacts on 17 other characterisation factors are also studied. All characterisation factors can be seen in table 2.6 and 2.7, and an overview of the used abbreviations can be found on page 1.

The calculated impacts per unit input can be seen in table 2.6 and 2.7. Due to the high number of scenarios the impact assessment calculations are done in Excel for faster calculations. A sheet containing the inventory list (displayed for each scenario in appendix B) and a table of the impacts per unit input is created for each scenario. The impacts per unit input are multiplied with the amount of each input in order to get the environmental impacts from inputs of each scenario.

A similar table to table 2.6 and 2.7 is made for emissions to air, displayed in table 2.8. Table 2.8 only includes the midpoint characterization factors that are affected by the emissions to air present in this study, namely GWP, Ozone formation - human health, PM, Ozone formation - terrestrial ecosystems and TA. The impacts for each scenario by emissions to air are calculated the same way as the environmental impacts from the inputs.

Table 2.6: Impact per unit input, part 1

Environmental impacts	**Name in Simapro**		**Unit**	**GW**	**OD**	**IR**	**Ozone formation - human health**	**PM**	**Ozone formation - terrestrial ecosystems**	**TA**	**FE**	**ME**
Ammonia	Ammonia, liquid {RER}— market for — Cut-off, S	1	kg	2.05E+00	8.21E-07	4.63E-02	2.35E-03	2.18E-03	2.43E-03	5.46E-03	1.86E-04	1.15E-05
Bauxite	Bauxite, without water {GLO}— market for bauxite — Cut-off, S	1	kg	3.69E-02	3.17E-08	1.27E-03	4.21E-04	1.64E-04	4.25E-04	4.87E-04	4.65E-06	3.39E-07
Calcareous marl	Calcareous marl {GLO}— market for — Cut-off, S	1	kg	6.67E-03	7.71E-09	1.56E-04	6.53E-05	2.43E-05	6.66E-05	4.53E-05	1.77E-06	1.05E-07
Cement factory	Cement factory {GLO}— market for — Cut-off, S	1	kg	4.51E+07	2.09E+01	1.38E+06	1.61E+05	1.84E+05	1.65E+05	4.85E+05	9.72E+04	5.75E+03
Clay	Clay {RoW}— market for clay — Cut-off, S	1	kg	1.00E-02	4.35E-09	2.49E-04	6.29E-05	2.43E-05	6.43E-05	5.40E-05	5.00E-06	2.60E-07
Coal	Hard coal {RoW}— market for — Cut-off, S	1	kg	5.15E-01	1.68E-07	1.25E-02	2.48E-03	1.37E-03	2.51E-03	4.27E-03	9.94E-04	6.13E-05
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	1	kWh	2.92E-02	7.25E-08	1.20E-02	4.18E-05	2.51E-05	4.26E-05	6.37E-05	9.62E-06	7.59E-07
Hydrated lime	Lime, hydrated, loose weight {RoW}— market for lime, hydrated, loose weight — Cut-off, S	1	kg	9.32E-01	1.26E-07	8.25E-03	7.54E-04	3.90E-04	7.72E-04	1.01E-03	2.73E-05	1.98E-06
Limestone	Lime {RER}— market for lime — Cut-off, S	1	kg	2.69E-02	1.86E-08	7.53E-03	1.11E-04	6.32E-05	1.13E-04	1.59E-04	1.82E-05	1.24E-06
Sand	Sand {GLO}— market for — Cut-off, S	1	kg	1.18E-02	5.56E-09	5.22E-04	7.06E-05	2.52E-05	7.18E-05	5.69E-05	2.68E-06	1.73E-07
Sewage sludge	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	1	kg	3.42E-02	1.56E-08	8.71E-04	2.26E-04	6.43E-05	2.29E-04	1.58E-04	4.12E-06	2.86E-07
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	1	kg	0.6040	5.02E-07	0.0011	0.0004	0.0001	0.0004	0.0002	0.0000	0.0000
Forest residues	Waste wood, post-consumer {GLO}— market for — Cut-off, S	1	kg	4.18E-03	2.57E-09	4.28E-04	2.58E-05	6.87E-06	2.62E-05	1.57E-05	5.16E-07	3.58E-08

Table 2.7: Impact per unit input, part 2

Environmental impacts	Name in Simapro		Unit	TET	FET	MET	HT-carcinogenic	HT-non carcinogenic	LU	MR	FR	WC
Ammonia	Ammonia, liquid {RER}— market for — Cut-off, S	1	kg	1.07E+01	2.26E-02	4.08E-02	2.52E-02	7.88E-01	1.10E-02	3.93E-03	9.00E-01	5.77E-02
Bauxite	Bauxite, without water {GLO}— market for bauxite — Cut-off, S	1	kg	1.29E-01	2.89E-04	4.65E-04	7.59E-04	7.77E-03	3.03E-04	4.15E-02	1.16E-02	5.79E-04
Calcareous marl	Calcareous marl {GLO}— market for — Cut-off, S	1	kg	6.18E-02	2.58E-04	3.84E-04	6.35E-04	8.44E-03	3.77E-04	2.66E-03	2.07E-03	8.56E-05
Cement factory	Cement factory {GLO}— market for — Cut-off, S	1	kg	2.28E+09	1.78E+07	2.55E+07	8.91E+06	6.04E+08	1.43E+07	2.00E+06	9.90E+06	3.99E+05
Clay	Clay {RoW}— market for clay — Cut-off, S	1	kg	1.19E-01	7.78E-04	1.13E-03	2.05E-03	2.57E-02	8.25E-04	1.06E-02	2.92E-03	6.11E-05
Coal	Hard coal {RoW}— market for — Cut-off, S	1	kg	4.44E-01	3.06E-02	4.25E-02	6.38E-02	9.16E-01	2.69E-02	5.06E-04	5.99E-01	1.27E-03
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	1	kWh	1.19E-01	4.32E-03	5.41E-03	2.09E-03	3.50E-02	1.58E-03	1.86E-04	6.57E-03	2.85E-02
Hydrated lime	Lime, hydrated, loose weight {RoW}— market for lime, hydrated, loose weight — Cut-off, S	1	kg	1.66E+00	1.87E-03	3.70E-03	3.99E-03	7.03E-02	2.15E-03	1.79E-04	1.06E-01	1.19E-03
Limestone	Lime {RER}— market for lime — Cut-off, S	1	kg	7.65E-02	8.05E-04	1.13E-03	1.55E-03	2.12E-02	1.47E-03	5.91E-05	7.06E-03	1.19E-03
Sand	Sand {GLO}— market for — Cut-off, S	1	kg	8.38E-02	2.98E-04	4.50E-04	5.35E-04	9.64E-03	6.85E-04	3.94E-05	3.73E-03	1.44E-03
Sewage sludge	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	1	kg	3.86E-01	5.25E-04	9.04E-04	1.06E-03	1.90E-02	1.66E-03	8.61E-05	1.16E-02	1.12E-04
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	1	kg	4.43E-01	2.826E-01	3.682E-01	0.0297	5.1436	0.0018	0.0002	0.0128	0.0011
Forest residues	Waste wood, post-consumer {GLO}— market for — Cut-off, S	1	kg	5.73E-02	7.98E-05	9.60E-01	9.68E-03	7.96E-01	2.24E-04	1.12E-05	1.47E-03	1.42E-05

Table 2.8: Impact per unit output for emissions to air

Emissions to air	Name in Simapro		Unit	GW	Ozone formation -human health	PM	Ozone formation -terrestrial ecosystems	TA
H20	water	1	kg	0	0	0	0	0
O2	oxygen	1	kg	0	0	0	0	0
SO2	sulfur dioxide	1	kg	0	0	0.29	0	1
NO2	nitrogen dioxide	1	kg	0	0	0.11	0	0.36
N2	nitrogen, atmospheric	1	kg	0	0	0	0	0
NO	nitrogen monoxide	1	kg	0	1.53	0.17	1.53	0.552
S	sulfur	1	kg	0	0	0	0	0
SO3	sulfur trioxide	1	kg	0	0	0.23	0	0.8
H2	hydrogen	1	kg	0	0	0	0	0
HCL	hydrogen chloride	1	kg	0	0	0	0	0
CL2	chlorine	1	kg	0	0	0	0	0
C	carbon	1	kg	0	0	0	0	0
CO2, biogenic	carbon dioxide, biogenic	1	kg	0	0	0	0	0
CO2, fossil	carbon dioxide, fossil	1	kg	1	0	0	0	0
CO	carbon monoxide	1	kg	0	0	0	0	0

2.4.4 Interpretation

Graphs of the life cycle impact assessment (LCIA) results are made in order to better interpret the results. Results from combustion in air and combustion in an oxy-fuel environment for all fuel mixes are displayed in the same graphics so that the benefits and trade-offs of implementing oxy-fuel CCS and biofuels can be identified easily. The impact contribution of each subsystem is also calculated and displayed in graphs for each scenario with 100% of of one fuel type, in order to see which subsystem contribute the most to each impact category for the different fuels.

As a way to check if the LCIA results of this study are within the normal range for clinker production the Ecoinvent dataset for existing European clinker production, “clinker production - Europe without Switzerland”, is analysed in Simapro using the ReCiPe midpoint (H) method to obtain results for the different midpoint indicators. Results from this analysis can be seen in table C.1 in the appendix. Literature review is also used to check the validity of the results.

3 Results and discussion

Results from the Aspen simulations and the LCA are to a large degree presented with tables in this chapter. Colour coding of the different scenarios are used to easily identify which results in the tables corresponds which scenario. Figure 3.1 shows an overview of this colour coding. Darker colours represent combustion in air, and lighter colours represents the oxy-fuel CCS scenarios. Grey hatching is used to visualize the scenarios that were deemed impossible due to too low combustion temperatures.

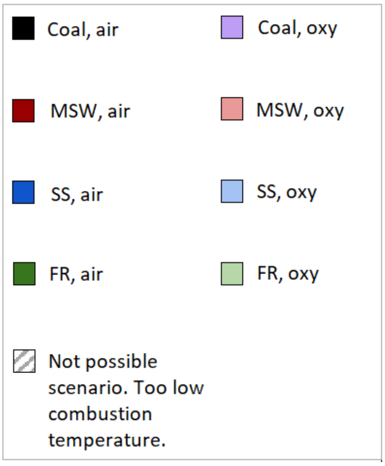

Figure 3.1

3.1 Aspen model simulations

The main results of interest from the Aspen simulations were the achievable temperatures for each scenario and the emissions to air associated to the combustion of the various fuel mixes. The emissions to air were used as input to the LCAs, and can be seen in table B.2 to table B.27. The fossil CO_2 in these tables are CO_2 from both the combustion process (varies for each scenario) and the calcination process (0.55 kg CO_2/kg clinker for all scenarios).

3.1.1 Combustion temperatures

Figure 3.2 show the temperatures achieved for the different fuel mix scenarios for both combustion in air and oxy-fuel combustion. The combustion temperature should approximately be in the range 1450-2000°C. From figure 3.2 it can be seen that for combustion in air, scenarios with high percentages of biofuel achieve a maximum temperature that is too low for clinker production. This means that the scenarios *100% MSW, air, 75% MSW, air, 50% MSW, air, 100% SS, air, 75% SS, air, 100% FR, air* and *75% FR, air* are not feasible. *50% SS, air* and *50% FR, air* are just under the 1450°C limit, but are assumed to be feasible scenarios as 1450°C is an approximate limit. *100% coal, air* is at the upper limit of the safe operating temperatures of the kiln system. These results show that the maximum share of biofuels in the fuel mix is dependant on what biofuels are being used. Based on the three biofuels studied here the maximum biofuel ratio for use in cement production with combustion in air lies between 25-50%.

Figure 3.2 shows that oxy-fuel combustion has the potential to significantly increase the combustion temperature without increasing the fuel flux. All oxy-fuel scenarios are within the acceptable temperature range. This shows that switching to oxy-fuel combustion makes it possible to significantly increase the biofuel share compared to combustion in air. Using re-circulation of CO_2 for temperature control appear to be a successful technique. Uncertainties and simplifications made to the combustion model may lead to results that are not 100% accurate. The simulations of *100% SS, oxy* and *100% FR, oxy* gave considerably higher combustion temperatures than what was needed before any CO_2 re-circulation to control the temperature was included. *100% MSW, oxy* did however only get a combustion temperature slightly over the lower limit, and only 8% of FGR could be used before the combustion temperature would become too low. It is therefore more likely that *100% MSW, oxy* won't be feasible in real life than that *100% SS, oxy* and *100% FR, oxy* will be proven to not work in real life.

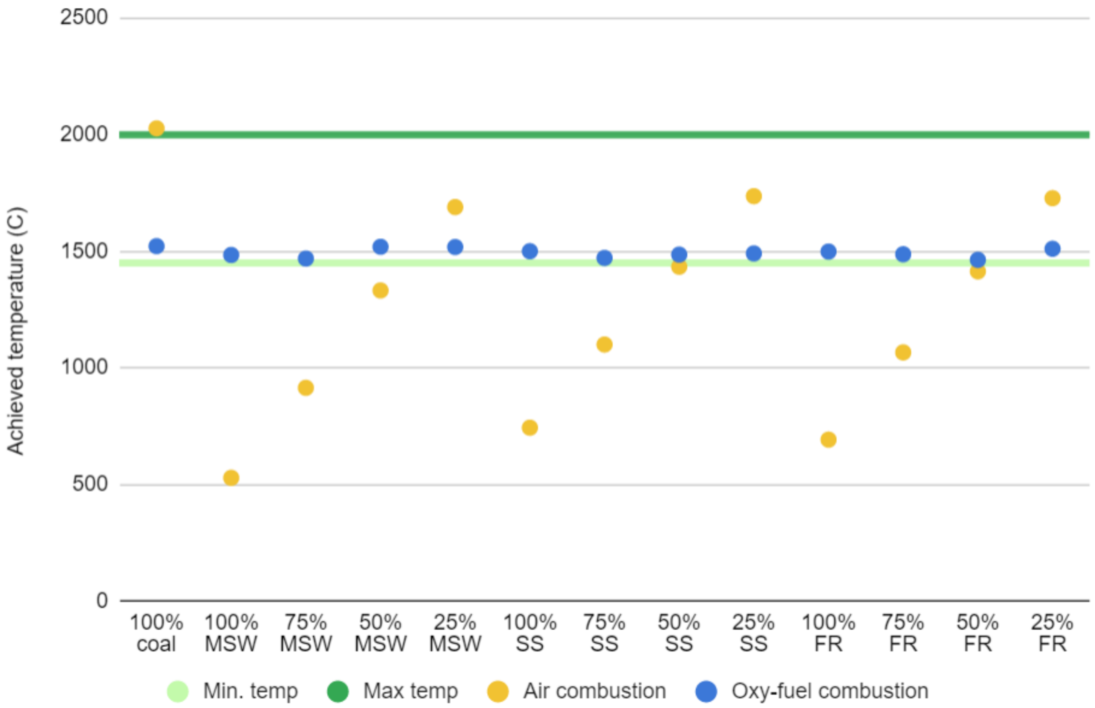

Figure 3.2: Achieved temperature for combustion in air and oxy-fuel environment

3.1.2 Emissions of carbon monoxide

Figure 3.3 show the emissions of carbon monoxide (CO) from the Aspen simulations. As a reference, Marceau et al. (2006) reported an emission of 0.00177 kg CO/kg cement from fuel combustion. The cement studied by Marceau et al. (2006) had a clinker content of 95%, so this equals an emission of 0.00186 kg CO/kg clinker. The CO emissions from the air simulations in this study are around 0.01-0.02 kg/kg clinker, around ten times higher than the emissions reported by Marceau et al. (2006).

The oxy-fuel scenarios have significantly higher emissions of CO than the air scenarios. This is in line with the findings of Carrasco et al. (2019), who reported that oxy-fuel combustion had much higher emissions of CO compared to combustion in air. The high CO emissions are believed to mainly be caused by CO_2 being present at high partial pressures in char gasification reactions, like the Boudouard reaction ($C(s) + CO_2 \longrightarrow 2\,CO$) (Carrasco et al., 2019; Ditaranto and Bakken, 2019).

CO emissions are in general formed due to incomplete combustion processes, either due to a low supply of oxygen compared to what is required for stoichiometric combustion of C to CO_2, inadequate mixing of fuel and air or insufficient combustion residence time Miller (2011). The high emissions of CO compared to Marceau et al. (2006) might therefore be lowered by looking into ways to improve the Aspen combustion model.

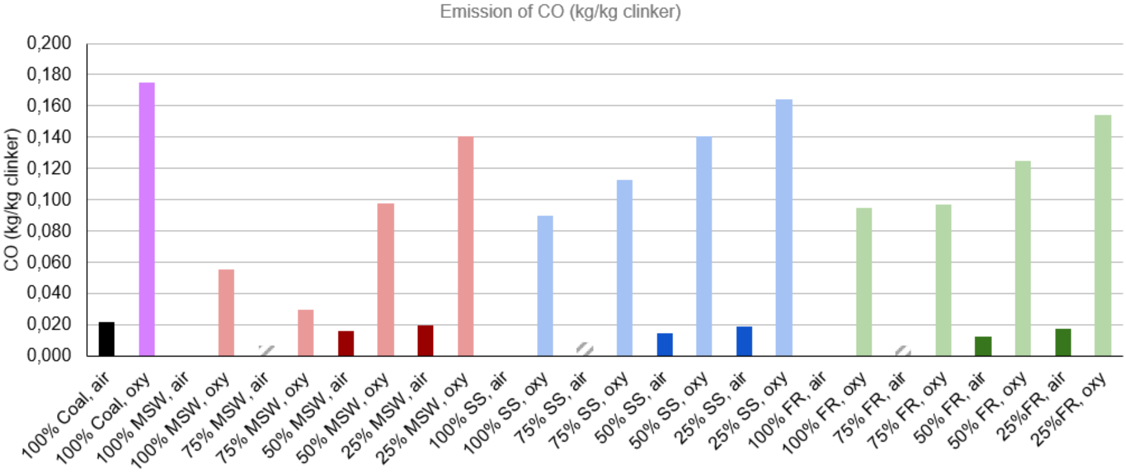

Figure 3.3: Emitted CO from combustion. (Impossible scenarios hatched in grey)

3.1.3 Share of CO_2 in the flue gas

Figure 3.4 contains an overview of the CO_2 concentration in dried flue gas for air combustion and for oxy-fuel combustion (before CO_2 capturing). This graphic show that the simulation of the oxy-fuel scenarios were successful in significantly increasing the CO_2 concentration in the flue gas compared to combustion in air, which is one of the main goals of oxy-fuel combustion.

According to Besong et al. (2013) the CO_2 concentration in the flue gas should not be lower than 85% in order to get recovery rates over 90%, obtain a high purity CO_2 product ($>$ 98%) and to keep the energy demand of the CPU down. Figure 3.4 shows that most of the oxy-fuel scenarios have CO_2 concentrations around 85%, while some are a bit lower. This study has assumed a constant capture rate/recovery rate of 96% CO_2 for all the scenarios with oxy-fuel CCS, which would imply that the captured CO_2 calculated for the scenarios with too low CO_2 concentrations in the flue gas is too high. These scenarios should therefore have a bit higher GWP than what is displayed in figure 3.6. This applies to the scenarios *100% coal, oxy, 25% MSW, oxy, 50% SS, oxy* and *25% SS, oxy*.

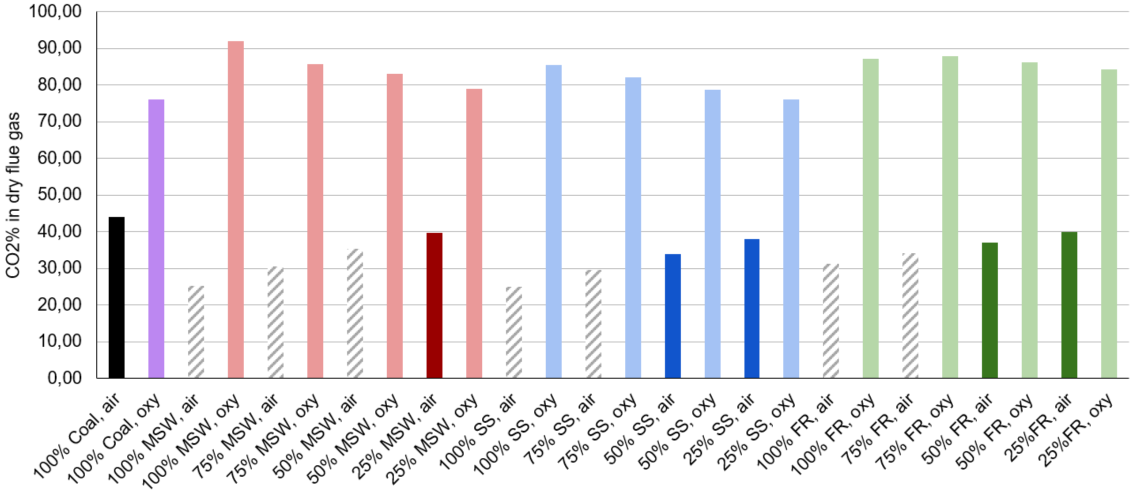

Figure 3.4: CO_2 percentage in dry flue gas. (Impossible scenarios hatched in grey)

3.2 Clinker production

The amount of clinker produced per hour (calculated using Bogue's formula) is displayed in figure 3.5. The clinker calculations are based on the heat of combustion for each fuel mix, which is non-dependant on if the combustion is in air or an oxy-fuel environment. The produced clinker per hour therefore only varies with the fuel mix. Figure 3.5 shows that the scenarios with higher percentages of biofuel in the fuel mix produce less clinker per hour (10 000 kg fuel is combusted per hour), i.e. more fuel is necessary in order to produce the same amount of clinker when biofuel is being used instead of coal. This can be seen in the LCI's for *100% coal, air* (table B.2) and *100% MSW, oxy* (table B.16), where the fuel input per kg clinker is almost three times as high for 100% MSW compared to 100% coal. This could potentially offset some of the environmental benefits of substituting coal for cleaner fuel sources.

Of the three biofuels studied combustion of MSW produce the least amount of clinker/kg fuel, followed by sewage sludge and then forest residues. Sewage sludge consumes approximately twice as much fuel per kg clinker compared to coal, and forest residues consume 1.5 times as much fuel per kg clinker.

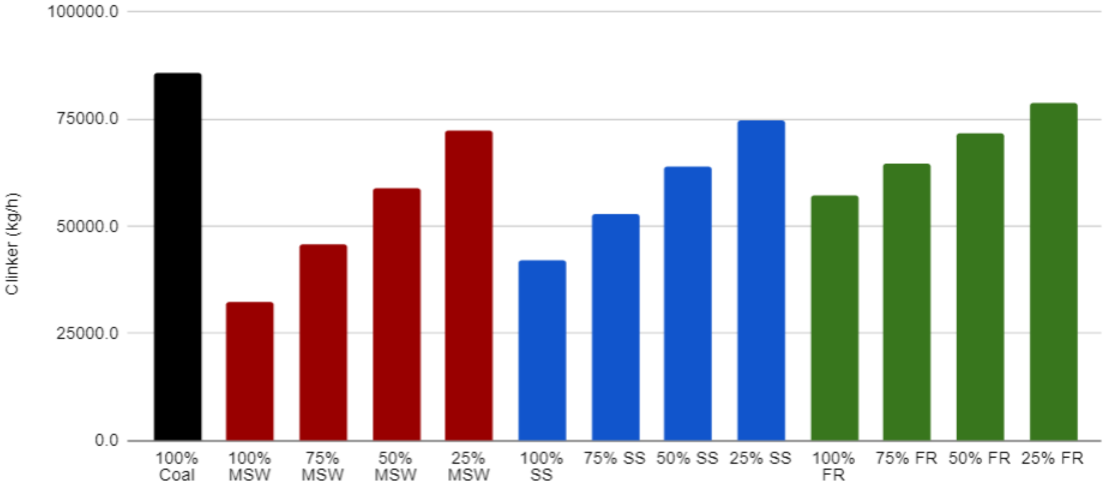

Figure 3.5: Produced clinker per hour. Valid for both air and oxy-combustion, except for the scenarios with too low combustion temperatures (*100% MSW, air, 75% MSW, air, 50% MSW, air, 100% SS, air, 75% SS, air, 100% FR, air* and *75% FR, air*).

3.3 Life Cycle Assessment

The results from the LCIA are displayed in figures 3.6 to 3.23. Each figure contains results for one impact category, for all scenarios (all fuel mixes and combustion in both air and oxy-fuel environment). Scenarios with oxy-fuel combustion are coloured in a lighter shade than the air combustion scenarios in order to separate them from the air combustion scenarios more easily. The scenarios that gave a too low kiln temperature for clinker production are included in the figures, but are hatched in grey to show that they are non-feasible scenarios, see figure 3.1.

Figure 3.6 shows the global warming potential (GWP) per kg produced clinker for all the scenarios. The reference scenario, *100% coal, air*, has a GWP of around 0.906 kg CO_2-eq/kg clinker. This correlates to the GWP reported by Valderrama et al. (2012) for the design of a new cement production line at 0.906 kg CO_2-eq/kg clinker (Spanish cement plant). For older, existing production lines Valderrama et al. (2012) reported a GWP of 0.987 CO_2-eq/kg clinker and Hossain et al. (2017) reported a GWP of 1.025 kg CO_2-eq/kg clinker for clinker production in Hong Kong. There are several variables that can affect the GWP of clinker production, e.g. choice of electricity mix and the technological standard of the production equipment. The result of 0.906 kg CO_2-eq/kg clinker obtained for the reference scenario looks to be within the normal range of GWP for existing clinker production. The fact that it is a bit lower than the reported GWP for older Spanish production lines could indicate that the model created in this study is suited to model clinker production using BAT.

Figure 3.6 shows that there is some potential to lower the GWP of clinker production by substituting part of the coal for biofuels. Although the scenarios with biofuels are emitting lower shares of fossil CO_2 per kg fuel (see table A.7), they also produce less clinker per kg fuel (see figure 3.5). This explains way the GWP of the scenario *50% SS, air* is not equal to half of the GWP of *100% coal, air* per kg clinker, even though the amount of fossil CO_2 emitted is halved. The GWP of *25% MSW, air* is higher than GWPs of *25% SS, air* and *25% FR, air*. This is likely due to the fact that the municipal solid waste scenarios produce less clinker per kg fuel than the scenarios using sewage sludge and forest residues and at the same time MSW is not 100% carbon neutral, so a part of the emitted CO_2 is considered to be fossil.

When looking into just fuel substitution, *50% FR, air* looks like the best scenario with regards to GWP, with *50% SS, air* following right behind. As the difference between FR and SS for GWP is so small they are assumed to have an approximately similar impact on global warming, as uncertainties in the model may be responsible for small differences between them.

The inclusion of oxy-fuel CCS shows a drastic reduction of GWP for all fuel-mix scenarios. *100% coal, oxy* has a GWP of 0.142 CO_2-eq/kg clinker, around 6.5 times smaller than the GWP of *100% coal, air*. It was of interest to see if the combined use of biofuels and oxy-fuel CCS in cement manufacturing had the potential to give a negative global warming potential. Figure 3.6 show negative GWP values for the scenarios *100% FR, oxy, 75% FR, oxy* and *100% SS, oxy*, but as these are only slightly negative, and since there are some uncertainties to the study, they are rather assumed to have a close to neutral impact on GWP. Even though significantly negative GWP does not look to be possible based on this study, close to neutral GWP is a significant improvement to the high GWP of the reference scenario *100% coal, air*.

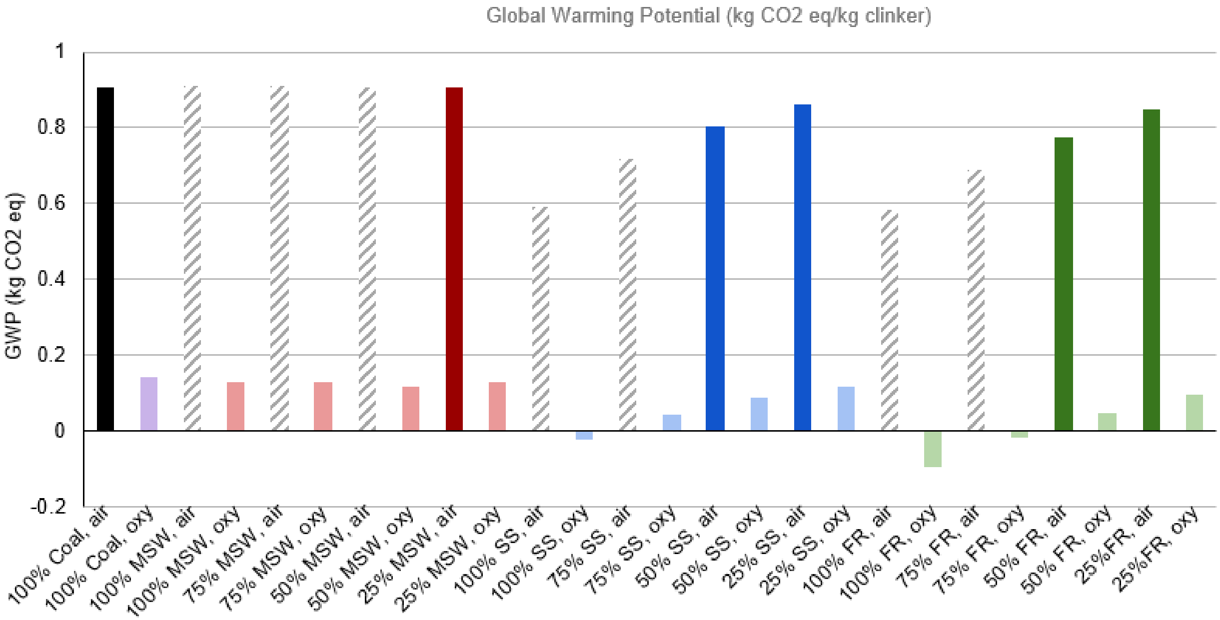

Figure 3.6: Global warming potential. (Impossible scenarios hatched in grey)

The stratospheric ozone depletion potential (OD) is displayed in figure 3.7. The OD potential of the reference scenario *100% coal, air* is close to that of the existing European clinker production (see table C.1), which had an OD potential of 6.7E-8 kg CFC11-eq/kg clinker. Use of oxy-fuel CCS technology appears to lead to a small increase in OD. The use of SS and FR does not seem to have a significant effect on OD. However, using a fuel mix with MSW appear to lead to increased OD potential as the ratio of MSW in the fuel mix increases. This could indicate that combustion of MSW emits more ozone depleting substances (ODSs) than the other fuels in this study. Emissions of ODSs should be limited as an increased amount of ODSs in the atmosphere leads to a decreased ozone concentration in the atmosphere, allowing more UVB radiation to hit the Earth.

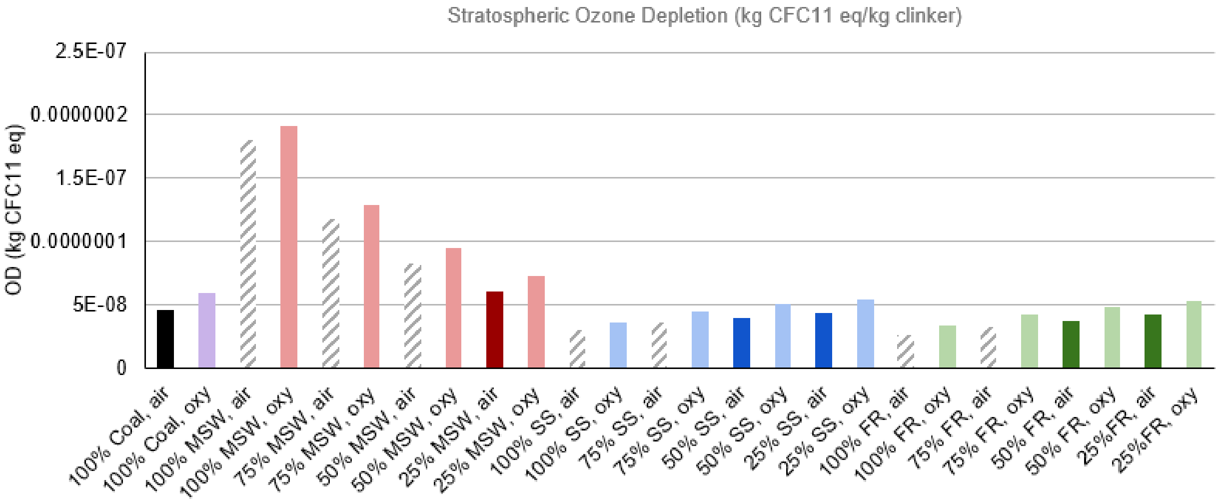

Figure 3.7: Stratospheric ozone depletion. (Impossible scenarios hatched in grey)

The ionizing radiation potential (IR) of the different scenarios is displayed in figure 3.8. The choice of fuel mix does not have an apparent impact on ionizing radiaton potential, but a slight increase can be seen for the oxy-fuel CCS scenarios. The IR potential of the existing European clinker production (figure C.1) is 0.022 kBq Co-60-eq/kg clinker, around twice as much as the IR potentials found for the scenarios in this study. The largest source of IR potential of the European clinker production was the use of European electricity mix, which contributed to 0.013 kBq Co-60-eq/kg clinker. In this study Norwegian electricity mix is assumed, and electricity was only responsible for 0.00033 kBq Co-60-eq/kg clinker for the reference scenario *100% coal, air*. As the Norwegian electricity mix is mostly based on hydropower, and the European electricity mix in larger shares are based on fossil fuels, a lower IR potential for the use of Norwegian electricity over European electricity seems reasonable. The oxy-fuel scenarios have much higher electricity demands than the air scenarios due to the operation of the ASU and the CPU, which is responsible for the small increase in ionizing radiation potential. This increase would likely be bigger if a European electricity mix was assumed. Ionizing radiation potential is determined based on anthropogenic emissions of radionuclides, which are typically generated in the nuclear fuel cycle or from burning of coal (Huijbregts et al., 2017).

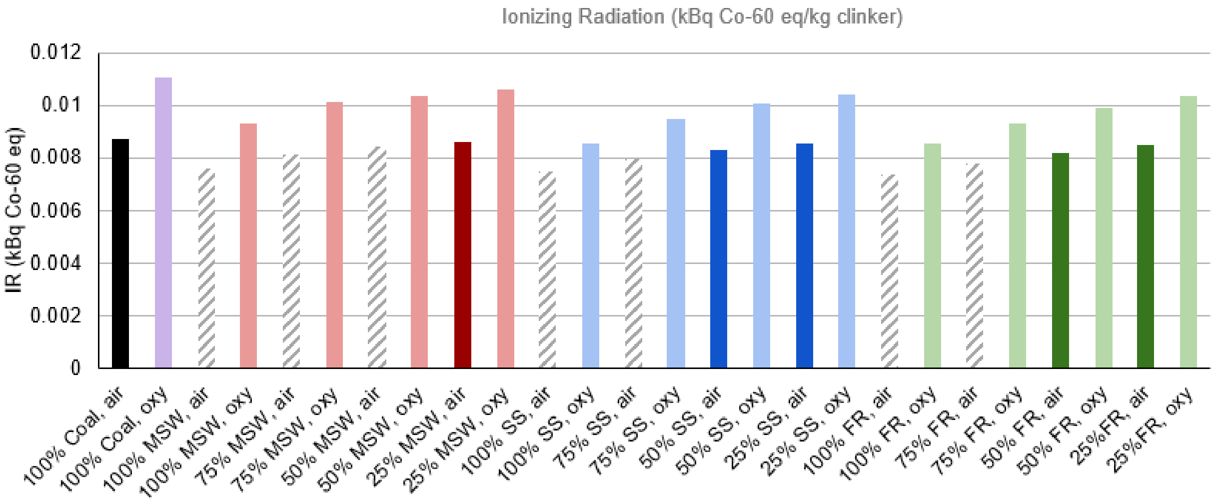

Figure 3.8: Ionizing radiation. (Impossible scenarios hatched in grey)

The scenarios' fine particulate matter (PM) formation potential is displayed in figure 3.9. As a reference, the PM formation potential of existing European clinker production is approximately 0.0005 kg PM 2.5-eq/kg clinker, which is around the same as the PM formation potential for most of the scenarios displayed in figure 3.9. Using oxy-fuel CCS appear to lower the formation potential of fine particulate matter. There are small variations between the scenarios using 100% coal and fuel-mixes with MSW and FR. The scenarios that use fuel-mixes with SS have considerable higher PM formation potential than the other scenarios. PM formation potential is determined based on emissions of fine particulate substances like NOx, NH_3, SO_2 and PM2.5. Most of the PM formation potential for the scenarios with SS comes from emission of SO_2 and SO_3. SS has a much higher sulfur content than the other fuels (see table A.1), which is likely the reason why higher PM formation potentials are seen for the SS scenarios.

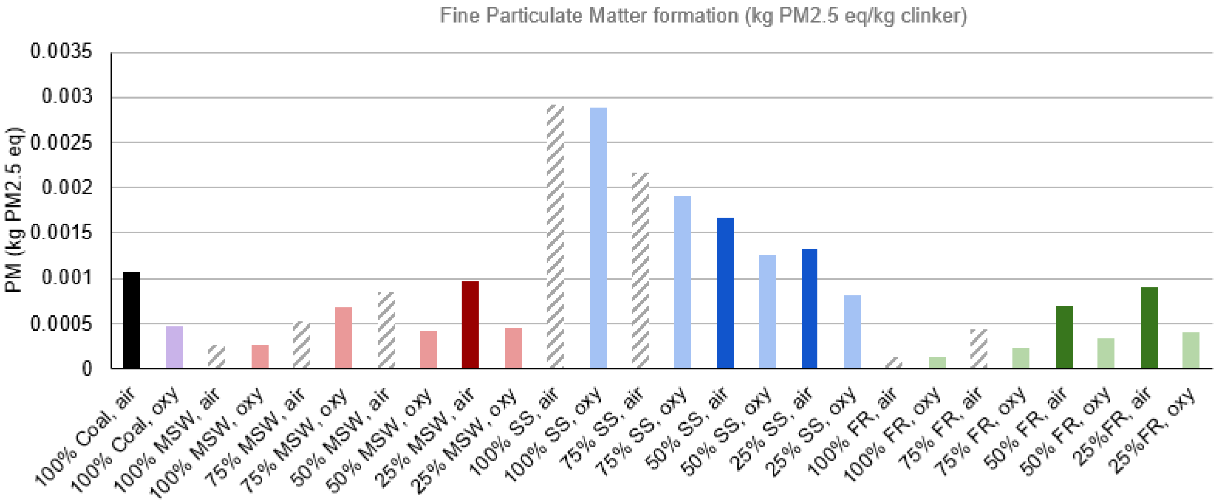

Figure 3.9: Fine particulate matter formation. (Impossible scenarios hatched in grey)

The tropospheric ozone formation potential with impacts on human health and terrestrial ecosystem are shown in figure 3.10 and 3.11, respectively. The impacts on human health and terrestrial ecosystems due to ozone formation potential are similar for the studied scenarios. From the figures it can be seen that increased amounts of biofuels in the fuel mix will decrease the ozone formation potentials. Using oxy-fuel CCS looks to be very effective to reduce ozone formation, with all oxy-fuel scenarios having minimal ozone formation potential. The ozone formation potentials for existing European clinker production is approximately 0.00145 kg NOx-eq/kg clinker for both human health and terrestrial ecosystems, which is several times smaller than what was found for the scenarios using combustion in air in this study. The largest contributor to the ozone formation potential for the studied scenarios is emission of NO, which is considerably smaller for the scenarios using oxy-fuel CCS compared to the scenarios using air combustion.

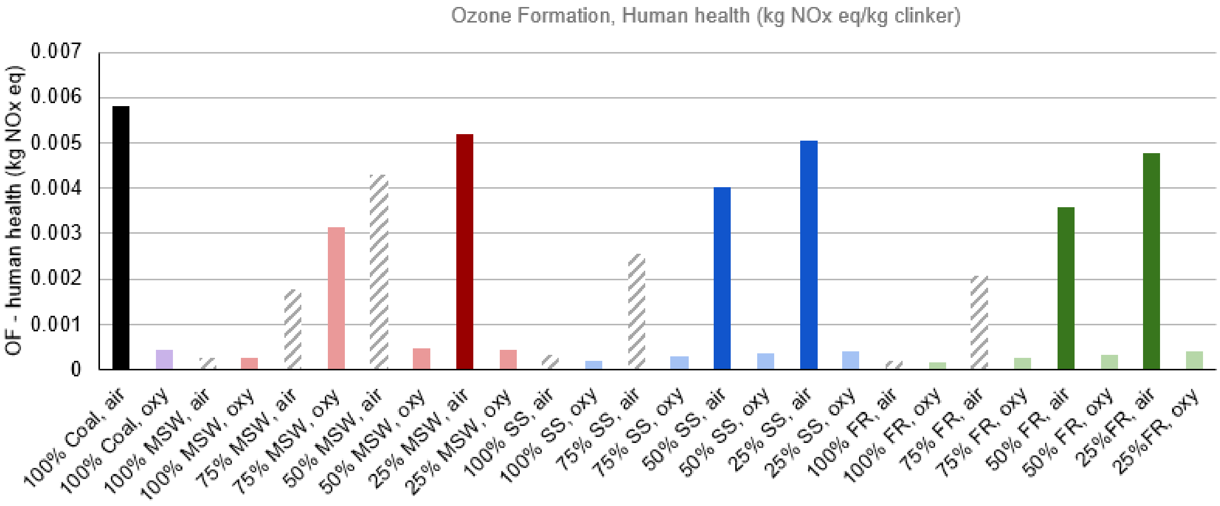

Figure 3.10: Ozone formation, human health. (Impossible scenarios hatched in grey)

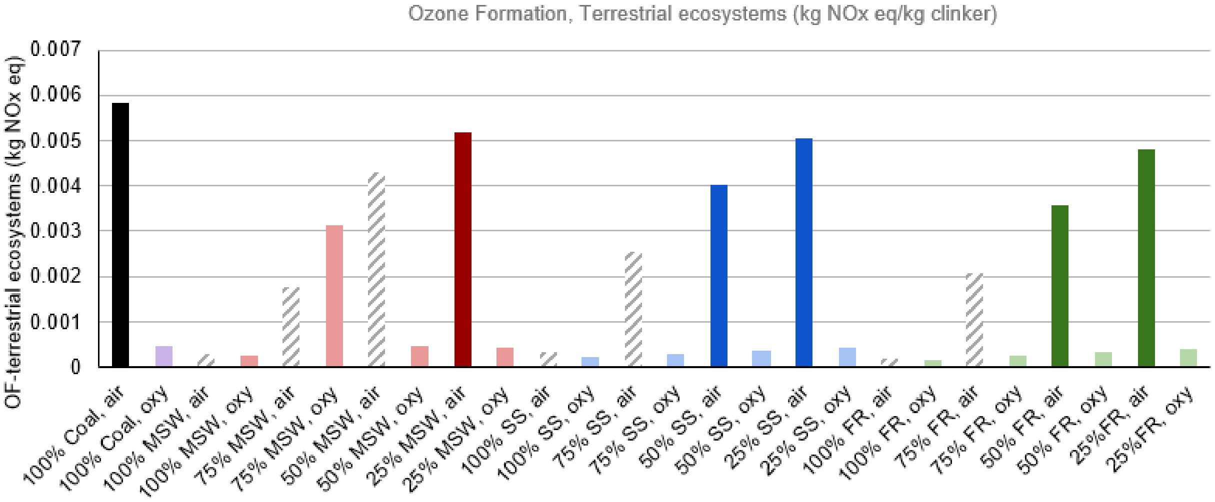

Figure 3.11: Ozone formation, terrestrial ecosystems. (Impossible scenarios hatched in grey)

Terrestrial acidification (TA) potential is displayed in figure 3.12. Emissions of acidifying compounds such as NOx, NH_3 and SO_2 can cause a change in the acidity level of the soil that can be harmful for the plant species living there (Huijbregts et al., 2017). The existing European clinker production (table C.1) has a TA potential of 0.0014 kg SO_2-eq/kg clinker and Valderrama et al. (2012) reported a TA potential of 0.0025 kg SO_2-

eq/kg clinker for existing clinker production, so the TA potential of the reference scenario seems to be around the normal range for clinker production. The scenarios using SS have higher TA potential than both the reference scenario and the scenarios using MSW and FR, with increasing TA potential as the share of SS in the fuel mix increases. The higher TA potential of the SS scenarios is mainly caused by higher emissions of SO_2 and SO_3, which likely comes from the amount of sulfur in SS being higher than in the other fuels (see table A.1). Inclusion of oxy-fuel CCS technology appear to lower the TA potential to levels similar to that of the European clinker production, and even lower for some of the scenarios.

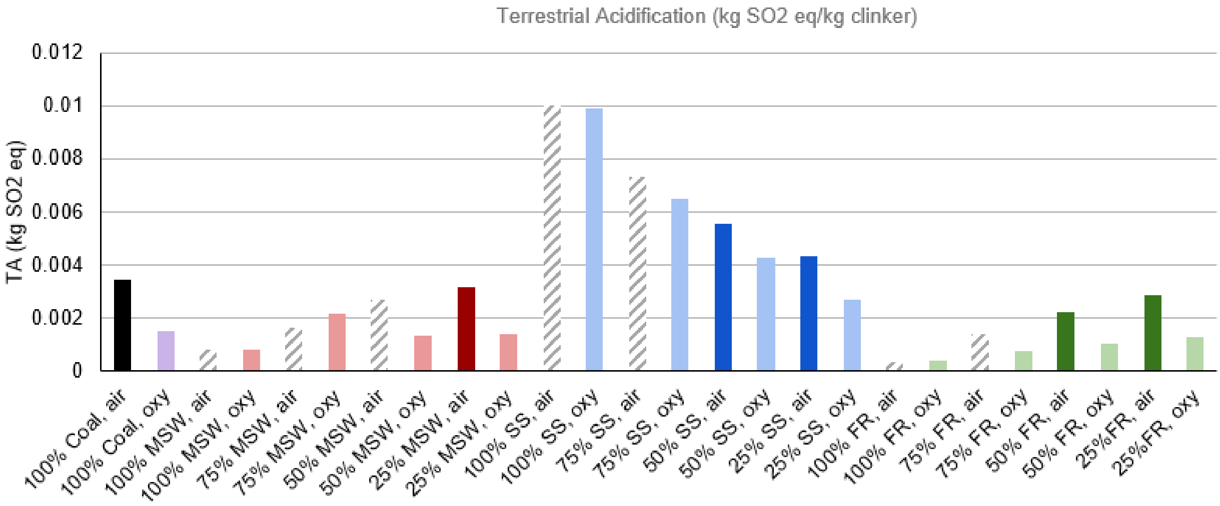

Figure 3.12: Terrestrial acidification. (Impossible scenarios hatched in grey)

Figure 3.13 shows the freshwater eutrophication (FE) potential of the different scenarios. The results for the reference scenario *100% coal, air* is a bit higher than for the existing European clinker production, at 0.000135 kg P-eq/kg clinker compared to 0.000083 kg P-eq/kg clinker (see table C.1). The FE potential of the scenario *100% coal, air* mainly comes from combustion of coal, which is likely the reason why it is higher than for the European clinker production which uses a variety of fuels (coal, natural gas, petroleum coke and some biogenic fuels), most of which have lower impacts on FE potential. Increasing the share of biofuels in the fuel mix appears to lower the freshwater eutrophication potential for combustion in air, which seems logical as the amount of coal per kg clinker reduces. The use of oxy-fuel CCS does not appear to have an impact on freshwater eutrophication.

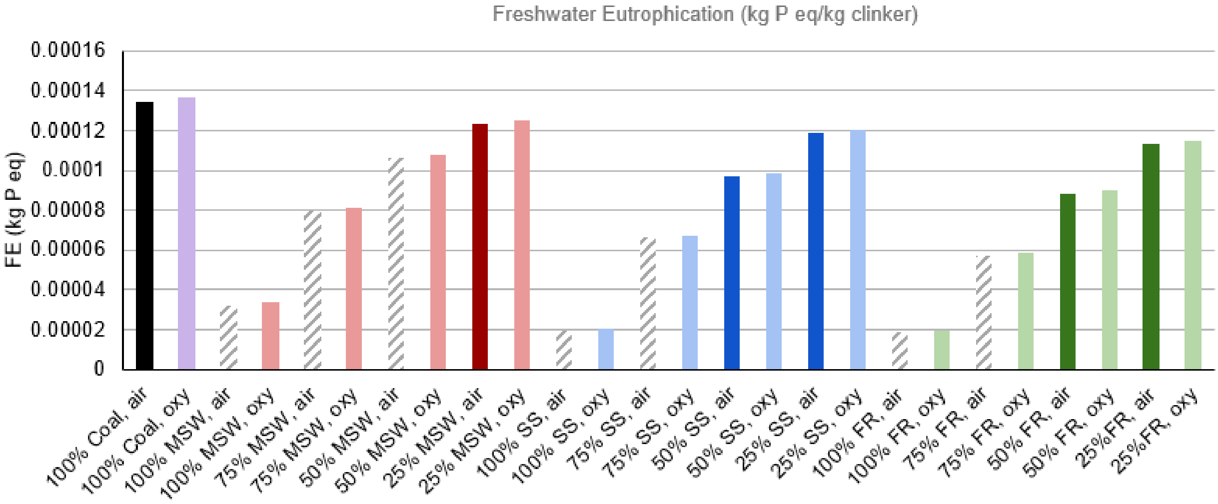

Figure 3.13: Freshwater eutrophication. (Impossible scenarios hatched in grey)

The marine eutrophication (ME) potential for the scenarios can be seen in figure 3.14. Similarly to the freshwater eutrophication potential, the marine eutrophication potential is a bit higher for *100% air, coal* than for the existing European clinker production, at 8.4E-6 kg N-eq/kg clinker compared to 5.5E-6 kg N-eq/kg clinker (see table C.1). The use of coal is also here the main contributor to ME potential, which explains this difference. Figure 3.14 shows that the ME potential is lowered by increasing the amount of biofuels (and thereby decreasing the use of coal) for the SS and FR scenarios. The scenarios using MSW have increasing ME potential as the share of MSW increases. Results from the LCIA show that MSW is responsible for 1.04E-5 kg N-eq/kg clinker in *100% MSW, air*, which is almost twice as much as the ME potential that coal contributes to in *100% coal, air*, at only 7.16E-06 kg N-eq/kg clinker.

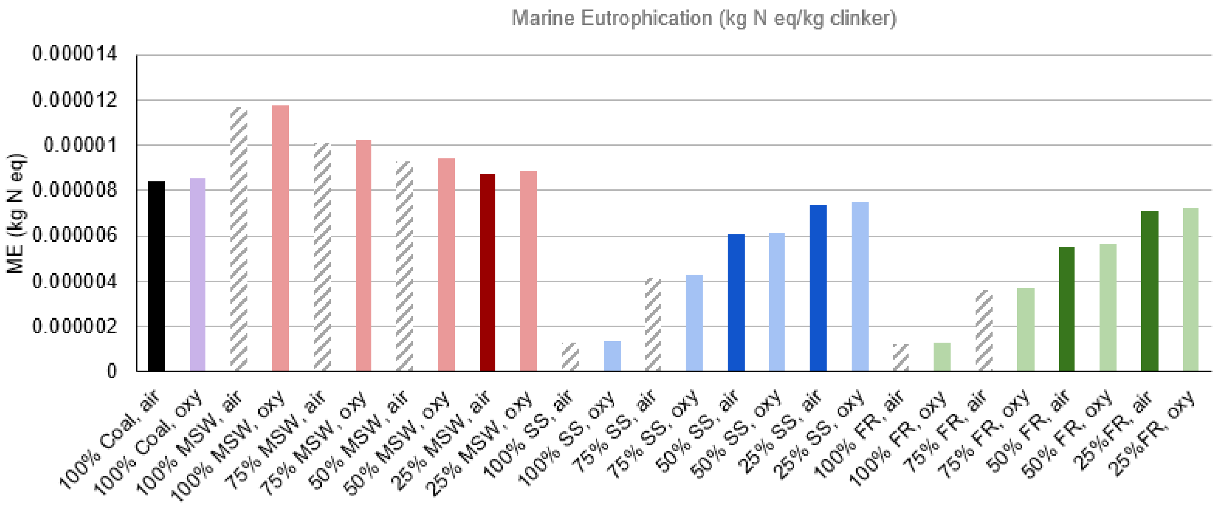

Figure 3.14: Marine eutrophication. (Impossible scenarios hatched in grey)

The terrestrial ecotoxicity (TET) potential is displayed in figure 3.15. There is not a large deviation in the values for the different scenarios, and they are close to the TET potential of European clinker production at 0.31 kg 1.4-DCB/kg clinker (see table C.1). Some of the scenarios using MSW and SS show a bit higher values than the reference scenario, but the overall variation in TET potential looks small. The inclusion of oxy-fuel CCS appears to lead to a small increase in TET.

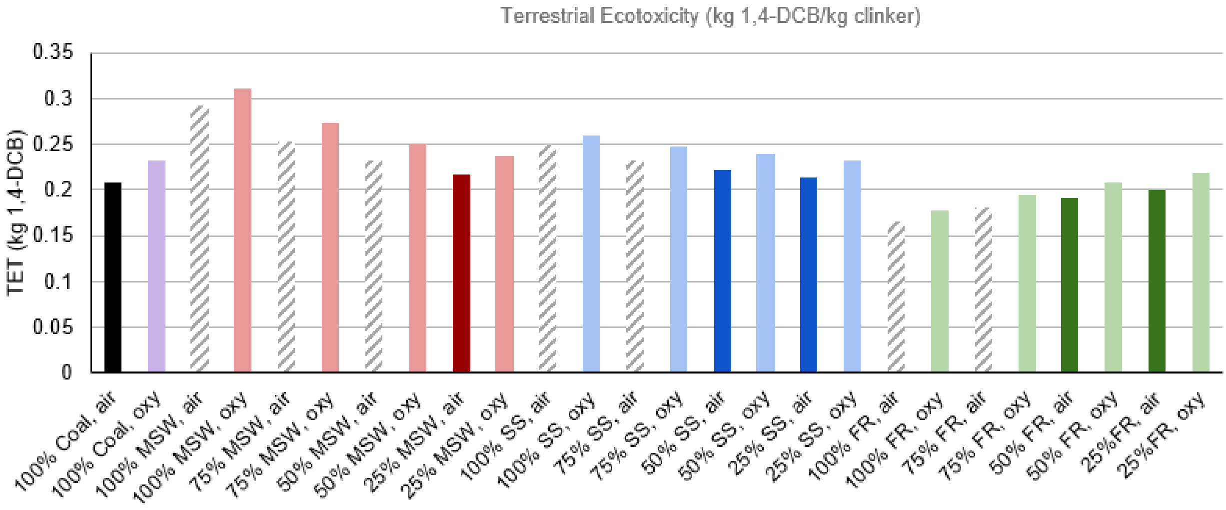

Figure 3.15: Terrestrial ecotoxicity. (Impossible scenarios hatched in grey)

The freshwater ecotoxicity (FET) potential is displayed in figure 3.16. The results show a FET potential under 0.005 kg 1.4-DCB/kg clinker for all scenarios except the MSW scenarios. The FET potentials of the coal, SS and FR scenarios are close to the FET potential of the European clinker production at 0.0035 kg 1.4-DCB/kg clinker (see table C.1). MSW has a much higher impact on freshwater ecotoxicity potential than the other fuels per kg fuel, which can be seen in table 2.7. As scenarios with MSW also produce less clinker per kg fuel than the other fuels do, the FET potential of MSW scenarios will naturally be higher. The inclusion of oxy-fuel CCS does not appear to have any significant impact on the freshwater ecotoxicity potential.

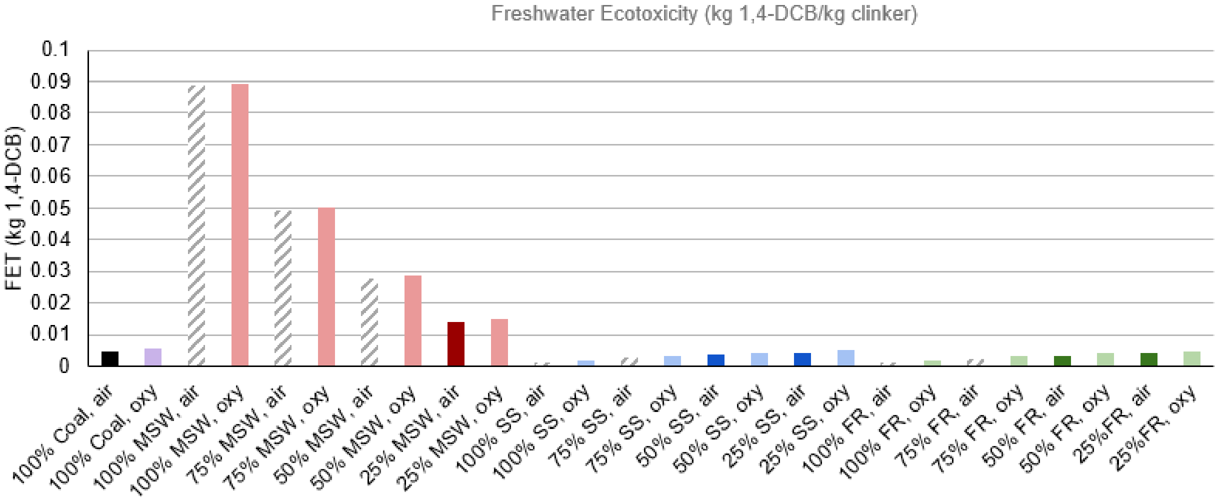

Figure 3.16: Freshwater ecotoxicity. (Impossible scenarios hatched in grey)

Figure 3.17 shows the marine ecotoxicity (MET) potentials. The scenarios with only coal and the scenarios with a SS fuel mix have MET potentials under 0.007 kg 1.4-DCB/kg clinker, which is close to that of the European clinker production that has a MET potential of 0.005 kg 1.4-DCB/kg clinker (see table C.1). The fuel mixes with FR and MSW have several times higher MET potentials than the other scenarios. The high impact FR and MSW has on marine ecotoxicity compared to SS and coal can be seen in table 2.7. Inclusion of oxy-fuel CCS technology does not seem to have a significant impact on the MET potential.

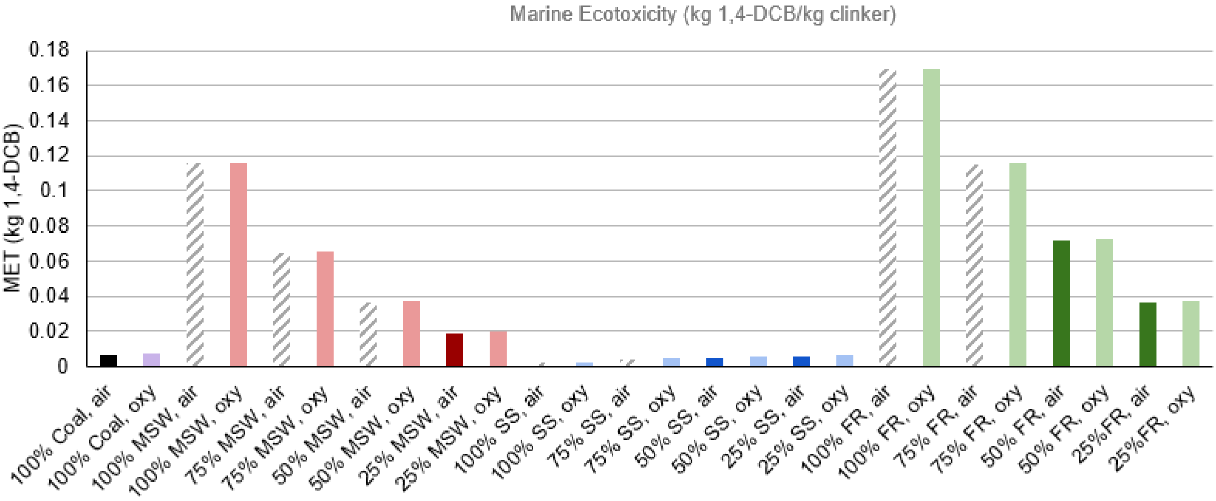

Figure 3.17: Marine ecotoxicity. (Impossible scenarios hatched in grey)

The human carcinogenic toxicity potential is displayed in figure 3.18. For combustion using 100% coal the difference between the air combustion and the oxy-fuel CCS scenario is minimal. The human carcinogenic toxicity potential for European clinker production is a bit lower than for the coal scenarios, with 0.007 kg 1.4-DCB/kg clinker (see table C.1). This difference is likely due to less use of coal per kg/clinker for the European clinker. The use of SS and FR fuel mixes appear to lower the human carcinogenic toxicity potential of cement production, with decreasing values as the share of SS and FR increases. This is reasonable as SS and FR have much lower impacts on human carcinogenic toxicity potential than coal per kg fuel, see table 2.7. The inclusion of oxy-fuel CCS show slight increases in human carcinogenic toxicity, but the difference from the air-scenarios is small. MSW has a bit lower impact on human carcinogenic toxicity potential than coal per kg fuel, but the increase in human carcinogenic toxicity potential could be explained by the much higher demand for fuel per kg clinker produced for the MSW scenarios compared to pure coal combustion.

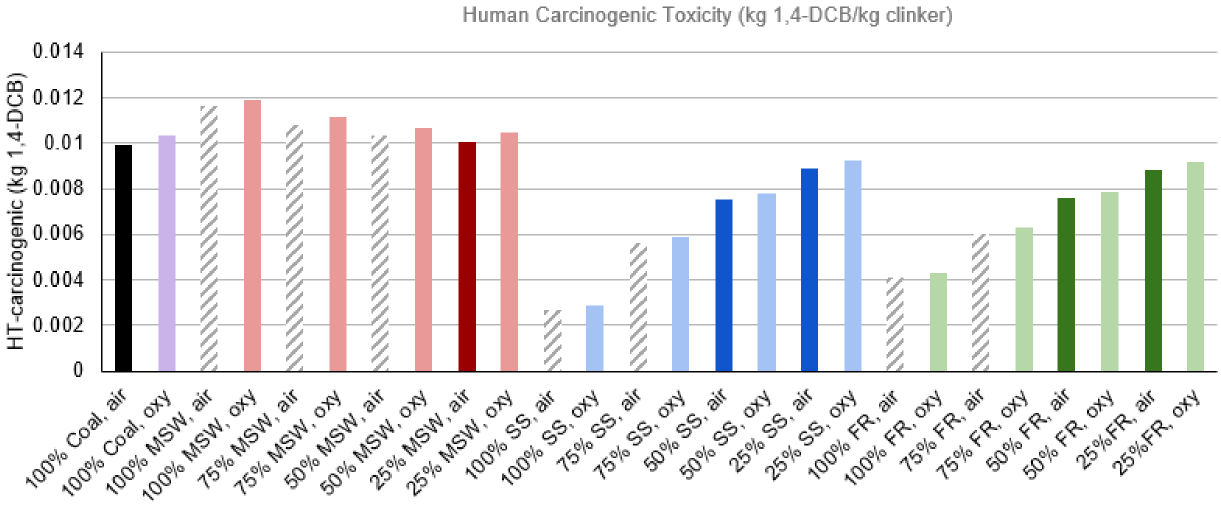

Figure 3.18: Human carcinogenic toxicity. (Impossible scenarios hatched in grey)

The human non-carcinogenic toxicity potential is displayed in figure 3.19. As a point of reference, the European clinker production has a human non-carcinogenic toxicity potential of 0.1 kg 1.4-DCB/kg clinker (see table C.1), which is close to the results for the scenarios with coal, SS and FR. The scenarios with MSW in the fuel mix stand out in figure 3.19, with increasing toxicity potentials as the share of MSW increases. Table 2.7 shows that MSW has a much larger impact on human non-carcinogenic toxicity potential per kg fuel compared to the other fuels. Oxy-fuel CCS does not appear to have any impact on human non-carcinogenic toxicity.

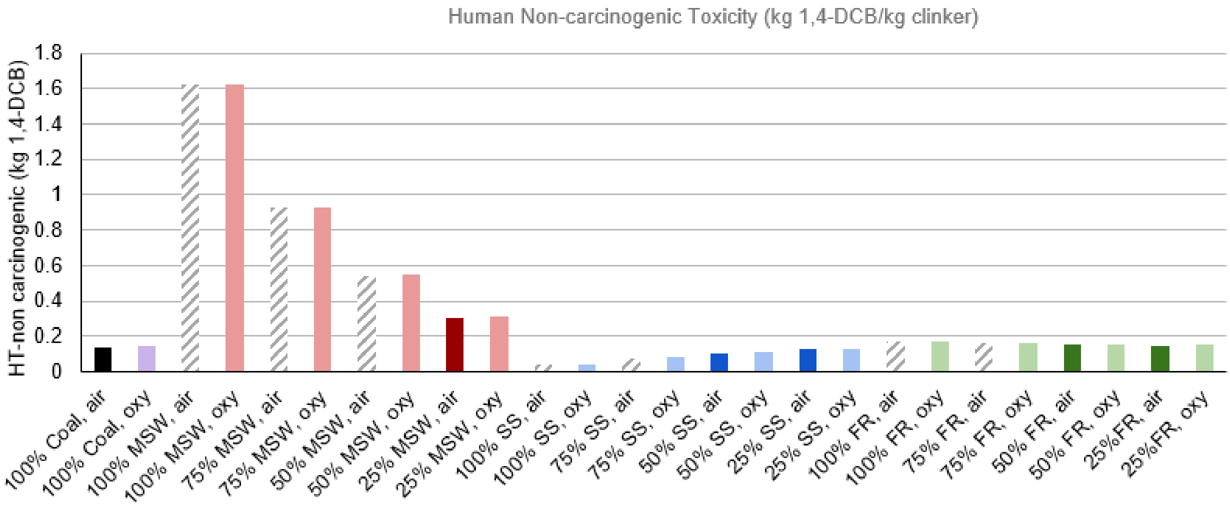

Figure 3.19: Human non-carcinogenic toxicity. (Impossible scenarios hatched in grey)

Figure 3.20 displays the land use (LU) change potential of the different scenarios. The European clinker production has a LU potential of 0.004 (see table C.1), which is close to that of the scenarios with combustion in air. The land use change potential decreases with increasing amounts of biofuels in the fuel mix, as coal has a higher impact on LU change than the biofuels (see table 2.7). Including oxy-fuel CCS appears to give a slight increase in land use change due to the increased electricity demand.

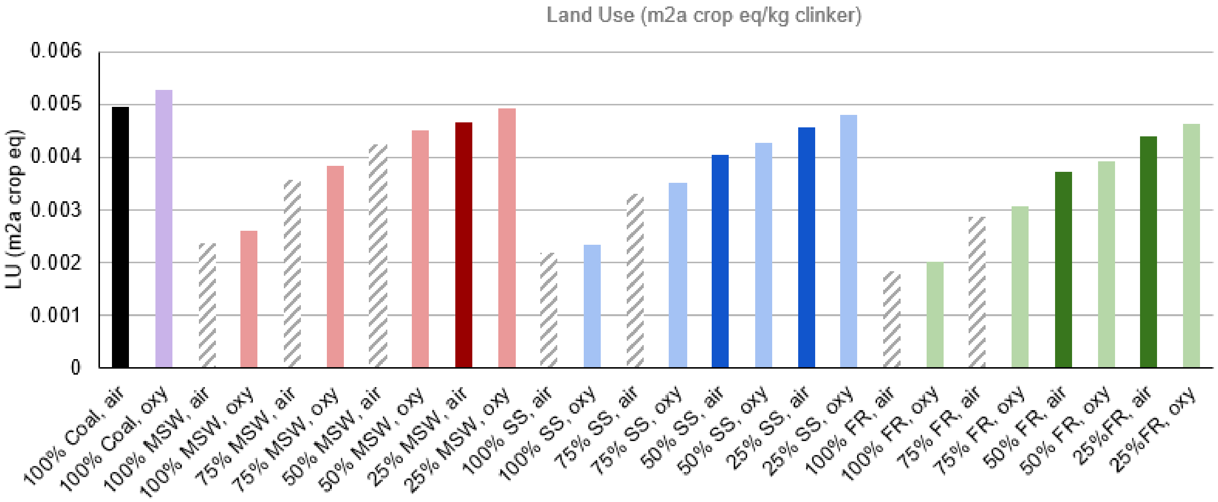

Figure 3.20: Land use change. (Impossible scenarios hatched in grey)

The mineral resource scarcity (MR) potential is displayed in figure 3.21. There appears to be relatively small differences between the different scenarios, and the MR potential of the European clinker production is similar to the results seen for all the scenarios, at 0.0049 kg Cu eq/kg clinker (see table C.1).

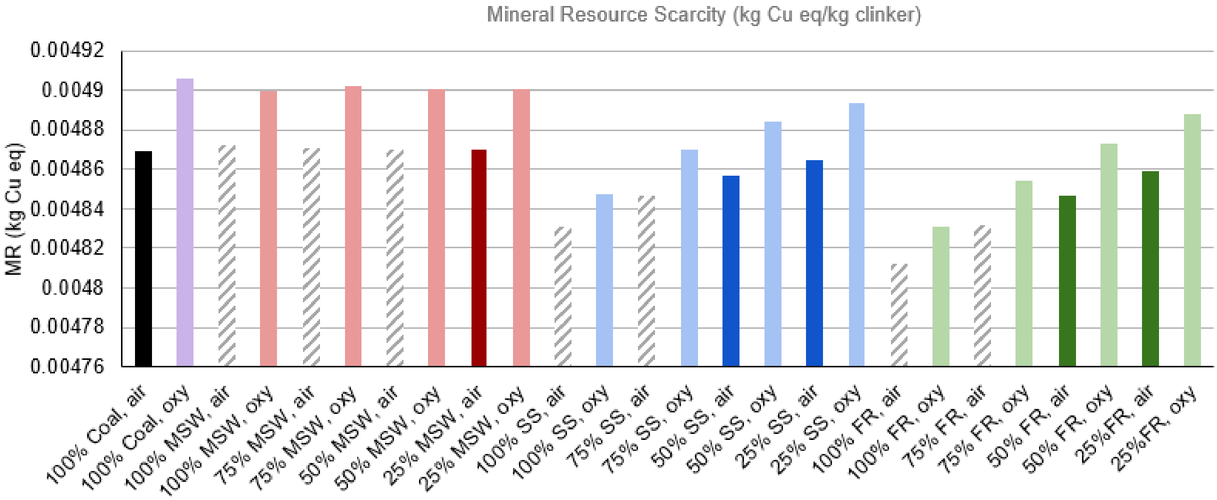

Figure 3.21: Mineral resource scarcity. (Impossible scenarios hatched in grey)

Figure 3.22 shows the fossil resource scarcity potential (FRP) of the different scenarios. The FRP for the scenarios with 100% coal is around 0.08 kg oil eq/kg clinker, which is close to that of the European clinker production which had a FRP of 0.7 kg oil-eq/kg clinker (see figure C.1). The figure shows a decrease in fossil resource scarcity as the share of biofuels in the fuel mix increases. This is logical as the use of coal, which is a fossil resource, decreases. Oxy-fuel CCS does not appear to have any significant impact on fossil resource scarcity.

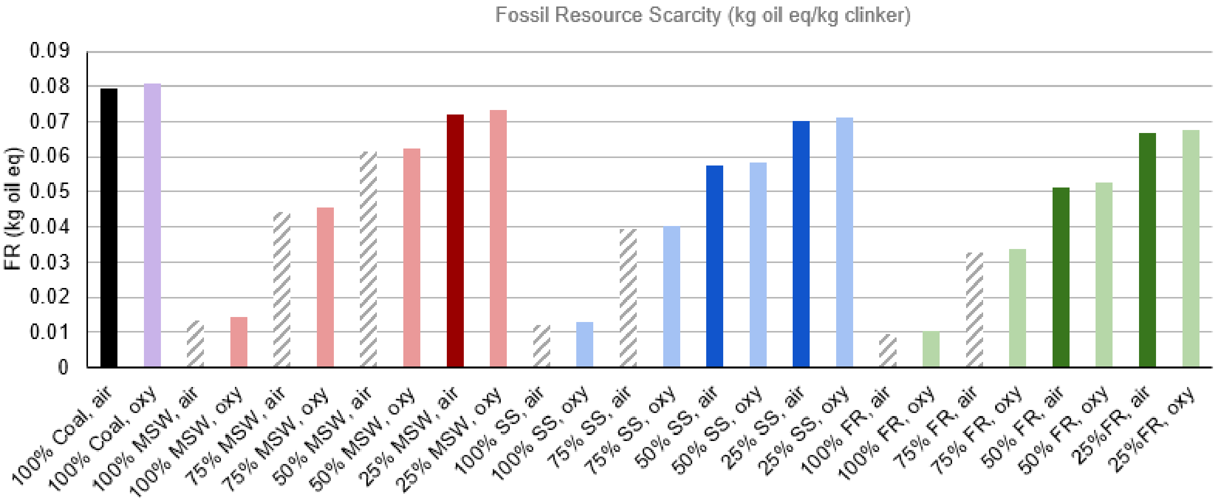

Figure 3.22: Fossil resource scarcity. (Impossible scenarios hatched in grey)

The water consumption potential (WC) is displayed in figure 3.23. The water consumption looks to be constant for all the scenarios in air, and is only slightly higher than the WC of the European clinker production at 0.002 m3/kg clinker (see table C.1). The water consumption per kg clinker for the scenarios using oxy-fuel CCS technology appears to be more than the double of the air scenarios' WC. The increase in WC for the CCS scenarios likely comes from the increased electricity demand associated to the ASU and the CPU.

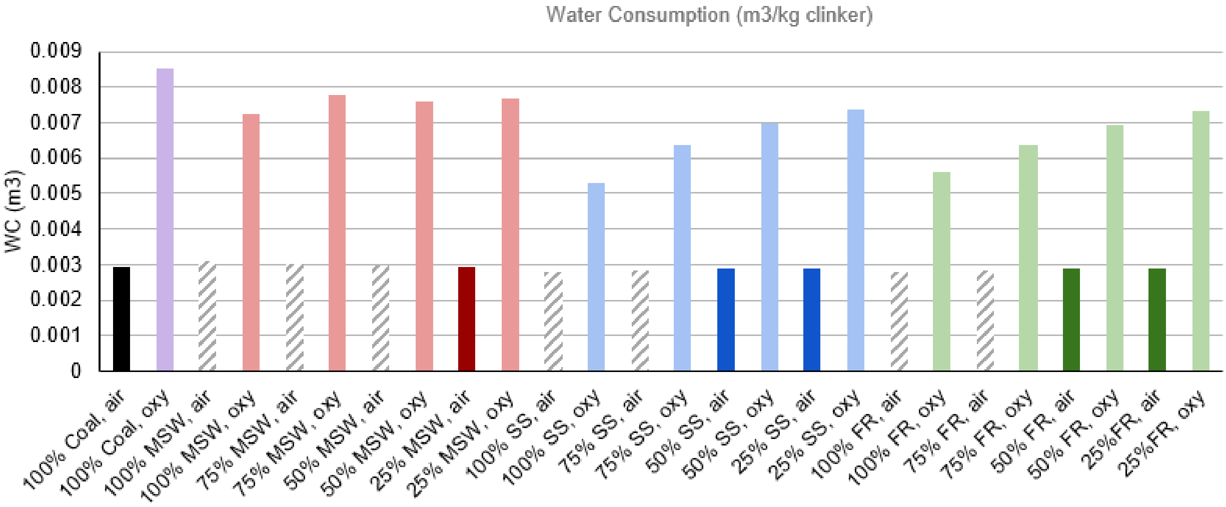

Figure 3.23: Water consumption. (Impossible scenarios hatched in grey)

3.3.1 Breakdown of impacts by subsystems

The contributions of the different subsystems to each impact category are displayed by using stacked bar charts. Figure 3.24 to 3.31 contain the breakdown results for the scenarios with 100% of one fuel type so that the impact each fuel type has on the system can be better understood. These figures do not display any quantities of environmental impacts like table 3.6 to 3.23 do, but rather how much each subsystem contributes to the total environmental impacts. Subsystem S1: Raw material processing has the same inputs for all the scenarios, while inputs and emissions from S2: kiln system and S3: Retrofit machinery operation varies for each scenario. A larger or smaller share of impacts caused by S1 for some scenarios does therefore not mean that the impacts caused by S1 varies, but rather that the impacts from S2 or S3 have changed so that the share of impacts caused by raw material processing increases or decreases.

From these charts it can be seen that the S2: Kiln system is responsible for over 90% of the GWP for all the scenarios, and that S3: Retrofit machinery operation for the oxy-fuel CCS scenarios can mitigate almost 100% of the GWP caused by the kiln system and the raw material processing. This corresponds to the large decrease seen in GWP for the oxy-fuel scenarios in figure 3.6. S2: Kiln system has a high impact on GWP due to the combustion of fuel and the calcination process which emits a lot of CO_2. S1: raw material processing consists of raw material extraction and preparation processes that uses electricity. All the processes in S1 have low impacts on GWP compared to S2. That the kiln system is the part of the cement production system with the highest CO_2 emissions is a known fact stated by IEA (2018) among others. An increase in the impacts caused by S1 would likely be seen if a European electricity mix was used for the analysis instead of a Norwegian electricity mix, as the European electricity mix has a considerably higher carbon intensity. S1 would however still have a much lower impact than S2 on GWP.

For the scenarios with 100% coal and 100% MSW (figure 3.24, 3.25, 3.28 and 3.29) S2 has an overall higher impact than S1 on most of the impact categories. This impact is likely due to the share of fossil material in both coal and MSW, which tend to have a negative impact on several impact categories.

The scenarios with SS and FR (figure 3.26, 3.27, 3.30 and 3.31) show that subsystem S1 contributes increasingly more to the total impact of most of the impact categories when the coal is substituted. This means that the impact on for example freshwater and marine eutrophication potential now mainly come from raw material extraction and electricity use as energy sources with fossil contents is no longer used.

Some of the effects oxy-fuel CCS has on the clinker production can be seen quite well in figure 3.28 to 3.31. The large decrease in GWP is clearly visualized alongside the impact the increased electricity demand has on the different impact categories.

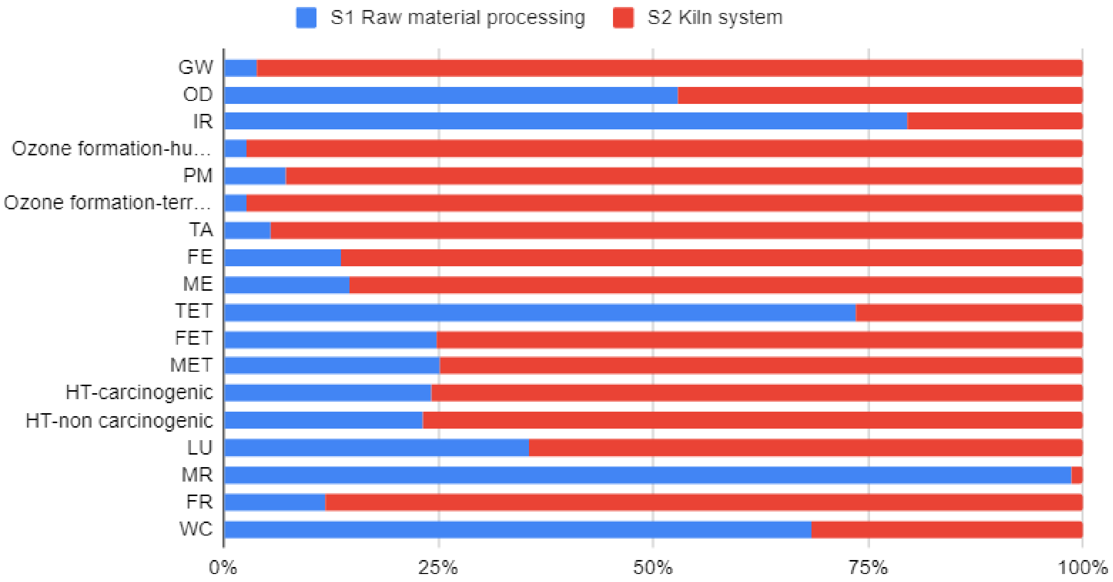

Figure 3.24: Impact contributions of each subsystem for *100% coal, air*

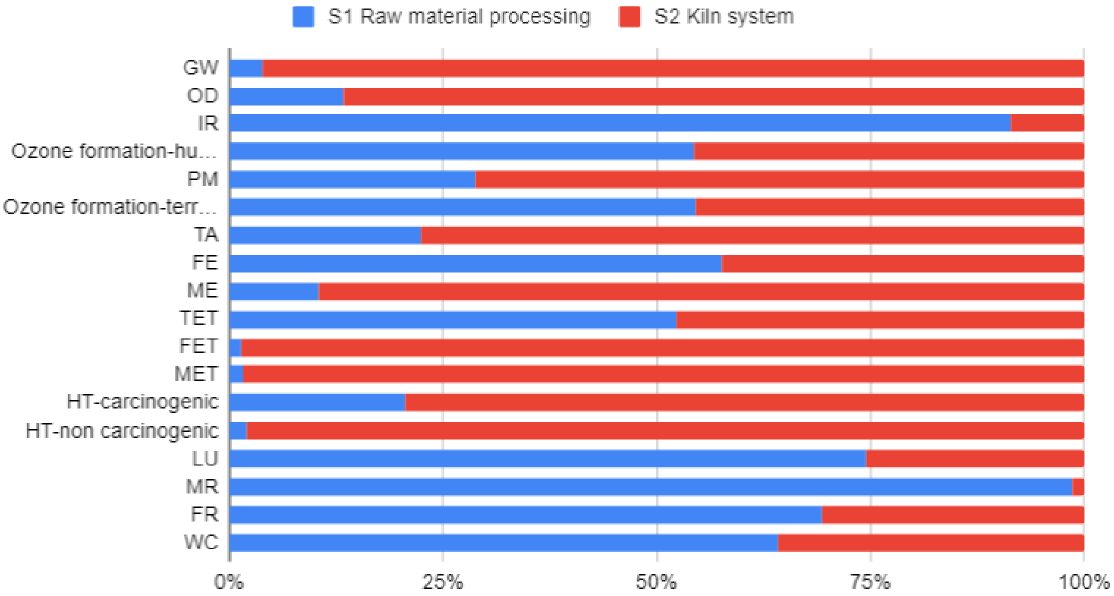

Figure 3.25: Impact contributions of each subsystem for *100% MSW, air*

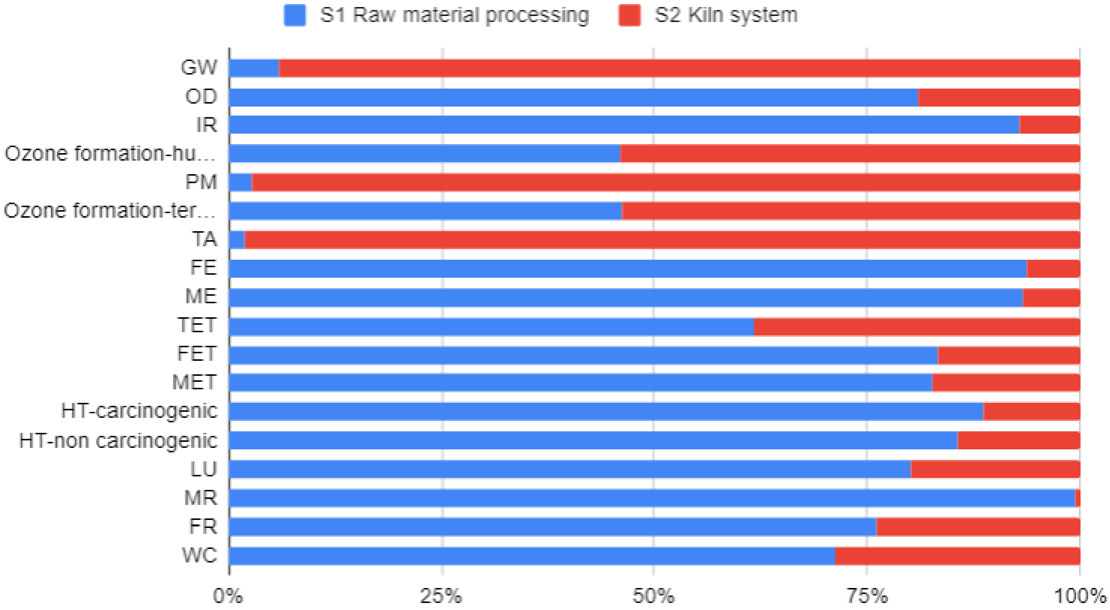

Figure 3.26: Impact contributions of each subsystem for *100% SS, air*

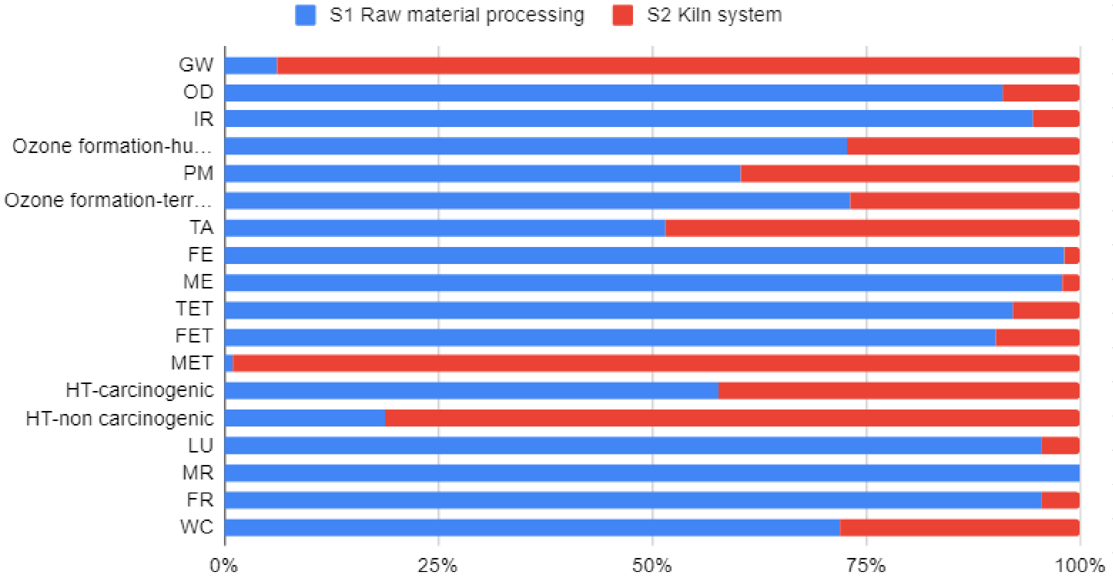

Figure 3.27: Impact contributions of each subsystem for *100% FR, air*

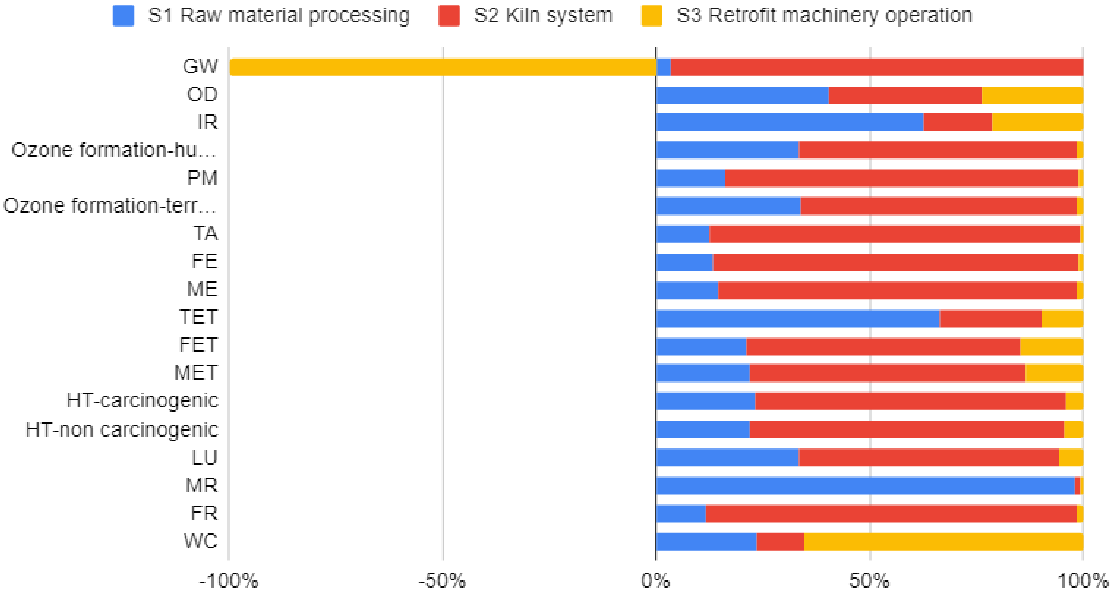

Figure 3.28: Impact contributions of each subsystem for *100% coal, oxy*

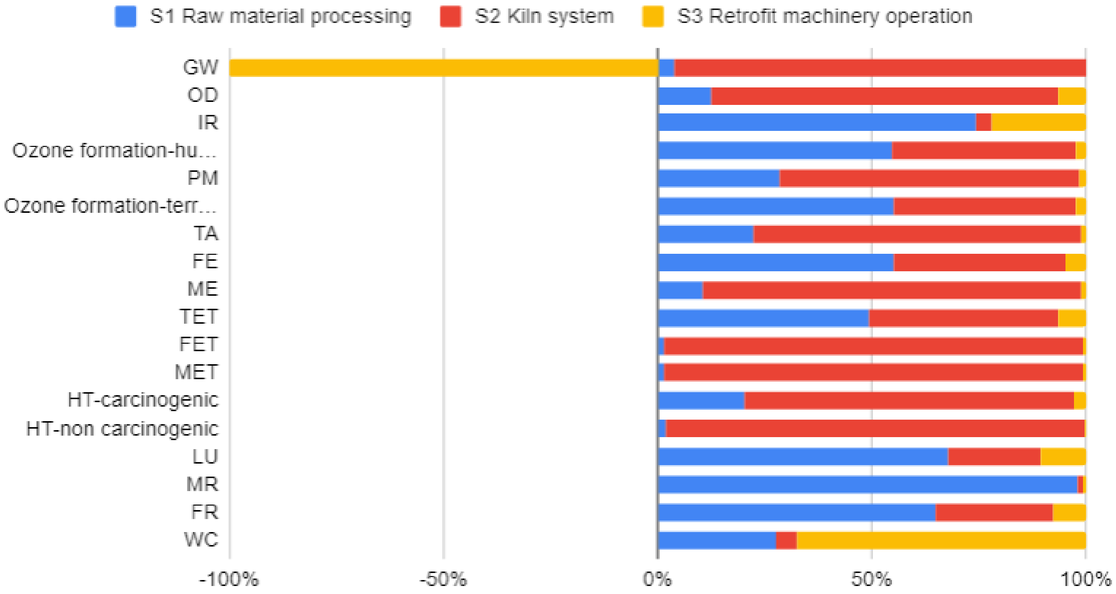

Figure 3.29: Impact contributions of each subsystem for *100% MSW, oxy*

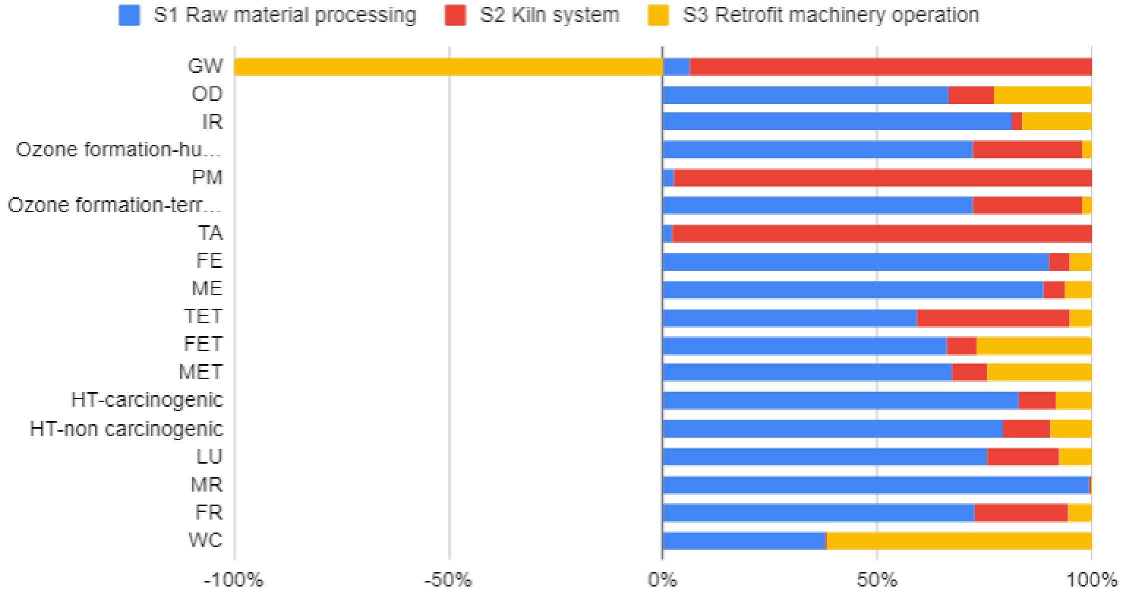

Figure 3.30: Impact contributions of each subsystem for *100% SS, oxy*

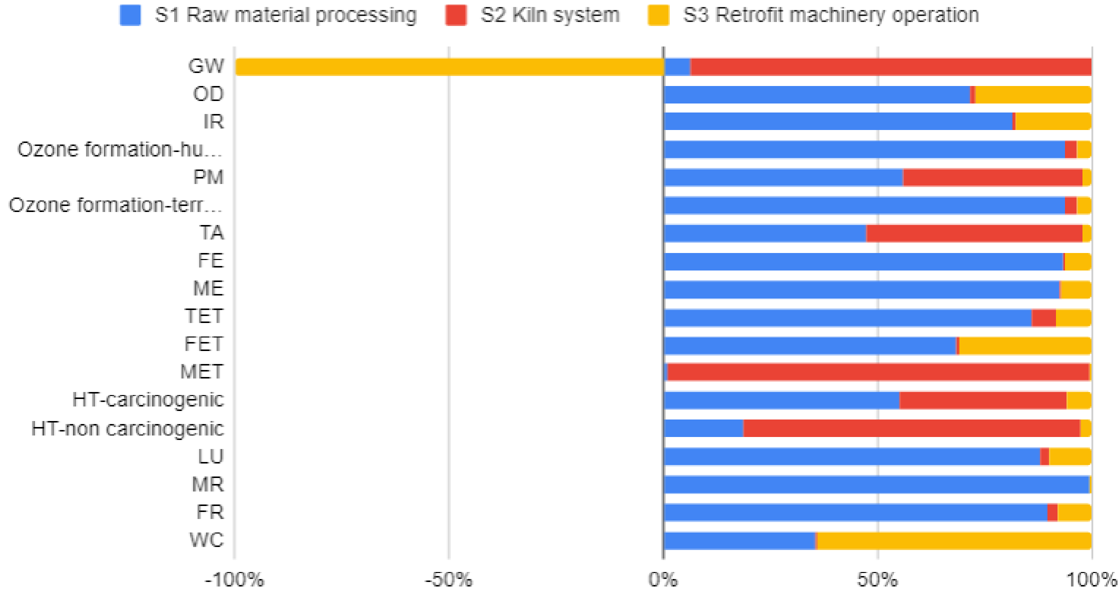

Figure 3.31: Impact contributions of each subsystem for *100% FR, oxy*

3.3.2 Review of the LCIA results

The LCIA showed that implementation of oxy-fuel CCS had a large improvement potential for the GWP of clinker production. Using oxy-fuel CCS together with fuel substitution appears to lower the GWP of clinker production so much that the clinker production can become close to carbon neutral. This is an enormous improvement compared to the GWP of the clinker made today. Although some of the improvement comes from increased shares of biofuels, most of it is due to inclusion of oxy-fuel CCS. Cement production might not be a fitting industry for achieving negative CO_2 emissions, but the carbon mitigation potential that comes with a reduction from around 0.9 kg CO_2-eq/kg clinker to around 0.0 kg CO_2-eq/kg clinker is large when the amount of clinker and cement produced each year is considered.

The implementation of oxy-fuel CCS has other co-benefits, such as decreased PM formation potential, reduction in ozone formation that impacts both human health and terrestrial ecosystems and slightly lower terrestrial acidifaction potential. There are however some negative effects associated to using biofuels and oxy-fuel CCS in cement production. The LCIA showed that the implementation of oxy-fuel CCS could give slightly higher ionizing radiation potential, stratospheric ozone depletion potential, terrestrial ecotoxicity potential, human carcinogenic toxicity potential and land use change, and could lead to a substantial increase in water consumption due to a high increase in electricity demand. In addition to this, combustion simulations in Aspen showed significantly increased emissions of carbon monoxide when oxy-fuel combustion was used. The use of MSW gave higher ozone depletion potentials, higher freshwater and marine ecotoxicity potentials and higher impacts on human non-carcinogenic toxicity. Using a fuel mix with SS gave higher emissions of fine particulate matter and higher terrestrial acidification potentials, and the use of FR as fuel gave an increased marine ecotoxicity potential. The use of fuel mixes with MSW gave lower clinker production/kg fuel (so more fuel is needed to produce 1 kg clinker), lower reductions of GWP per kg clinker due to a higher share of fossil constituents and more trade-off effects than the two other studied biofuels. Using fuel mixes with forest residues and sewage sludge does therefore look like better options for fuel substitution than municipal solid waste.

Although some environmental trade-offs are seen with the inclusion of oxy-fuel CCS and biofuels, most of the negative effects are minor compared to the large environmental benefits of large reductions in GWP. The best scenarios overall appear to be *100% FR, oxy* and *100% SS, oxy*, with a slight advantage to *100% FR, oxy* based on the environmental performance. Both of these scenarios give large reductions in GWP, have low impacts on most of the other impact categories and have only higher impacts than the other scenarios for a few of the impact categories. The FR and SS oxy-fuel scenarios with 75% biofuel shares also showed great results, with neutral global warming potentials and only small differences in the environmental impact compared to the scenarios with 100% FR or SS. This would mean that the impact caused by cement production could be lowered substantially even if using 100% biofuel for combustion in a real cement kiln would turn out to not be possible for real cement production. It is also interesting to see how much improvement that is possible to achieve with only implementing oxy-fuel CCS and not including any share of biofuels. For the scenario *100% coal, oxy* the GWP is lowered to around 1/5 of the GWP of the reference scenario, and improvements were seen for many of the other impact categories as well. Using MSW does not seem to give any substantial improvements compared to pure coal combustion in this study due to much smaller amounts of clinker being produced per kg fuel.

The results of the LCIA are based on the production of clinker, and not cement. The project thesis that this work is built on identified reduction of the clinker ratio in cement and inclusion of CCS as the mitigation options with the biggest mitigation potentials for cement production. Blended cements with low clinker ratios around 50-70% are already common practice at many cement plants, but the mitigation potential from lowering the clinker ratio worldwide is still large as many plants still uses higher clinker ratios (up to 95%). Continued work to lower the clinker ratios around the world can therefore give further improvements of the environmental impacts of cement production alongside the use of oxy-fuel CCS and biofuels.

3.4 Uncertainties and suggested improvements

There are several factors of the work done that affects the uncertainty of this study. The Aspen Plus model used to model the combustion system of clinker production is a simplified model of the complex clinker manufacturing system you find in real life. This will naturally contribute to increase the uncertainties of the results. For this study it was of interest to see what potential the use of alternative fuels and oxy-fuel CCS had to lower the environmental impacts of clinker production and for that purpose a simple model was deemed sufficient. Comparisons of the results obtained in the LCIA showed that the obtained results for the reference scenario of this study to a large degree coincided with results from other studies, such as Valderrama et al. (2012), and the results from analysis of the Ecoinvent dataset “clinker production - Europe without Switzerland” (see table C.1), which indicates that the simplified Aspen model did a decent job at simulating the combustion system. A more complex combustion model that better simulates the pre-heater, the pre-calciner and the re-circulation of flue gas can be beneficial if further work is to be done on the subject and more precise results are needed.

Another uncertainty factor of the study is the fuel information that is used in the Aspen model. There exists many different variations of both coal and the studied biofuels, which can have different moisture contents and different proximate and ultimate compositions. This will naturally affect the fuel’s heat of combustion, which in turn has an impact on the combustion process and on how much clinker can be produced per kg fuel. The results obtained for the fuels chosen for this study might not be precise for all variations of the fuels, but the study does provide a good overview of the potential environmental benefits and trade-offs associated to using biofuels in cement manufacturing.

Other uncertainties of the study are associated to the assumptions and choices made for the model. ASUs and CPUs can have varying electricity demands and the CPU can have varying CO_2 capture potential, which naturally has the potential to give different results depending on what values are chosen for the model. For this study a Norwegian electricity mix was assumed. The Norwegian electricity mix is mainly based on clean energy and has a much lower carbon intensity than European and global electricity mixes. The choice of a Norwegian electricity mix over an international mix has likely contributed to a lower impact on GWP and several other impact categories that are affected by the use of fossil energy sources. Increased emissions would likely be seen from electricity intensive parts of the system if an electricity mix with higher carbon intensity was chosen. The choice of electricity mix should be made based on where the results of the study are of interest. Norwegian electricity mix was chosen to model Norwegian cement production, and the results are therefore not necessarily representative for cement production in other parts of the world. Retrofitting the cement system to an oxy-fuel CCS system would likely come off a little worse with regards to the environmental benefits if an international electricity mix was chosen as the ASU and the CPU have high electricity demands.

This study only analysed biofuel shares of 100%, 75%, 50% and 25%, as including a larger variety of biofuel shares when three different biofuels were being studied would increase the workload a lot. The optimal share of biofuel in the fuel mix is dependent on what biofuel is being used. More biofuel shares should be analysed if a precise optimal biofuel share is needed. In this study using 100% biofuel was found to be possible for all three biofuels when oxy-fuel combustion was being used. This might not be true in real life due to uncertainties with the combustion model. 100% MSW gave a combustion temperature only slightly higher than the needed combustion temperature before any CO_2 was re-circulated. If the use of 100% MSW for clinker production is possible is therefore more uncertain than if 100% SS or 100% FR is possible, and validation of these results should be made before combustion of 100% biofuels is done in real life.

4 Conclusion

This thesis has studied the environmental benefits and potential environmental trade-off effects of using biofuels and oxy-fuel CCS in clinker production. It was of interest to see how much biofuels could be used in the fuel mix and if negative CO_2 emissions from cement manufacturing was possible.

Simulations of the combustion system in Aspen Plus showed that combustion in air limited the maximum share of biofuel in the fuel mix to around 50% for sewage sludge (SS) and forest residues (FR) and around 25% for municipal solid waste (MSW). The share of biofuels can potentially be increased up to 100% for all of the studied fuels if oxy-fuel combustion is used, with a bit higher uncertainty for MSW than for SS and FR.

The combined use of a fuel mix with high shares of biofuel and oxy-fuel CCS appears to have the potential to lower the GWP so much that clinker production becomes approximately carbon neutral. It appears to be difficult to get negative emissions from clinker and cement manufacturing, but a reduction of GWP from around 0.9 kg CO_2-eq/kg clinker to around 0.0 kg CO_2-eq/kg clinker is still a large improvement that can contribute to significantly lower CO_2 emissions from the industry sector.

The use oxy-fuel CCS also show improvements for several other impact categories, like a decrease in PM formation and reduction in ozone formation. Many of the environmental impact categories see improvements when the share of biofuels in the fuel mix is increased, e.g. ozone formation, freshwater eutrophication, land use change and fossil resource scarcity. The inclusion of oxy-fuel CCS and biofuels do however come with some negative environmental impacts as well, like increased emissions of carbon monoxide, higher water consumption, slightly higher ionizing radiation potential and slightly higher ozone depletion potential due to the use of oxy-fuel CCS. The negative effects associated to biofuel use varies based on the fuel type, but overall the number of impact categories that showed environmental improvements were significantly higher than those that showed worse impacts. Use of MSW leads to higher impacts on ozone depletion potential, freshwater- and marine ecotoxicity potential and human non-carcinogenic toxicity potential. SS use can lead to increased particulate matter formation potential and higher terrestrial acidification potentail and the use of FR can lead to increased marine ecotoxicity potential. SS and FR looks like the best biofuel choices for cement manufacturing as

MSW contributed to more negative environmental impacts, can produce less clinker per kg fuel and because MSW is less likely to be able to replace as much coal as SS and FR in the fuel mix. Of the 26 different scenarios that were studied *100% FR, oxy* and *100% SS, oxy* appear to be the scenarios that give the overall lowest environmental impact, but *75% FR, oxy* and *75% SS, oxy* are also very good alternatives if a share of 100% biofuel should prove to not be possible in real life due to uncertainties of this study.

Before the use of biofuels and oxy-fuel CCS is implemented in real cement factories the negative environmental impacts should be studied further. Results from this thesis point to a very large climate change mitigation potential due to lower CO_2 emissions, but more research can be beneficial to ensure that the environmental benefits outweigh the negative trade-off effects. A more comprehensive model of the combustion system could also be beneficial if it is of interest to lower the uncertainties of the study.

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A Model input and calculations

Table A.1: Fuel properties

		Coal[1]	**MSW**[2]	**Sewage sludge**[3]	**Forest residues**[4]
PROXANAL	FC	56.18	77.3*	5.35	13.62
	VM	34.23	15.1	50.25	82.41
	ASH	9.59	7.6	44.4	3.97
ULTANAL	ASH	9.59	7.6	44.4	3.97
	C	71.91	52.19*	27.6*	50.31
	H	4.65	6.4	4.3	4.59
	N	1.23	1.9	2.1	1.03
	Cl	2.71*	0.73	0	0.04*
	S	0.35	0.18	3.8	0.11
	O	9.56	31	17.8	39.95
SULFANAL**	Pyritic	0.162	0.083	1.75	0.051
	Sulfate	0.027	0.014	0.3	0.008
	Organic	0.162	0.083	1.75	0.051
MOISTURE	%	3	49.5	46.4	48.91
	FLUX WATER (kg/h)	300	4950	4640	4891
	FLUX SOLIDS (kg/h)	9700	5050	5360	5109
	FLUX TOTAL (kg/h)	10000	10000	10000	10000
SUM TOTAL (verification)	**PROXANAL**	100	100	100	100
	ULTANAL	100	100	100	100
	SULFANAL	0.35	0.18	3.8	0.11
Heat of combustion	**BTU/lb (dry basis)**	12954.5	4900	6342	8672.1
	MJ/kg HHV (dry basis)	30.13	11.4	14.75	20.17

* Value is slightly altered to get the total to equal 100%

** Sulfate analysis was not available for the specific chosen fuels, so the sulfanal compositions are calculated based on the sulfate analysis for wet coal (Aspentech, 2004), by assuming the ratio of pyritic, sulfate and organic sulphur to be the same.

[1]Phyllis2 (a), [2]Hla and Roberts (2015),[3]He et al. (2013), [4]Phyllis2 (b)

Table A.2: CO2% in flue gas for various air/fuel ratios

For air with 95% O2/5% N2	**COAL**	**MSW**	**SS**	**FR**
kg air/ kg biomass	**Flue gas CO2%**	**Flue gas CO2%**	**Flue gas CO2%**	**Flue gas CO2%**
0.2	7.8	17.2	12.8	13.4
0.4	0.8	42	26.1	27.2
0.5	0.1	61.7	27.4	29.6
0.6	0	57	27.9	30.7
0.7	0	55.5	**28.1**	31.3
0.8	0	**64.1**	28.1	31.8
0.9	2.5	63.7	27.9	32
1	6.8	61.1	27.7	32.2
1.2	14.5	55.6	27	**32.3**
1.3	16.7	53	26.5	32.2
1.5	19.3	48.1	25.5	32
2	22.8	38.8	22.1	30.7
3	26.5	27.8	16.1	25.8
4	28.2	21.6	12.5	20.7
5	**28.8**	17.7	10.1	17
6	28.6	15	5.8	14.4

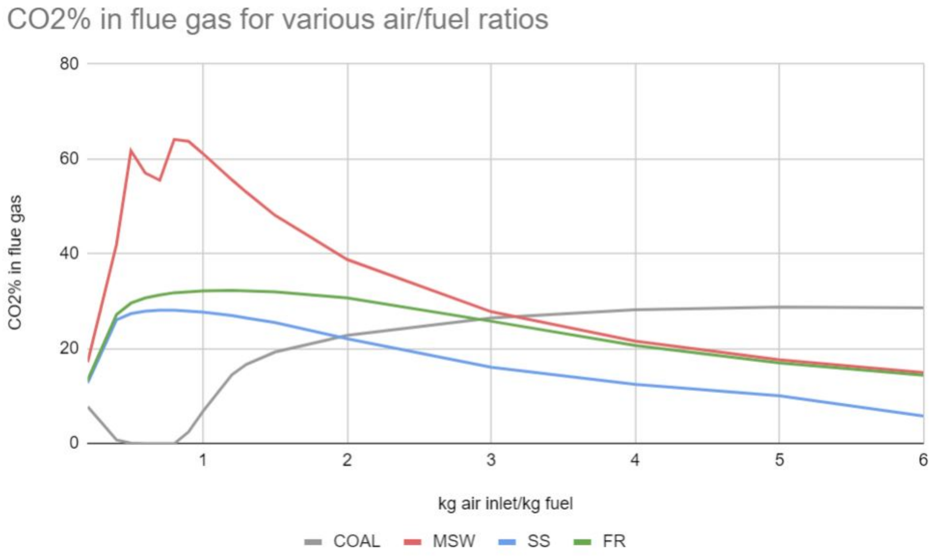

Figure A.1: Graph of CO_2% in flue gas for various air/fuel ratios

Table A.3: Mass flux calculations for raw meal components, clinker components and calcination CO2 emissions for the 100% coal scenario.

	100% Coal
Heat of combustion, MJ/kg fuel	30.13
Total heat (MJ/10000 kg fuel)	301300.00
Consumed raw meal (kg/h)	136954.55
Mass flux, raw meal components (kg/h)	
CACO3	108659.74
SIO2	19118.85
AL2O3	3957.99
FE2O3	2643.22
MGO	917.60
SO3	986.07
K20	671.08
Total mass (kg raw meal/h)	**136954.55**
Mass flux, clinker components (kg/h)	
CaO	2739.11
(CaO)2*SiO2	14765.96
(CaO)3*Al2O3	6016.38
(CaO)4*Al2O3*Fe2O3	8043.39
(CaO)3*SiO2	53216.46
MgO	917.60
Total mass (kg clinker/h)	**85698.90**
Calcination CO2 emissions	
kg CO2/hr	46822.94
kg CO2/kg Clinker	0.55

Table A.4: Mass flux calculations for raw meal components, clinker components and calcination CO2 emissions for the MSW scenarios.

	100% MSW	75% MSW	50% MSW	25% MSW
Heat of combustion (MJ/kg fuel)	11.40	16.08	20.76	25.45
Total heat (MJ/10000 kg fuel = MJ/h)	113966.05	160799.54	207633.02	254466.51
Consumed raw meal (kg/h)	51802.75	73090.70	94378.65	115666.60

Mass flux, raw meal components (kg/h)				
CACO3	72740.35	81720.20	90700.05	99679.89
SIO2	12798.78	14378.80	15958.82	17538.84
AL2O3	2649.60	2976.70	3303.80	3630.89
FE2O3	1769.46	1987.90	2206.34	2424.78
MGO	614.27	690.10	765.93	841.76
SO3	660.11	741.60	823.09	904.58
K20	449.24	504.70	560.16	615.62
Total mass (kg raw meal/h)	**91681.82**	**103000.00**	**114318.18**	**125636.36**

Mass flux, clinker components (kg/h)				
CaO	1036.05	1461.81	1887.57	2313.33
(CaO)2*SiO2	5585.15	7880.32	10175.50	12470.67
(CaO)3*Al2O3	2275.66	3210.83	4146.00	5081.16
(CaO)4*Al2O3*Fe2O3	3042.37	4292.61	5542.85	6793.09
(CaO)3*SiO2	20128.86	28400.66	36672.45	44944.25
MgO	347.08	489.71	632.34	774.97
Total mass (kg clinker/h)	**32415.17**	**45735.94**	**59056.71**	**72377.47**

Calcination CO2 emissions				
kg CO2/hr	17710.54	24988.55	32266.56	39544.57
kg CO2/kg Clinker	0.55	0.55	0.55	0.55

Table A.5: Mass flux calculations for raw meal components, clinker components and calcination CO2 emissions for the SS scenarios.

	100% SS	**75% SS**	**50% SS**	**25% SS**
Heat of combustion (MJ/kg fuel)	14.75	18.60	22.44	26.29
Total heat (MJ/10000 kg fuel = MJ/h)	147504.63	185953.47	224402.31	262851.16
Consumed raw meal (kg/h)	67047.56	84524.31	102001.05	119477.80

Mass flux, raw meal components (kg/h)				
CACO3	53195.53	67061.58	80927.63	94793.69
SIO2	9359.84	11799.59	14239.35	16679.10
AL2O3	1937.67	2442.75	2947.83	3452.91
FE2O3	1294.02	1631.32	1968.62	2305.92
MGO	449.22	566.31	683.41	800.50
SO3	482.74	608.58	734.41	860.24
K20	328.53	414.17	499.81	585.44
Total mass (kg raw meal/h)	**67047.56**	**84524.31**	**102001.05**	**119477.80**

Mass flux, clinker components (kg/h)				
CaO	1340.95	1690.49	2040.02	2389.56
(CaO)2*SiO2	7228.78	9113.05	10997.31	12881.58
(CaO)3*Al2O3	2945.36	3713.10	4480.85	5248.59
(CaO)4*Al2O3*Fe2O3	3937.70	4964.10	5990.51	7016.92
(CaO)3*SiO2	26052.49	32843.38	39634.27	46425.17
MgO	449.22	566.31	683.41	800.50
Total mass (kg clinker/h)	**41954.49**	**52890.43**	**63826.37**	**74762.31**

Calcination CO2 emissions				
kg CO2/hr	22922.50	28897.52	34872.54	40847.56
kg CO2/kg Clinker	0.55	0.55	0.55	0.55

Table A.6: Mass flux calculations for raw meal components, clinker components and calcination CO2 emissions for the FR scenarios.

	100% FR	**75% FR**	**50% FR**	**25% FR**
Heat of combustion (MJ/kg fuel)	20.17	22.66	25.15	27.64
Total heat (MJ/10000 kg fuel = MJ/h)	201700.00	226600.00	251500.00	276400.00
Consumed raw meal (kg/h)	91681.82	103000.00	114318.18	125636.36

Mass flux, raw meal components (kg/h)				
CACO3	72740.35	81720.20	90700.05	99679.89
SIO2	12798.78	14378.80	15958.82	17538.84
AL2O3	2649.60	2976.70	3303.80	3630.89
FE2O3	1769.46	1987.90	2206.34	2424.78
MGO	614.27	690.10	765.93	841.76
SO3	660.11	741.60	823.09	904.58
K20	449.24	504.70	560.16	615.62
Total mass (kg raw meal/h)	**91681.82**	**103000.00**	**114318.18**	**125636.36**

Mass flux, clinker components (kg/h)				
CaO	1833.64	2060.00	2286.36	2512.73
(CaO)2*SiO2	9884.74	11105.02	12325.29	13545.57
(CaO)3*Al2O3	4027.53	4524.73	5021.93	5519.13
(CaO)4*Al2O3*Fe2O3	5384.46	6049.18	6713.90	7378.61
(CaO)3*SiO2	35624.56	40022.43	44420.31	48818.18
MgO	614.27	690.10	765.93	841.76
Total mass (kg clinker/h)	**57369.19**	**64451.46**	**71533.72**	**78615.99**

Calcination CO2 emissions				
kg CO2/hr	31344.56	35214.07	39083.57	42953.08
kg CO2/kg Clinker	0.55	0.55	0.55	0.55

Table A.7: Biogenic and fossil CO2 from combustion (kg/h) for each scenario

	100% Coal, air			
Biogenic CO2 (kg/h)	0			
Fossil CO2 (kg/h)	22536.6			
Total combustion CO2 (kg/h)	22536.6			
	100% MSW, air	**75% MSW, air**	**50% MSW, air**	**25% MSW, air**
Biogenic CO2 (kg/h)	5182.9	3887.2	2591.5	1295.7
Fossil CO2 (kg/h)	4596.2	9356.2	13566.4	18051.5
Total combustion CO2 (kg/h)	9779.1	12968.4	16157.8	19347.2
	100% SS, air	**75% SS, air**	**50% SS, air**	**25% SS, air**
Biogenic CO2 (kg/h)	5427.5	4070.6	2713.8	1356.9
Fossil CO2 (kg/h)	0	5634.1	11268.3	16902.4
Total combustion CO2 (kg/h)	5427.5	9704.8	13982.1	18259.3
	100% FR, air	**75% FR, air**	**50% FR, air**	**25% FR, air**
Biogenic CO2 (kg/h)	7150.6	5362.9	3575.3	1787.6
Fossil CO2 (kg/h)	0	5634.1	11268.3	16902.4
Total combustion CO2 (kg/h)	7150.6	10997.1	14843.6	18690.1
	100% Coal, oxy			
Biogenic CO2 (kg/h)	0			
Fossil CO2 (kg/h)	38134.9			
Total combustion CO2 (kg/h)	38134.9			
	100% MSW, oxy	**75% MSW, oxy***	**50% MSW, oxy***	**25% MSW, oxy***
Biogenic CO2 (kg/h)	4124.4	3093.3	2062.2	1031.1
Fossil CO2 (kg/h)	3657.5	12513.6	22177.2	30274.1
Total combustion CO2 (kg/h)	7781.8	15606.9	24239.4	31305.2
	100% SS, oxy	**75% SS, oxy***	**50% SS, oxy***	**25% SS, oxy***
Biogenic CO2 (kg/h)	4057.7	3043.3	2028.9	1014.4
Fossil CO2 (kg/h)	0	10191.3	19567.2	28615.2
Total combustion CO2 (kg/h)	4057.7	13234.6	21596	29629.6
	100% FR, oxy	**75% FR, oxy***	**50% FR, oxy***	**25% FR, oxy***
Biogenic CO2 (kg/h)	9371.2	7028.4	4685.6	2342.8
Fossil CO2 (kg/h)	0	10388	19880.7	28892.9
Total combustion CO2 (kg/h)	9371.2	17416.4	24566.3	31235.7

*calculated total CO2 (kg/h) was slightly lower than the actual total CO2 from combustion for these scenarios as kg CO2/kg fuel is not constant due to varying FGR rates for each scenario. The calculated total CO2 was adjusted to equal the actual total by increasing the amount of fossil CO2.

B Life Cycle Inventory

Table B.1: LCI S1: raw material processing. Same for all scenarios.

S1 Raw material processing	Name in SimaPro	Value	Unit/FU
Ammonia	Ammonia, liquid {RER}— market for — Cut-off, S	0.000908	kg/kg clinker
Bauxite	Bauxite, without water {GLO}— market for bauxite — Cut-off, S	0.00012	kg/kg clinker
Calcareous marl	Calcareous marl {GLO}— market for — Cut-off, S	0.466	kg/kg clinker
Clay	Clay {RoW}— market for clay — Cut-off, S	0.331	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0306	kWh/kg clinker
Hydrated lime	Lime, hydrated, loose weight {RoW}— market for lime, hydrated, loose weight — Cut-off, S	0.00392	kg/kg clinker
Limestone	Lime {RER}— market for lime — Cut-off, S	0.841	kg/kg clinker
Sand	Sand {GLO}— market for — Cut-off, S	0.00926	kg/kg clinker

Table B.2: LCI 100% coal, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.1167	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.049	kg/kg clinker
O2	oxygen	0.009	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	0.805	kg/kg clinker
NO	nitrogen monoxide	0.004	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.000	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.809	kg/kg clinker
CO	carbon monoxide	0.022	kg/kg clinker

Table B.3: LCI 100% MSW, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.3085	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.107	kg/kg clinker
O2	oxygen	0.396	kg/kg clinker
SO2	sulfur dioxide	0.000	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	2.130	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.001	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.001	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.160	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.688	kg/kg clinker
CO	carbon monoxide	0.000	kg/kg clinker

Table B.4: LCI 75% MSW, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.05466160536	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.1639848161	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.080	kg/kg clinker
O2	oxygen	0.213	kg/kg clinker
SO2	sulfur dioxide	0.000	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.510	kg/kg clinker
NO	nitrogen monoxide	0.001	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.002	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.085	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.745	kg/kg clinker
CO	carbon monoxide	0.007	kg/kg clinker

Table B.5: LCI 50% MSW, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.08466439143	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.08466439143	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.065	kg/kg clinker
O2	oxygen	0.115	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.169	kg/kg clinker
NO	nitrogen monoxide	0.003	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.044	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.776	kg/kg clinker
CO	carbon monoxide	0.016	kg/kg clinker

Table B.6: LCI 25% MSW, air

S2 Kiln system	Name in SimaPro	Value	Unit/FU
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.1036234039	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.03454113464	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.055	kg/kg clinker
O2	oxygen	0.052	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	0.954	kg/kg clinker
NO	nitrogen monoxide	0.003	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.018	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.796	kg/kg clinker
CO	carbon monoxide	0.020	kg/kg clinker

Table B.7: LCI 100% SS, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0	kg/kg clinker
SS	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.2383534905	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.063	kg/kg clinker
O2	oxygen	0.379	kg/kg clinker
SO2	sulfur dioxide	0.006	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.648	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.004	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.000	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.129	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.546	kg/kg clinker
CO	carbon monoxide	0.000	kg/kg clinker

Table B.8: LCI 75% SS, air

S2 Kiln system	Name in SimaPro	Value	Unit/FU
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.04726752736	kg/kg clinker
SS	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.1418025821	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.057	kg/kg clinker
O2	oxygen	0.229	kg/kg clinker
SO2	sulfur dioxide	0.004	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.307	kg/kg clinker
NO	nitrogen monoxide	0.001	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.003	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.001	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.077	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.653	kg/kg clinker
CO	carbon monoxide	0.009	kg/kg clinker

Table B.9: LCI 50% SS, air

S2 Kiln system	Name in SimaPro	Value	Unit/FU
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.07833752377	kg/kg clinker
SS	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.07833752377	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.053	kg/kg clinker
O2	oxygen	0.131	kg/kg clinker
SO2	sulfur dioxide	0.003	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.082	kg/kg clinker
NO	nitrogen monoxide	0.002	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.001	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.002	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.043	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.723	kg/kg clinker
CO	carbon monoxide	0.015	kg/kg clinker

Table B.10: LCI 25% SS, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.1003179243	kg/kg clinker
SS	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.03343930809	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.051	kg/kg clinker
O2	oxygen	0.061	kg/kg clinker
SO2	sulfur dioxide	0.002	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	0.924	kg/kg clinker
NO	nitrogen monoxide	0.003	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.001	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.018	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.772	kg/kg clinker
CO	carbon monoxide	0.019	kg/kg clinker

Table B.11: LCI 100% FR, air

S2 Kiln system	Name in SimaPro	Value	Unit/FU
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0	kg/kg clinker
FR	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.1743095852	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.035	kg/kg clinker
O2	oxygen	0.277	kg/kg clinker
SO2	sulfur dioxide	0.000	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.204	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.000	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.125	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.546	kg/kg clinker
CO	carbon monoxide	0.000	kg/kg clinker

Table B.12: LCI 75% FR, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.03878888277	kg/kg clinker
FR	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.1163666483	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.040	kg/kg clinker
O2	oxygen	0.188	kg/kg clinker
SO2	sulfur dioxide	0.000	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	1.072	kg/kg clinker
NO	nitrogen monoxide	0.001	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.001	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.083	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.634	kg/kg clinker
CO	carbon monoxide	0.007	kg/kg clinker

Table B.13: LCI 50% FR, air

S2 Kiln system	Name in SimaPro	Value	Unit/FU
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.06989710406	kg/kg clinker
FR	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.06989710406	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.043	kg/kg clinker
O2	oxygen	0.117	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	0.965	kg/kg clinker
NO	nitrogen monoxide	0.002	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.002	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.050	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.704	kg/kg clinker
CO	carbon monoxide	0.013	kg/kg clinker

Table B.14: LCI 25% FR, air

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.09540044322	kg/kg clinker
FR	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.03180014774	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.046	kg/kg clinker
O2	oxygen	0.058	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	nitrogen, atmospheric	0.878	kg/kg clinker
NO	nitrogen monoxide	0.003	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.023	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.761	kg/kg clinker
CO	carbon monoxide	0.018	kg/kg clinker

Table B.15: LCI 100% coal, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.1167	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.043	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.022	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.000	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.991	kg/kg clinker
CO	carbon monoxide	0.175	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.04	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.16	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.95	kg/kg clinker

Table B.16: LCI 100% MSW, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.3085	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.098	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.011	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.001	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.127	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.659	kg/kg clinker
CO	carbon monoxide	0.056	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.05	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.12	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.75	kg/kg clinker

Table B.17: LCI 75% MSW, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0547	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.1640	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.078	kg/kg clinker
O2	oxygen	0.047	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.016	kg/kg clinker
NO	nitrogen monoxide	0.002	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.002	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.023	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.068	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.815	kg/kg clinker
CO	carbon monoxide	0.030	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.05	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.14	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.85	kg/kg clinker

Table B.18: LCI 50% MSW, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0847	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.0847	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.063	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.019	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.000	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.019	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.035	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.900	kg/kg clinker
CO	carbon monoxide	0.098	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.04	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.15	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.92	kg/kg clinker

Table B.19: LCI 25% MSW, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.1036	kg/kg clinker
MSW	Municipal solid waste {NO}— market for municipal solid waste — Cut-off, S	0.0345	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.051	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.021	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.008	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.014	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.954	kg/kg clinker
CO	carbon monoxide	0.141	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.04	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.16	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.94	kg/kg clinker

Table B.20: LCI 100% SS, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0	kg/kg clinker
Sewage sludge	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.2384	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.045	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.010	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.009	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.002	kg/kg clinker
HCL	hydrogen chloride	0.000	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.097	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.546	kg/kg clinker
CO	carbon monoxide	0.090	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.01	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.10	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.62	kg/kg clinker

Table B.21: LCI 75% SS, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0473	kg/kg clinker
Sewage sludge	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.1418	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.043	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.006	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.014	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.002	kg/kg clinker
HCL	hydrogen chloride	0.001	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.058	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.739	kg/kg clinker
CO	carbon monoxide	0.113	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.03	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.13	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.76	kg/kg clinker

Table B.22: LCI 50% SS, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0783	kg/kg clinker
Sewage sludge	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.0783	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.042	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.004	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.018	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.002	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.032	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.853	kg/kg clinker
CO	carbon monoxide	0.141	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.03	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.14	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.85	kg/kg clinker

Table B.23: LCI 25% SS, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.1003	kg/kg clinker
Sewage sludge	Sewage sludge, dried {RoW}— market for sewage sludge, dried — Cut-off, S	0.0334	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.042	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.002	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.020	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.014	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.929	kg/kg clinker
CO	carbon monoxide	0.164	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.03	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.15	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.90	kg/kg clinker

Table B.24: LCI 100% FR, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0	kg/kg clinker
Forest residues	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.1743	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.037	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.000	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.008	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.000	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.163	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.546	kg/kg clinker
CO	carbon monoxide	0.095	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.01	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.11	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.68	kg/kg clinker

Table B.25: LCI 75% FR, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0388	kg/kg clinker
Forest residues	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.1164	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.035	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.000	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.013	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.001	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.109	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.708	kg/kg clinker
CO	carbon monoxide	0.097	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.02	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.13	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.78	kg/kg clinker

Table B.26: LCI 50% FR, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0699	kg/kg clinker
Forest residues	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.0699	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.038	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.016	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.002	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.066	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.824	kg/kg clinker
CO	carbon monoxide	0.125	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.03	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.14	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.85	kg/kg clinker

Table B.27: LCI 25% FR, oxy

S2 Kiln system	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Coal	Hard coal {RoW}— market for — Cut-off, S	0.0954	kg/kg clinker
Forest residues	Waste wood, post-consumer {GLO}— market for — Cut-off, S	0.0318	kg/kg clinker
Electricity	Electricity, medium voltage {NO}— market for — Cut-off, S	0.0274	kWh/kg clinker
Emissions to air			
H20	water	0.041	kg/kg clinker
O2	oxygen	0.000	kg/kg clinker
SO2	sulfur dioxide	0.001	kg/kg clinker
NO2	nitrogen dioxide	0.000	kg/kg clinker
N2	ninotrogen, atmospheric	0.019	kg/kg clinker
NO	nitrogen monoxide	0.000	kg/kg clinker
S	sulfur	0.000	kg/kg clinker
SO3	sulfur trioxide	0.000	kg/kg clinker
H2	hydrogen	0.001	kg/kg clinker
HCL	hydrogen chloride	0.003	kg/kg clinker
CL2	chlorine	0.000	kg/kg clinker
C	carbon	0.000	kg/kg clinker
CO2, biogenic	carbon dioxide, biogenic	0.030	kg/kg clinker
CO2, fossil	carbon dioxide, fossil	0.914	kg/kg clinker
CO	carbon monoxide	0.154	kg/kg clinker
S3 Retrofit machinery operation	**Name in SimaPro**	**Value**	**Unit/FU**
Input			
Electricity, ASU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.03	kWh/kg clinker
Electricity, CPU	Electricity, medium voltage {NO}— market for — Cut-off, S	0.15	kWh/kg clinker
Emissions to air			
CO2, fossil	carbon dioxide, fossil	-0.91	kg/kg clinker

C Reference data

Table C.1: Results from LCIA of existing European clinker production. Ecoinvent dataset ”clinker production - Europe without Switzerland” analyzed in Simapro using the ReCiPe midpoint (H) method.

Impact category	**Unit**	**Value**
Global warming	kg CO2 eq	0.93350388
Stratospheric ozone depletion	kg CFC11 eq	0.000000066756262
Ionizing radiation	kBq Co-60 eq	0.021600218
Ozone formation, Human health	kg NOx eq	0.0014476707
Fine particulate matter formation	kg PM2.5 eq	0.00046634569
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.0014615284
Terrestrial acidification	kg SO2 eq	0.0013835585
Freshwater eutrophication	kg P eq	0.000082690852
Marine eutrophication	kg N eq	0.0000054893862
Terrestrial ecotoxicity	kg 1,4-DCB	0.31289127
Freshwater ecotoxicity	kg 1,4-DCB	0.0034689334
Marine ecotoxicity	kg 1,4-DCB	0.0049132201
Human carcinogenic toxicity	kg 1,4-DCB	0.0068525389
Human non-carcinogenic toxicity	kg 1,4-DCB	0.10163484
Land use	m2a crop eq	0.0038530602
Mineral resource scarcity	kg Cu eq	0.004928113
Fossil resource scarcity	kg oil eq	0.070126507
Water consumption	m3	0.0020521326

Solveig Heggvoll

Life-Cycle Assessment of alternative bio-fuelled cement plants for negative emissions

NTNU
Norwegian University of
Science and Technology