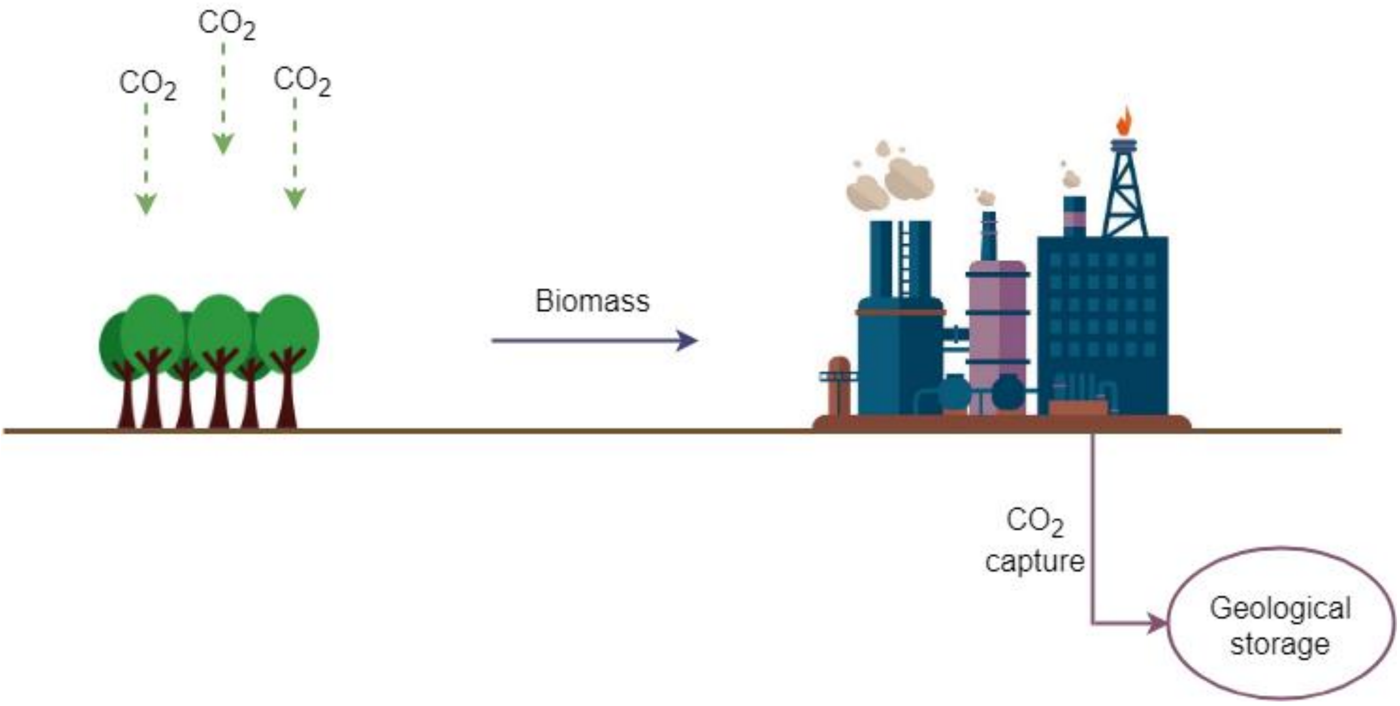
TOWARDS NEGATIVE EMISSIONS IN THE CEMENT INDUSTRY

A comparative techno-economic assessment of bioenergy with carbon capture and storage as a decarbonization option for the cement industry

Vikash Arvind K S

TU Delft



TOWARDS NEGATIVE EMISSIONS IN THE CEMENT INDUSTRY – BIOENERGY WITH CARBON CAPTURE AND STORAGE

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Vikash Arvind Krishnamurthy Sanmugasekar

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Supervisors: Prof.dr.ir. C Andrea Ramirez Ramirez
Ir. Samantha Eleanor Tanzer

ABSTRACT

Negative emission technologies aim to remove historic CO_2 from the atmosphere. Bioenergy with carbon capture and storage (BECCS) is regarded as a possible negative emission technology. This thesis aims to study the technological and economic feasibility of implementing BECCS in the cement industry. Four different types of biomass - rice husk pellets, wood pellets, sewage sludge, and municipal solid waste were chosen to substitute 30% of the coal (on a mass basis) in a model of a European cement plant. With an emphasis on retrofitting, three CO_2 capture technologies, absorption using monoethanol amine (MEA), calcium looping (CaL) based capture, and oxyfuel combustion capture were chosen for a comparative study. This thesis compares the techno-economic performance of the BECCS technologies in a cement plant using the key performance indicators (KPIs) of specific primary energy consumption per CO_2 avoided (SPECCA), cement production costs and costs of CO_2 avoided. Mass balance results and estimates of capital and operating expenses were used to calculate the KPIs. The parameters for each biomass-CO_2 capture combination are compared to each other and also compared to the reference value of a cement plant which uses 100% coal without CCS. The results were subjected to sensitivity analysis to determine the effect of uncertainty of fuel prices (coal and biomass), electricity prices, CO_2 taxation, CO_2 storage costs and variation in electricity generation cases. CO_2 accounting was performed for a defined limited gate-to-gate boundary, to estimate the carbon footprint of the BECCS technologies.

The BECCS technologies studied have a lower rate of cement production as a result of co-firing biomass in existing boilers (with no modifications to the capacity of the furnace). This can be attributed to the reduced thermal energy supplied due to the low calorific value of biomass. Of the three CO_2 capture technologies, oxyfuel combustion capture is the least energy consuming option (1.8 MJ/t_{CO_2}, with wood pellets) and the highest range of SPECCA is visible in the case of MEA (8.6 MJ/t_{CO_2}, with municipal solid waste). The cement production costs increase by 42 to 89% compared to the costs without CO_2 capture. The cost of CO_2 avoided is between 45 €/t_{CO_2} (wood pellets with oxyfuel) to a higher range of 96 €/t_{CO_2} (sewage sludge with MEA). The variation in costs are significantly affected by the type of biomass used. CaL technology has a moderate performance in energy consumption and costs. SPECCA obtained for CaL process is in the range of 4.1 to 4.4 MJ/t_{CO_2} and the cost of CO_2 avoided is in the range of 57 to 74 €/t_{CO_2}. CaL also entails the highest CO_2 capture rates, in comparison with MEA and oxyfuel technologies. In terms of total CO_2 emissions avoided, CaL based CO_2 capture gives the highest CO_2 avoided for the system boundary defined in this thesis. Therefore, when the CO_2 removed from the atmosphere through the growth of biomass is included, the net CO_2 emissions are the least for CaL capture technology. The reason is the additional thermal energy requirements the retrofitted CaL process units, which are met with 100% biomass. Although theoretically, a net negative value of CO_2 emissions was visible in the case of CaL, it must be noted that upstream process emissions are not included in this thesis. But in practice, it is still unclear as to whether negative emissions are attainable with the information at hand.

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CONTENTS

1 INTRODUCTION

1.1 CLIMATE CHANGE MITIGATION

Global energy consumption is increasing at a rapid rate and the negative effect of fossil fuels on the environment and climate change is alarming. This has spurred research on sustainable development to enhance the existing climate mitigation strategies. Countries across the globe have committed to limit global temperature rise to well below 2 degrees above pre-industrial levels annually, to comply with the Paris Agreement of 2016 [1]. This means that rapid reduction of green-house gas emissions to zero is imperative.

To achieve this, policy makers focus largely on developing renewable energy systems and making the building and transport sectors carbon-free. A sector that requires equal attention to meet these climate goals is the industrial sector. The industrial sector produces every day materials like steel, cement, plastics, and is a source of 30% of global emissions [2]; it is therefore important to focus on decarbonizing industry to achieve the Paris goals.

Overall, the cement industry accounts for 5-8% of the global anthropogenic CO_2 emissions [3] [4] [5]. Concrete is the world's most widely used material next to water [6]. World cement production has been increasing steadily, therefore embracing less carbon-intensive technologies would be crucial to reduce the carbon footprint of the cement industry.

1.2 CEMENT INDUSTRY – A MASSIVE CO_2 EMITTER

In the cement industry, thermal energy consumption is not the only source of CO_2 emissions. The manufacturing process accounts for more than half of the CO_2 emissions [2]. Over the years, attempts have been made to reduce emissions from cement manufacture - primarily improvements in thermal and electric efficiency. Alternative fuels like wastes and other low-carbon options are often employed in the industry to provide the thermal energy for the manufacturing process; mostly for co-combustion with the conventionally used fuels in existing burners [7]. As per the data provided by IEA (2016) [8], fossil fuels account for about 94% of the average thermal energy consumption for cement plants worldwide. Figure 1.1 shows this breakup.

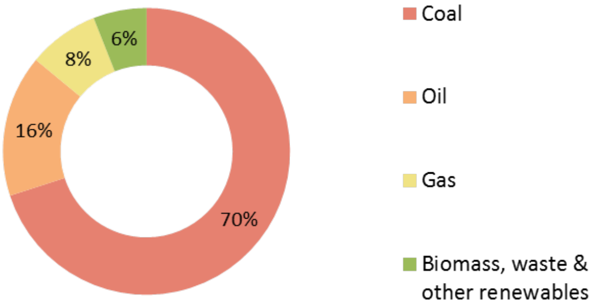

Figure 1.1: Average share of different fuels in global thermal energy consumption for cement production (data from IEA [8])

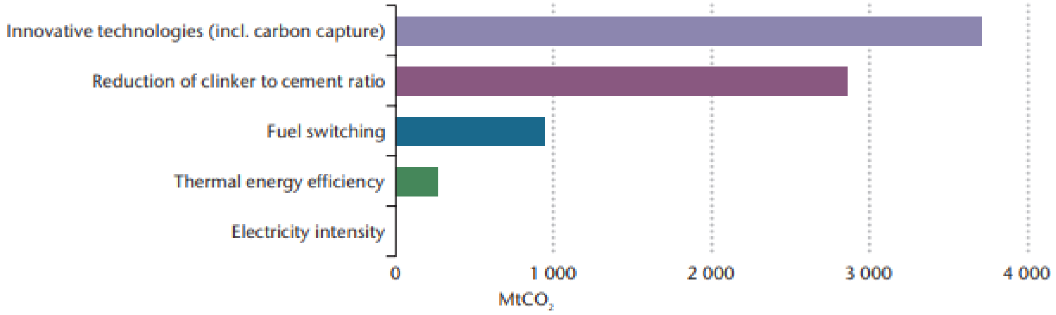

Figure 1.2: Global cumulative CO_2 emission reductions predicted for the period from 2020 to 2050 by applying various decarbonization options to cement production [14]

The portion of alternative fuels being used in cement plants has been increasing [9]. But extensive adoption of decarbonization strategies, beyond efficiency improvements and switching to low carbon fuels, has been touted to be the way to reach the climate goals faster. In fact, some reports predict that it would be impossible to meet those targets, unless these decarbonization options and other steps for circularity are implemented with immediate effect [10].

Decarbonization is the name given to a broad range of options which have the potential to facilitate large-scale removal (or) avoidance of CO_2 from the energy and industrial sectors. Carbon capture and storage (CCS) is one among them, seen as a bridge between the current fossil fuel-based economy and a future carbon-free economy [11]. Other decarbonization options considered for the cement industry include reducing the share of clinker in cement [12] [3]. Clinker is the primary component of cement, the process of clinker production is the source of almost 90% of the CO_2 emissions from the cement industry [13]. Hence (partial) substitution of clinker with other additives is capable of reducing emissions (depending on the carbon footprint of the other additives). A prediction of the CO_2 reduction potential, made by IEA [14] for the above mentioned decarbonization options is shown in Figure 1.2.

1.3 THE ROLE OF NEGATIVE EMISSIONS

Negative emissions are among the latest inclusion in the climate debate, as more technical reports increasingly emphasize [15]. The crux of negative emissions is to facilitate **permanent** removal of CO_2 from the atmosphere. The CO_2 emitted to the atmosphere must be lower than the CO_2 removed from the atmosphere, over the entire **lifecycle** of the technology under consideration [16]. This deliberate removal by human intervention is **possibly** capable of stabilizing climate [17]. Negative emissions can be attained:

- by using technologies that allow direct removal from air, followed by permanent storage;
- by applying decarbonization options to power plants and industries where bio-based sources are used to generate/provide energy, followed by capture and permanent storage.

To keep warming less than 2°C, CCS is crucial [13]. Studies suggest that without viable CCS, realizing negative emissions on a large-scale is uncertain [18] [19]. Along with afforestation, the production of sustainable bioenergy with carbon capture and storage (BECCS) has been explicitly put forth as a climate mitigation option by a majority of the scenarios aimed at keeping warming below 2°C [20] [17].

The development of appropriate governance and policy frameworks is a necessary prerequisite for these technologies, and these are only starting to be discussed. For example, many techniques will require protocols to verify and account for CO_2 removed from the atmosphere, including provision for impermanent reductions [17].

1.4 OBJECTIVES OF THIS RESEARCH

The primary aim of this research is:

"To assess the techno-economic performance of BECCS as a decarbonization option for the cement industry."

The focus of this study is on short-term options. Within a short span of 10-15 years, building new set-ups for a cement plant accommodating new technological options is unrealistic; therefore addition of capture technologies to existing cement plants are prioritized in this techno-economic assessment. This is termed as the ease of retrofitting, and formed the basis of selecting the technological options in this thesis.

The following research questions are devised:

1. What are the possible ways of using biomass as inputs in a cement plant?
2. What is the impact on the product yield (cement) and/or raw material consumption in the options considered?
3. Among the selected biomass inputs and CO_2 capture technologies, which options are the least energy consuming and most economically viable?
4. Are the net emissions for the assessed BECCS system in a cement plant actually carbon-negative?
5. How do the most significant economic parameters vary due to the effect of uncertainties?

To answer these questions, the following approach is used:

A literature review was carried out to select biomass options to be used as alternate fuels in a cement plant and to examine the possibilities of using alternative raw materials that may potentially reduce further CO_2 emissions. A summary of this review is in chapter 2. Different CO_2 capture technologies are compared on the basis of their ease of retrofitting to narrow down on three options for a comparative analysis. Key Performance Indicators (KPIs) were identified to compare the BECCS scenarios chosen, which include incremental primary energy consumption and production costs. Chapter 3 comprises of a comparison of the retrofitability of various CO_2 capture scenarios, definition of the KPIs and a description of the methodology used for techno-economic assessment.

A reference cement plant was modelled, which consumes only fossil fuel. Mass balance for the base case was performed and parameters like raw material consumption, rate of clinker produced, fuel consumption, production costs are estimated. Mass balances of the three BECCS scenarios were performed, energy consumption values specific to the capture technologies have been estimated based on the process design requirements. An estimation of CO_2 emissions in each case and the value of CO_2 avoided on employing BECCS technologies are calculated. To assess the economic performance, cement plant capital expenses, operating expenses and CO_2 avoidance costs have been estimated. Sensitivity analysis of the economic and technological parameters used in the study was performed to determine the possible effects of uncertainties. The results of the techno-economic analysis are presented in chapter 4. Chapter 5 comprises of a summary of the findings of this techno-economic analysis and provides limitations and recommendations for future work.

2 LITERATURE

2.1 CEMENT PRODUCTION

The cement manufacturing process is resource and energy intensive. Fossil fuels are used to heat a high temperature kiln and decompose limestone ($CaCO_3$) and other additives (like clay, iron ore, bauxite, etc) to form a substance called clinker [21]. Clinker is combined with gypsum (and other additives) and ground to a fine powder known as cement. The raw materials are first extracted (quarried from rocks) and transported to a blender where they are subjected to homogenization and grinding [22]. Then the ground 'raw meal' is pre-heated to a temperature of 300°C and then heated in a rotary kiln at temperatures as high as 1450°C. This process of decomposition of $CaCO_3$ into lime (CaO) and CO_2 is called calcination. The lime then combines with other mentioned components in the raw meal, to form clinker, the main component of portland cement.

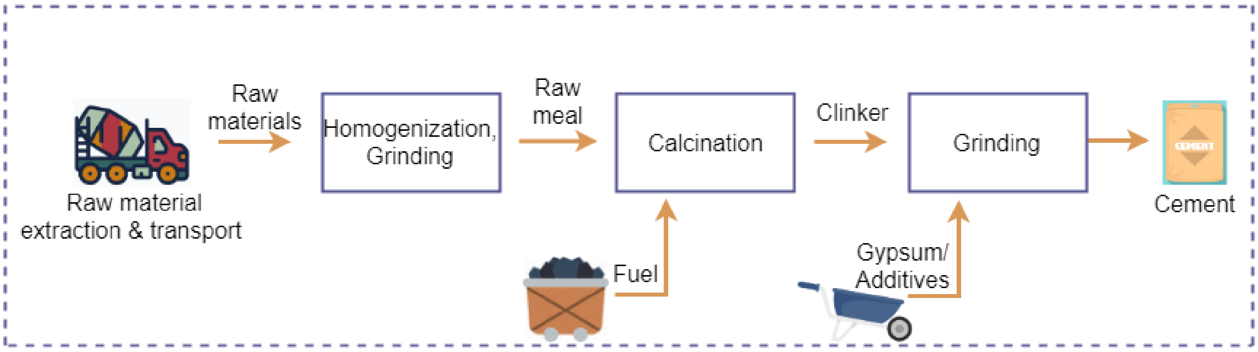

Figure 2.1: Schematic of cement production

The raw meal usually comprises of calcite ($CaCO_3$), quartz (SiO_2), clay minerals (SiO_2-Al_2O_3-H_2O), iron oxide (Fe_2O_3) and magnesite ($MgCO_3$). Clinker is primarily composed of the following [23]:

- Alite (C_3S)[1] - Tricalcium silicate (Ca_3SiO_5) modified in composition and structure by ionic substitution, this is the primary component of clinker (50-70%)
- Belite (C_2S) - Dicalcium silicate (Ca_2SiO_4) modified in composition and structure by ionic substitution, this makes up for 15-30% of the clinker.
- Aluminate (C_3A) - Tricalcium aluminate ($Ca_3Al_2O_6$) modified in composition and structure by ionic substitution, this makes up for 5-10% of the clinker.
- Ferrite (C_4AF) - Tetracalcium alumino ferrite (Ca_4AlFeO_5) modified in composition and structure by ionic substitution, this makes up for 5-10% of the clinker.

The reactions involved in the cement manufacture process are [24]:

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[1] Note that C, S, A and F which are indicated as part of clinker composition are acronyms for the following: C - CaO, S - SiO_2, A - Al_2O_3 F - Fe_2O_3.

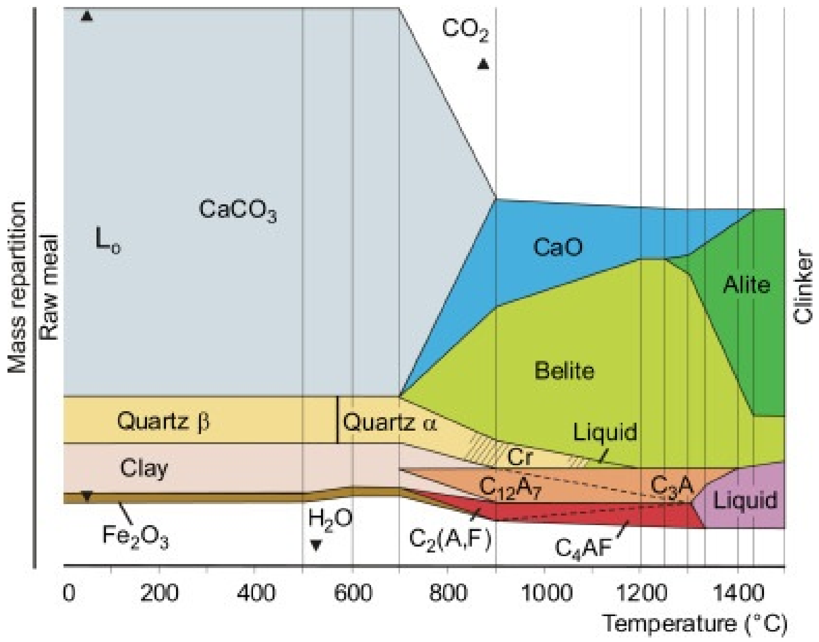


Figure 2.2: Reactions that take place during clinker formation [26]

$$CaCO_3 \longrightarrow CaO + CO_2$$
$$MgCO_3 \longrightarrow MgO + CO_2$$
$$2\,CaO + SiO_2 \longrightarrow 2\,CaO \cdot SiO_2 \text{ (or) } C_2S$$
$$CaO + C_2S \longrightarrow 3\,CaO \cdot SiO_2 \text{ (or) } C_3S$$
$$3\,CaO + Al_2O_3 \longrightarrow 3\,CaO \cdot Al_2O_3 \text{ (or) } C_3A$$
$$4\,CaO + Al_2O_3 + Fe_2O_3 \longrightarrow 4\,CaO \cdot Al_2O_3 \cdot Fe_2O_3 \text{ (or) } C_4AF$$

Homogenization of raw materials and kiln feed is necessary to ensure a consistent clinker quality and soft burning inside the kiln. Variations in the composition of kiln feed alter the combustion process and the rate of fuel consumption [25].

The temperature profile of the reactions involved can be observed from figure 2.2. Starting from the left of the figure, the feedstock (with the components mentioned earlier) starts to undergo the reactions and up to a temperature of about 700° C, activation through the moisture removal and changes in crystal structure take place. At a temperature range of 700°C to 900°C, decarbonation of the $CaCO_3$ starts to occur, along with the initial formation of C_3A and C_4AF from the combination of alumina, ferric oxide and of activated silica with lime [23]. Belite (C_2S) forms from 900°C to 1200°C. It is only above a temperature of 1250°C that the liquid phase appears and alite (C_3S) begins to form by the reaction between belite and free lime [23].

2.1.1 CO_2 emissions associated with cement manufacture

Primarily, the CO_2 emissions in the cement industry arise from the clinker production process (process emissions and from fuel combustion). These CO_2 emissions are termed as **direct** CO_2 emissions; they are emitted at the site of the cement plant. And the other sources of CO_2 emissions include electricity generation and transportation which are termed as **indirect** CO_2 emissions. The CO_2 emissions associated with cement manufacture can be grouped into three categories [12] [27]:

- **Calcination:** The process of calcination of the raw materials accounts for about 60% of the direct CO_2 emissions in the cement industry [28]. The CO_2 emissions in this step arise from the decomposition of limestone.

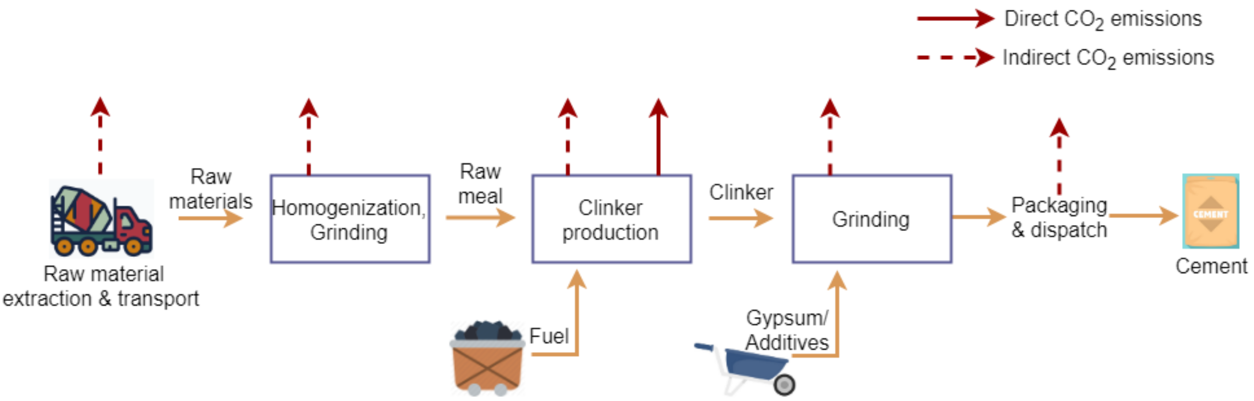


Figure 2.3: Sources of CO_2 emissions indicated in the cement production chain.

- **Fuel combustion:** The fuel (carbonaceous) consumed for the calcination process accounts for (usually) less than 40% of the direct CO_2 emissions [29]. The type of fuel used in kilns influences the amount of CO_2 emissions.

- **Indirect emissions:** This category includes the CO_2 emitted due to electricity (power) generated for cement production (includes raw material grinding, clinker production and cement grinding), the extraction and transportation of raw materials, packaging and dispatch of the cement produced. During transportation, the consumption of liquid fuels in transport vehicles is a source of CO_2 emissions. Less than 10% of the cement industry's CO_2 emissions are indirect emissions.

The European BAT (best available techniques) cement plant mentions CO_2 emissions (including electricity) are in the range of 0.66 to 0.68 t_{CO_2}/t_{cement} [7]. From the break-up of CO_2 emissions discussed, it is evident that addressing the emissions from clinker production is crucial, particularly, the process of calcination. This can't happen unless a pathway to curtail CO_2 with the existing manufacturing processes is developed or the requirement for clinker itself is reduced.

There is a need for low carbon materials, that is raw materials or fuel which might emit lower CO_2 if they are used in the cement industry. Finding substitutes or suitable replacements for limestone and fossil fuels can ensure this, Also, it is possible to capture the CO_2 emitted from the industry and store it in a geological formation (CCS). Of course, if CCS is integrated with a cement plant in operation, perhaps the same initial material (limestone) and/or fuel (coal) could be used. However it is better to have a simultaneous search for alternative fuel and material options.

2.2 DECARBONIZATION STRATEGIES FOR CEMENT INDUSTRY

This section starts with a description of some of the conventional options adopted to decarbonize the cement industry; these include improvements in thermal and electric efficiency and this is discussed in the first subsection. Followed by this, using alternative fuels (which include biomass or bio-based fuels), alternative raw materials and employment of CCS are explored individually. This research entails clubbing the two strategies - using biomass and CCS.

2.2.1 Efficiency improvements

The conventional way to ensure that CO_2 emissions (or any wastes) are kept to a minimum is to enhance thermal and electrical efficiency. Deployment of state-of-the-art technologies in new ce-

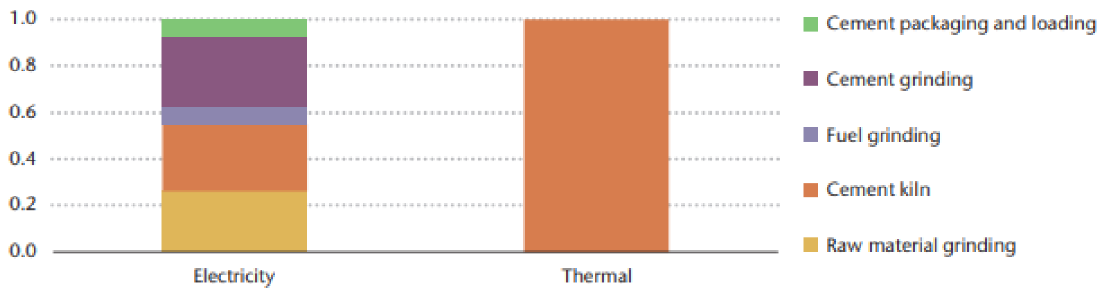


Figure 2.4: Distribution of energy demand in a cement plant by process steps [14]

ment plants and retrofitting efficiency plants wherever feasible is therefore crucial. A breakdown of the total energy consumption in a cement plant by various stages of the manufacture process is illustrated in figure 2.4.

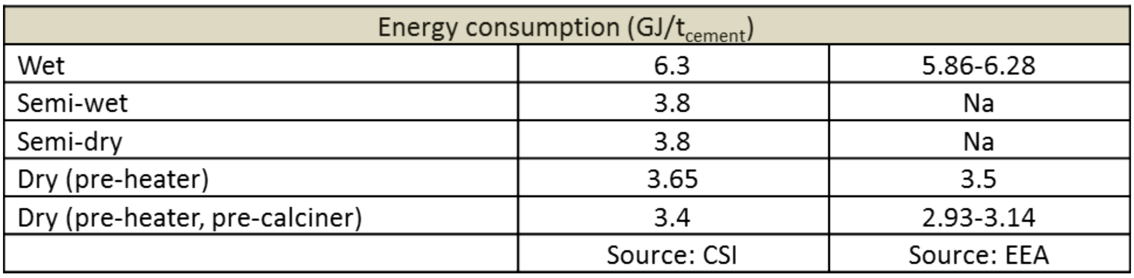
In the raw material grinding step of the manufacture process, it is mostly ball milling that is employed (this step is often referred to as raw milling). About 60% of the cement plants still use ball mills and this has been attributed to their reliability [30]. The ball mills can be made more efficient by employing the following:

- Vertical roller mills can be used; this can reduce the energy consumption by about 25 to 30% compared to regular ball mills [7].
- High pressure grinding rolls. Energy savings of a broad range from 10 to 50% can be attained by employing this [31].
- Moreover, additives can be added to improve grindability and transportation could be made more efficient [30].

Reduction of thermal energy usage pertaining to clinker production can help curtail direct CO_2 emissions that stem from the cement plant [32]. Changes such as the following can be implemented at the clinker production level [30]:

- Improvements in kiln combustion processes such as flame control, burners with multiple air channels for better air distribution. These improvements are found to save about 2 to 10% of energy consumption [33].
- Refractory improvements in kiln; insulation linings for energy savings can help.
- Pre-heaters and/or pre-calciners could be added to upgrade kiln technologies. This would ensure that calcination is carried out in stages and it helps reduce energy supplied for the calcination. The reason for this is the exchange of heat through the counterflow principle by the hot exit gas in every stage. Dry kilns with pre-heaters and pre-calciners can reduce energy consumption by 8 to 11% [33].
- Efficient classifiers can be placed after grinders. The function of the classifiers is to separate particles according to their size and re-send the bigger particles back to the grinder. Less efficient classifiers can send very small particles back and result in unnecessary extra energy consumption [30]. Focusing on this aspect can help achieve savings in energy of up to 8% [34].
- Efficient clinker coolers can help. Employing grate coolers in the kiln can enable energy savings close to 8% [33].
- Efficient energy management, using more manpower for better control systems.

Table 2.1: Energy consumption of different types of cement production processes [30] [36]



Energy consumption (GJ/t_{cement})		
Wet	6.3	5.86-6.28
Semi-wet	3.8	Na
Semi-dry	3.8	Na
Dry (pre-heater)	3.65	3.5
Dry (pre-heater, pre-calciner)	3.4	2.93-3.14
	Source: CSI	Source: EEA

- Embedding digital technology within industrial machinery can further reduce resource and fuel consumption in industry. This kind of 'intelligent efficiency' has been reported to be capable of reducing global CO_2 emissions by roughly 20% by 2030 [35].

As far as thermal energy consumption is concerned, dry processes (dry kiln types) consume lesser energy than wet processes. So dry (or even semi-dry) types can be employed. This is substantiated by the information in table 2.1.

2.2.2 Replacement of clinker (blended cements)

Clinker is ground with other additives (primarily gypsum) to get cement, this process is referred to as cement milling (or) grinding. Replacements of clinker while milling, with fly ash (from coal-based power plants) or slag (from steel plants) is a possibility. These types of blended and composite cements are known to avoid emissions arising from calcination [37]. A type of blend called geopolymer concrete consumes only one-third of the fuel needed to produce ordinary portland cement and it also emits lesser CO_2 [38].

Geopolymerization[2] helps produce green concrete or building materials with lower carbon footprint [39] and life cycle assessment (LCA) studies have suggested this [40] [41] [42]. Blended cement (fly-ash based) has the potential to reduce almost half of the CO_2 emitted from portland cement [43]. Studies have estimated that in addition to lower CO_2 emissions, this material displays higher binding and tensile strengths in comparison with portland cement [44].

The European standard EN 197-1 lists 27 different types of cements available on the market based on their composition and characterisation [45]. But those products are broadly grouped into five typologies [46]:

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

The most common cement produced is Portland-composite cement (CEM II) [47]. In this type of cement, up to 35% of various kinds of additives are mixed with clinker during milling. These additives include any one (or a blend) of fly ash, blast furnace slag, limestone or pozzolana. When unconventional additives of this kind are used following reduced usage of clinker, the blends obtained are usually tested for their compression strength, setting time, sulphates (SO_3)

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[2] Geopolymers are amorphous three dimensional aluminosilicate materials with ceramic-like properties that are synthesized and hardened at ambient temperatures

and chlorine content. The values must comply with the international standards and the limits fixed for traditional cements [47].

The extent to which the quantity of blended cements can be increased depends mainly on their availability in the quantities (scale) required and the permission to use them by relevant institutions as there are restrictions on usage of such alternative materials [37].

2.2.3 Use of alternate fuels

Using alternative low-carbon fuels for burning is an effective decarbonization strategy as that would generate lower CO_2 emissions than carbonaceous (fossil) fuels. 'Alternative' fuels include non-fossil fuel options which range from agricultural and non-agricultural biomass to wastes (residential, industrial, chemical). The primary fuel used in cement industry is coal [48]; and other fuels such as petcoke, gas, oil and wastes have also been employed for firing the kilns, either individually or in some combinations [12]. Using wastes to provide the thermal energy offers simultaneous benefits of destroying them and generating energy from the wastes [12]. It also offers a variety of ecological benefits and conserves our limited non-renewable fuels. The burden of waste disposal is lessened when they are burnt in the cement kiln [49]. If the wastes were to be incinerated, that would consume additional fossil fuels to burn, leading to further CO_2 emissions; plus adapting a cement kiln for waste usage is cheaper than setting up waste incineration plants [9].

'Biomass' for energy use is a term that refers to all organic material, directly from plants or trees, indirectly from plant-derived industrial, commercial or urban waste, or from agricultural and forestry residues [50]. There is debate on the carbon-neutral nature of biomass, and the other environmental impacts[3] are being explored. Still, partial replacements of fossil fuels with such alternative options, including biomass are being considered with low co-firing rates. Direct co-firing is deemed to be a realistic way and a good stepping stone towards more viable and sustainable energy practices [48].

Solid waste management is one of the most challenging environmental issues in urban settings in today's times [49]. If the wastes are burnt in the cement kiln, this might be a way to divert them from the landfills clearing up some landfill space. However, the major influencing factors for deciding upon the alternative fuel to be used remain to be cost and availability of the alternative fuels, more than environmental impacts [48]. It has been reported that more than 64% of the cement plants in the EU incorporate wastes in their fuel mix [12].

Most arguments are based on the so-called carbon neutrality of these wastes, which are high in biogenic content. However, while it is true that biomass or bio-based fuels are part of the natural carbon cycle, environmental impacts are not merely restricted to carbon emissions [51]. And proper waste management is imperative for this. Proper heat distribution, complete combustion, stable operation, ensuring minimal emissions of NO_x, SO_2, CO_2 and dust would be crucial too [52]. Approval from relevant authorities is mandatory to burn alternative fuels in many countries on account of the potential environmental hazards [23]. With such emission control regulations that can monitor the impact of the fuels accurately, alternative fuel options seem to be a viable decarbonization option that can control the carbon footprint of the cement industry.

Treatment of biomass before co-firing:

Direct co-firing of biomass with coal in the same boiler is one among the methods to employ biomass as a fuel along with fossil fuels. Other methods include indirect co-firing (gasification followed by co-firing) and parallel co-firing (in two separate boilers). To enhance the fuel quality before usage for direct co-firing, some form of pre-treatment is required for biomass (or any

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[3] Other environmental impacts such as SO_x and NO_x emissions, chlorine, heavy metals and other particulates.

unconventional fuel). The energy density of the biomass feedstock can be improved by primarily drying (natural or accelerated means), or by methods like torrefaction, pelletisation or briquetting [53]. To be used in the cement industry, some treatment options that can be considered before usage for co-combustion are listed here, for different biomass types [9]:

- Agricultural biomass – filtering, drying, torrefaction, gasification, grinding.
- Municipal solid waste – filtering, drying, crushing, grinding, shredding.
- Waste wood – like other solid wastes such as MSW, and torrefaction
- Sewage sludge – filtering, drying, pelletising.

Torrefaction (also referred to as slow pyrolysis) is the thermochemical treatment of biomass at temperatures between 200 and 350°C with bio-char as primary product [54]. This process is used as a means to upgrade biomass characteristics and to produce biomass fuels with improved quality (comparable to that of coal), making torrefaction a viable option to process biomass despite its energy intensive nature. This pre-treatment technology ensures a more coal like structure of the biomass because it increases the energy density and durability [55]. The torrified biomass product approximately has 70% of the initial weight and 90% of the original energy content [56].

Options for biomass that are considered in this research as alternative fuel sources for the cement industry are discussed in the upcoming section. The focus of this thesis is to explore the possibilities of using biomass in the cement industry, one way is to use them as a fuel for the clinker production. As the ease of retrofitting is an important determinant in this study, complete replacement of fossil fuels is unrealistic. The lower heating value (per mass) would entail higher rates of fuel consumption to replace the current rates. The capacity of the existing boilers won't be sufficient to accommodate the new fuel. As a result, retrofitting would be cumbersome. Therefore further discussions will be based on the concept of co-combustion of coal with the selected biomass options.

2.2.4 Biomass as fuel

Rice husks:

Rice husk, which is the outer shell of the rice grain is an agricultural by-product obtained from paddy. It is partly organic and partly inorganic. Rice husk is used in cement plants as an energy source that is liberated by combustion of the husk, and also as a raw material represented by the remaining ash after combustion. It contains SiO_2 as a major component which is an important additive in the raw meal used for clinker production [57] [12]. Rice husk can be used by partially replacing the conventional fossil fuel in a cement plant by the following ways [58]:

- by mixing crushed and pulverized rice husk with fossil fuel
- by the direct-feeding of rice husk in the form of pellets into the combustion chamber of the cement plant [59].

High volatile, low-energy fuels have low combustion temperatures and they are best suited for usage in a cement kiln in torrified and pelletised forms [60]. Studies indicate that it is difficult to obtain complete combustion of low-volatile fuels in a pre-calciner [61] [52].

For co-firing torrified pellets of rice husk with coal, a substitution rate of 30% has been stated in a study to be a safe value, in terms of its environmental impacts (NO_x emissions in particular) [62]. Other studies [63] [64] mention 35% substitution rate (as an upper limit) in cement plants for rice husk. Above this, there is a possibility of increased chlorine emissions that could be harmful.

Wood pellets:

Forestry residues from a wide range of sources can potentially be used at industrial scale through various thermochemical pathways (gasification, pyrolosis, combustion). The potential of forest biomass for energy and industrial sectors in Europe has been widely studied and is seen as a promising option, particularly in the context of Europe [65]. The European standard for concrete (EN 450), permits the co-firing of wood-based biomass in cement kilns up to 50% on a mass-basis if no other fuels are co-fired [66] [67]. Torrefied wood is particularly more suited for usage as a fuel; in fact, combined torrefaction and pelletisation can give a calorific value of roughly 21 GJ/t [55]. A life cycle assessment study reported that at 30% co-firing rate (on a thermal basis), there are positive environmental impacts like climate change potential and reduced emissions (SO_2, Hg and particulate matter) [68]. Another life cycle study which was in the context of a cement plant, reported a possible reduction in many environmental indicators (including global warming potential) when wood-based biomass is considered as a fuel. Key issues that pertain to the usage of forestry residues include availability and it is also not seen as economical to harvest these residues [69] [70].

Sewage sludge:

Treatment of wastewater from residential, commercial and industrial settings gives rise to sludge formation [71]. The disposal of sewage sludge is usually through incineration and depositing the ash in landfills, usage in agriculture or dumping in water bodies [3]; however, toxic by-products and emissions is a common concern for all the options. For instance, with sulphur content as high as that of coal, almost all of it is emitted as SO_2 [72]. In fact studies have suggested that by limiting the feed rate of dry sewage sludge in a cement plant to 5% of the clinker production capacity, it is possible to keep the levels of such toxic by-products within prescribed limits [71] [73]. Above this, harmful emissions of heavy metals and dust may pose a problem.

By using sewage sludge as a fuel in cement industry, it is possible to evade part of the environmental damage that incineration would result in [3]. The high water content of sludge is an important aspect to be considered in combustion process [12]. Sludge is usually co-fired with coal in pre-dried form as it is easier for storage and transportation [71]. In cement plants, waste heat from the kiln can be used to dry the sludge. In addition to this, the residual non-combustible components of sludge (ash) can be used as a raw material in cement production (discussed further in section 2.2.5) [3] [74].

The use of sewage sludge as alternative fuel is a common practice in cement plants around the world, Europe in particular [75]. It could be an attractive business proposition for wastewater treatment plant operators and the cement industry to work in collaboration to tackle the issues of sludge disposal, high energy requirements and GHG emissions from the cement industry [48].

Municipal solid waste:

Municipal solid waste (MSW), which includes garbage from residential and commercial sources, is a type of solid wastes that poses a problem to urban settings. Garbage (waste) is not all biomass; roughly half of its energy content comes from plastics [76]. Owing to cost and land availability issues, MSWs are usually disposed of in landfills or subject to incineration[4]. On decomposition in landfills, the bio-degradable components of MSW lead to negative impacts such as groundwater pollution and unpleasant odors, in addition to green house gas emissions [77]. Some valuable resources could also get wasted if wastes aren't utilized properly [78]. One such strategy would

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[4] Incineration is a way to treat/dispose wastes by combustion of organic substances contained in the wastes.

be to make it undergo thermal treatment or energy recovery to obtain cleaner renewable energy for industries and adopt waste-to-energy as a strategy to manage [79] [80].

Before being sent to the cement kilns for co-processing, MSW undergoes various processes which include [81] [82]:

- Separation at source, segregating the finer particles from bulkier ones.
- Magnetic separation to remove ferrous materials.
- Shredder to become a fine combustible powder.
- Drying

Cement kilns require homogeneity of the bio-based waste fuel used with respect to the composition and size [83]. To make them homogeneous and to keep moisture content to a minimum, appropriate mechanical treatment is crucial so that clinker quality is not affected. Otherwise, cement industry is particularly well-suited to the employment of such fuels [84] [85].

Rice husks and waste wood are widely studied and their torrefaction has been carried out [86] [87] [88]. Furthermore, pelletisation also ensures higher energy density and torrified rice husk and wood pellets will be considered in this study. In case of sewage sludge, de-watering (thermal drying to significantly reduce the water content) helps because the dry form of sludge is better as a fuel when used with coal. Belt drying technology is one among the methods that can be adopted to dry the sludge [89] [90].

2.2.5 Bio-based ash as raw material

As discussed in section 2.2.2, different types of cement have varying clinker compositions. There is an increasing interest among cement manufacturers to consider cement types with reduced clinker percentage as part of their attempts to decarbonize the industry [3] [51]. The underlying logic is that when the need for clinker itself is reduced, then reduced amount of limestone for calcination will ensure lesser emissions. Fly ash, slag and ash from biomass combustion are some of the options considered as substitutes of clinker. There are two ways of incorporating the ash [3] [13]:

1. As an **additive** during the milling of cement (grinding process)
2. As a **raw material** for clinker production

Cement plants consider biomass ash as a substitute raw material as they are carriers of CaO, SiO_2, Al_2O_3 and Fe_2O_3. A quality assurance system which includes technical and environmental criteria, to assess suitability of such unconventional raw materials is used, prior to its usage in the cement industry [67]. Before being used for any application, it is imperative to follow appropriate cleaning (water washing) in order to lessen the potential negative impacts of chlorine and heavy metals [91].

Rice husk ash and municipal solid waste ash, both have the potential to be utilized as an additive during the cement grinding process; During the grinding process, usually, clinker and other additives (which include gypsum) are ground together by ball milling. On employing ash from rice husk or MSW, the amount of clinker can be reduced, retaining the amount of other additives constant [92] - this way there is a possibility to avoid CO_2 emissions.

- Incorporation of **rice husk ash** as an additive into the cement mixture would lead to an increase in the composition of SiO_2 and decrease of Al_2O_3, Fe_2O_3 and CaO. Addition of up to 15% is desirable for improving the strength [92]. Moreover, being an agricultural by-product, its employment as substitute for a carbonaceous material in cement manufacture is another point in its favor [92] [67]. And it has been reported that using ash from agricultural waste has shown economic, technical, and environmental benefits [3].

- Up to 40% of substitution of **ash from MSW co-fired with coal** (MSW-fly ash) in cement has been examined and stated to be a safe limit [91], 44% upper limit for MSW-fly ash has also been reported [12]. Above this, there has been demonstrated high leaching concentration of heavy metals such as zinc, chromium and cadmium. Moreover, this type of ash would demand extensive washing treatments prior to its usage to reduce the content of chlorides [91]. But otherwise, it has been reported that this type of ash has a composition (high in silicates and alumino-silicates) that makes it suitable for usage in cement production [93].
- **Sewage sludge ash** has the potential to be utilized as a raw material in clinker production, by reducing the amount of limestone and other additives involved. It has been estimated in some studies [94] that a maximum of 5% replacement is appropriate for sewage sludge ash, without compromising on the strength or setting behaviour of the cement. Also, the formation of C_3S component of clinker would be hindered due to higher quantities of some oxides like P_2O_5 in sludge ash if substitution rates exceed 11% [95] [94]. There would be no potential negative environmental impacts due to chlorine, heavy metals or leaching if the suggested limitations are adhered to.

  Another study identified up to 10% substitution rate to possess strength comparable to CEM I type (ordinary Portland cement) [96]. The physical properties (mechanical strength) of sewage sludge ash make it a suitable inclusion in the cement manufacturing process [97]. In fact, sewage sludge ash and fly ash, both contain less than 0.1% of elements such as chromium, lead, nickel, copper, manganese, zinc and barium; hence no negative impact on cement properties [98].
- The direct use of **wood ash** as a cement raw material is limited due to its high content of alkali metals [67]; also its high sulphate and chloride content poses a limitation [99]. There are constraints for usage of biomass ash in most countries; of which, particularly usage of wood ash has been restricted owing to some of its environmental concerns [100].

Some major issues pertaining to the usage of ash in the cement industry would include: the availability of ash [101]; also the ash quality (clean ash) and consistency of the available ash would be crucial for usage as a raw material or additive [100]. The European standard for cement (EN 206) doesn't permit the usage of biomass ash in blended cements; its usage is not regulated. However application of ash from co-combustion has been practised in Europe [67].

2.2.6 Carbon capture and storage (CCS)

CCS is a key strategy in decarbonizing energy intensive industries (including cement industry). CCS involves three basic stages - CO_2 **capture and separation** from other gases at the source of emissions, CO_2 **transportation** from the source to the storage sites and **storage** of the CO_2 in geologically suitable locations. Large scale implementation of CO_2 capture in the cement industry has not been realized yet; but the industry is open to considering various research options. Three basic types of CO_2 capture are: post-combustion, pre-combustion and oxy-combustion. A schematic of the three types is shown in figure 2.5 and they are explained briefly below:

1. In **post-combustion** capture, CO_2 is captured from the flue gas stream emanating from the power plant or industry, then techniques such as absorption with solvents, adsorption to solids, membrane separation, cryogenic separation are used to capture the CO_2 from the other components of the flue gas (which comprises of primarily N_2). This is the most developed among the three basic types and it has an advantage of being able to provide retrofit options and the required modifications to the industry are minimal [102].

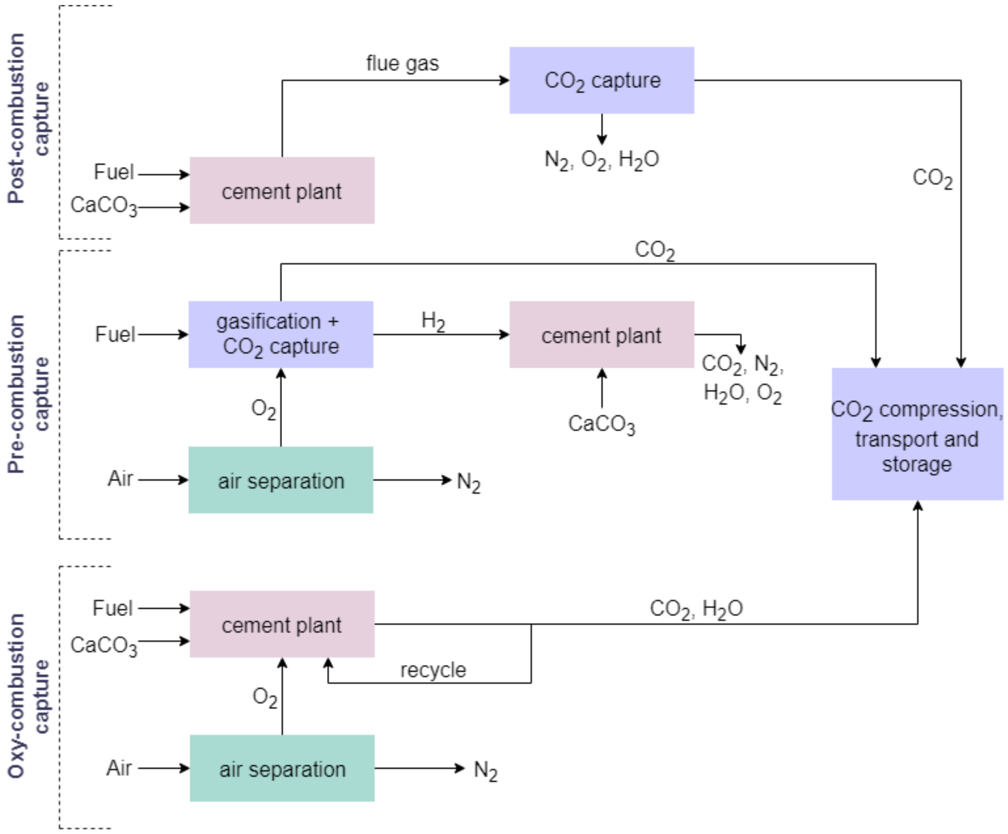

Figure 2.5: Schematic of CO_2 capture technologies applied to a cement industry

2. **Pre-combustion** capture involves partial combustion of the carbon-based fuel to give syngas ($CO+H_2$) which is moved to a water-gas shift reactor and CO_2 is formed along with hydrogen. Separating these two not only makes it possible to capture CO_2, but also leaves a pure stream of H_2 which can be used as a transport fuel. Energy requirements are lesser than that of post-combustion, however it is deemed to be expensive and far more complex owing to the high levels of process integration involved [103].

3. **Oxyfuel combustion** capture involves combustion of the fuel in oxygen. This results in a flue gas with just CO_2 and water, the high concentration of CO_2 makes it easier to separate on condensation. But this form of capture is energy intensive, needs a CO_2 purification and compression unit, recycling of flue gas - hence it is seen as less suitable for retrofitting owing to the complexity [103]. Economically, they are on par with post combustion technologies [104].

Some of the available post-combustion CO_2 capture technologies are:

- **Absorption:** Also referred to as amine scrubbing, this method of absorbing CO_2 is the most common way to capture CO_2 as of now and is very well established. This is a gas-liquid method, meaning liquid amine is used to absorb and capture gaseous CO_2. It is the most matured option both technologically and commercially. Currently it is used to remove CO_2 from ammonia synthesis and the process industry. Examples of some liquid solvents used are some alkanolamines such as monoethanol amine (MEA), methyl diethanol amine (MDA). There are some drawbacks of this technology - high energy required for solvent regeneration, formation of salts by reacting with oxides of N and S, and corossion [105].

- **Adsorption:** To combat the energy intensive nature of previously described absorption, here is a method to significantly reduce the energy required for CO_2 capture. This is called adsorption (gas-solid method) where a solid looping cycle can be realized. Calcium looping technology is seen as a promising option for capturing CO_2 in cement plants.

- **Cryogenic separation:** Cryogenic separation uses the difference in boiling temperatures and partial pressures to separate gases in a mixture by cooling or compression. It produces liquid CO_2 ready for transport to the storage site. The refrigeration process involved consumes a large amount of energy [105]. Also water has to be removed before the flue gas is cooled to avoid ice formation and corrosion. This method of carbon capture is most suited for oxy-fuel combustion capture in a cement industry [27].

- **Chilled ammonia process:** The flue gas is sent to an absorber, where the CO_2 concentration is reduced by the ammonia (NH_3) solution. The solution is regenerated in the desorber and high purity CO_2 is obtained [106]. The ammonia is stripped using cool water and it is re-used for CO_2 capture after recovery. Most part of this process is similar to the MEA absorption process.

- **Membrane liquefaction:** Polymeric membranes are used for bulk separation of CO_2 from the flue gas stream. This separated CO_2 stream is then liquefied and volatile components are removed. High purity CO_2 stream is obtained in this method [107].

Calcium looping (CaL) process:

This is a high temperature process based on the cyclic calcination and carbonation of a calcium containing sorbent. CO_2 is captured by the forward exothermic reaction (carbonation reaction) stripping the flue gas of its CO_2. By means of a circulating solid ($CaCO_3$) the CO_2 is transported into a calciner where the loaded sorbent is regenerated by the backward endothermic reaction (calcination reaction). To produce a high CO_2 concentration in the gaseous stream, the calciner is operated under oxyfuel conditions (high partial pressure) [102].

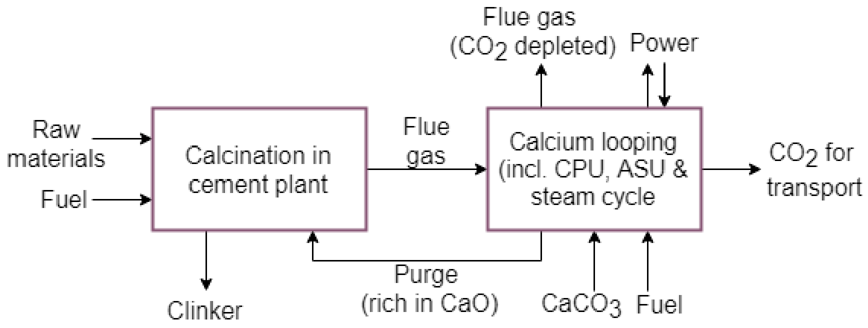

Figure 2.6: Tail end calcium looping (CaL) process as a post combustion CO_2 capture technology - schematic

There is good potential for integration between CaL and cement manufacture process [108]. CaL can be employed as a 'tail-end' (post-combustion) process by fitting into an existing plant like other post combustion options. Unlike a tail-end process where the CaL unit is partially integrated, it can also be fully integrated. In 'integrated' calcium looping, the CaL unit is built within the cement plant which means that major modifications are required. CaL capture has an advantage of recycling part of the CaO purge from the looping unit to the cement manufacture, thereby enhancing the clinker produce [109] or reducing the raw material consumption [108] [110].

CO_2 transport and storage

Realization of CCS will require the development of infrastructure to transport the captured CO_2 from its sources to the appropriate storage sites [11]. Ways of transporting CO_2 include:

- **Pipelines**: A reliable method for transporting large volumes of CO_2 is by pumping through through pipelines. Pipeline transport is a mature industry, however most of the existing pipelines are used for enhanced oil recovery, where CO_2 is injected into depleted oil fields to recover increased quantities of oil [111] [112].

- **Ships and road transport**: These alternatives can be used for transporting smaller quantities [113]. Transport by shipping dates back to more than 70 years and they are already prevalent in Europe, on a small scale [111].

Pipelines are considered to be more economical than other means of transport [113] [114]. Efficient form of transporting CO_2 through pipelines is in its **dense** form [112] [111]. The high pressure, varying temperature and presence of impurities in CO_2 fluids makes planning and design of pipelines very challenging [115]. To reach the desired pressure for pipeline transport (110 bar for offshore transport [111]), conditioning of the captured CO_2 is needed [114]. This includes removal of unwanted components (H_2O, N_2 among others), followed by compression. The presence of impurities may pose issues with densification [112]. Some major challenges with pipeline transportation include corrosion [114], two-phase flow [24] and large cost uncertainties [116].

Storage of the transported CO_2 can be realized onshore and offshore - with deep saline aquifers, depleted oil and gas fields (DOGF) and through enhanced oil recovery storage [117] [118]. In this thesis, the CO_2 capture technologies are assumed to give a CO_2 stream in a form suitable for **offshore pipeline** transport[5] and storage in **offshore DOGF**.

2.3 NEGATIVE EMISSION TECHNOLOGIES

Negative emission technologies (NETs) aim to remove CO_2 from the atmosphere over the life-cycle of the technologies and isolate them from the atmosphere for the long term. The approaches encompassed by this definition are diverse. Most NETs rely on photosynthesis to achieve CO_2 removal, either through afforestation or converting it to another form for permanent (geological) storage. Other options such as direct air capture, use chemical sorbents in industrial plants to extract CO_2 directly from the air [18]. Bio energy with carbon capture and storage (BECCS) has been widely regarded as a NET, which has the potential to be an effective strategy to achieve reduced emissions with removal of historic CO_2. It entails using CCS for an industry or power plant to capture the CO_2 emitted from combustion of bio energy sources.

While the decarbonization options discussed in section 2.2 address the root cause of anthropogenic climate change by curtailing GHG emissions, they do not remove the CO_2 from the atmosphere. Moreover, they may not be sufficient to deliver the scale and pace of emission reductions needed to keep GHG concentrations in the atmosphere within tolerable boundaries [119].

There are many inconsistencies in the usage of the term 'negative emissions' across literature [16]. If the emissions from a power plant or industry that uses biomass are considered in isolation, and a CO_2 capture plant is retrofitted - it would **theoretically** result in a negative value for emissions on assuming the biomass to be carbon-neutral (figure 2.7). But the net life-cycle removal, however, depends on emissions associated with supply, harvesting, processing and transport of biomass, any emissions associated with direct or indirect land use change or even the emissions

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[5] Offshore pipeline transport is more suited to regions in Europe where heavy industries are situated in proximity to many storage sites [111].

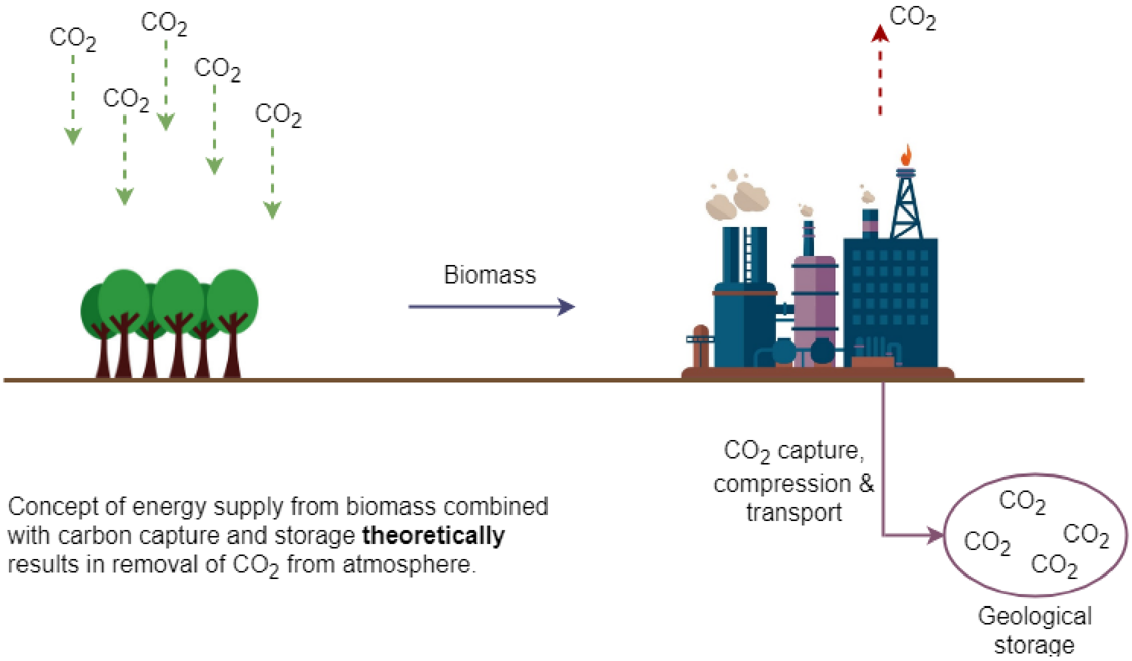

Figure 2.7: Illustration of BECCS: capturing and storing the carbon emissions from biomass combustion.

from transporting the compressed CO_2 [120]. Therefore, merely using biomass (wholly or partially) in conjunction with CCS does not guarantee removal of historic CO_2 from the atmosphere. That is, calculating the total emissions and getting a negative value should not be misconstrued as having achieved negative emissions. Defining appropriate boundaries is crucial, in addition to ensuring that the emissions captured and stored are greater than the quantity emitted to atmosphere [16].

The availability and accessibility of geological storage for CO_2 is a key uncertainty. If ultimately realisable storage is lower than current estimates due to physical or political factors, this could constrain the total negative emissions attainable through BECCS [18]. The extent to which the available storage sites are developed also constrains BECCS [121]. Deploying conventional CCS today uses finite geological storage that may constrain storage capacity in the future; but unless conventional CCS is deployed at a large-scale, a technology like BECCS cannot be developed. Another issue with CCS is that there are no political drivers to enforce its deployment; new policies are needed to incentivize commercial CCS [19].

There are constraints such as availability of land area for biomass usage, biological productivity, availability and mobilisation of biomass feedstock [122] [18]. But otherwise, they provide a possibility to lower CO_2 concentrations towards less risky levels; this may prevent an overshoot of total emissions. For this reason, studying the potential of BECCS to get a complete picture will aid policy makers in addressing the growing climate concerns [17]. The trade-offs related with the use of negative emissions also need to be further assessed.

This research doesn't aim for a net negative emission technology, but the idea is to envision a scenario for the future to realize 'actual' negative emissions that may result in removal of historic CO_2 from the atmosphere. The attempt here, however, is to try and move **"towards"** achieving negative emissions by employing BECCS in a heavy industry, starting with short-term replacements. Building up on this concept further by increasing the proportion of biomass used or more detailed studies about other sources of emissions within the system boundaries will take us even closer to determining if it is possible to achieve negative emissions in the real sense.

3 METHODOLOGY

The focus in this research is on the implementation of CO_2 capture in the short-mid term future (5 – 15 years). Short-mid term technologies are defined as those that are either in pilot plant, demonstration or commercialization phase today [123]. Even if a technology on the whole is yet to be tested or demonstrated, but all the equipment required is available today, that is also categorized as a short-mid term technology [124]. The other technologies, which are in laboratory phase today, are considered to be long-term future options (20 years or more). Three CO_2 capture technologies are selected for the assessment, based on their ease of retrofitting (discussed in section 3.2).

Technical assessments (using Microsoft Excel) are carried for each of the chosen technologies applied to a base cement plant. The mass flows in and out of each individual process unit are determined on the basis of performance equations derived from parameters characteristic to the cement industry. The energy flows are calculated using the basic thermodynamic properties of the components. The methodology and general assumptions used in the technical assessment are described in section 3.3. The results of the technical assessment are then utilized for the economic evaluation (methodology in section 3.4). For a comparative study of the techno-economic performance of the technologies, key performance indicators (KPIs) are calculated. KPIs are listed and defined in section 3.5. A detailed description of the BECCS scenarios is presented in section 3.7.

3.1 SYSTEM BOUNDARY

The system boundary defined for technical assessment is shown in figure 3.1. The only source of direct CO_2 emissions in cement manufacture is clinker production, and the CO_2 capture technologies are employed to capture the CO_2 from clinker production. Hence only the technical parameters pertaining to this stage and the CO_2 capture plant are taken into consideration. The technical assessment includes all the parameters until the stage where CO_2 is compressed to a form that makes it suitable for pipeline transportation.

The system boundary for the economic assessment includes the transportation and storage of CO_2, plus the cement grinding stage; this is depicted in figure 3.2. This is to estimate the key economic parameters per tonne of the final product of the cement industry (cement). Similarly

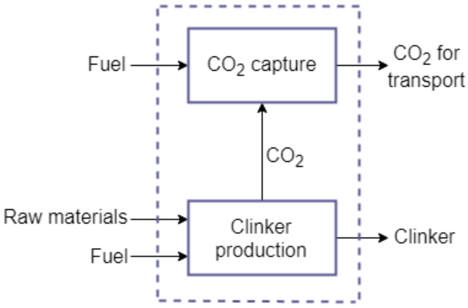

Figure 3.1: System boundary defined for technical assessment

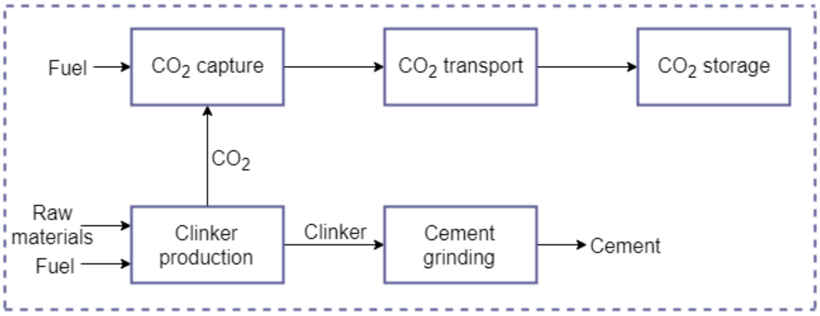

Figure 3.2: System boundary defined for economic assessment

for carbon accounting (section 3.6), the CO_2 emissions per tonne of cement are accounted for. In addition to this, the CO_2 removed from the atmosphere by biomass were also included.

3.2 RETROFITABILITY

Because cement plants typically have a lifetime ranging from 30 to 50 years, technologies have to be developed to enable the retrofit of CO_2 capture technologies to existing cement plants. Pre-combustion capture is not best suited for retrofit as it is only applicable to new plants [109]. Moreoever it only captures emissions from fuel combustion; this isn't beneficial in the context of cement industry as it cannot capture emissions from calcination of $CaCO_3$ (refer to figure 2.5 in section 2.2.6). So only post combustion and oxyfuel combustion capture technologies have been considered for retrofitting.

3.2.1 Comparing the ease of retrofitting for CO_2 capture technologies

A qualitative comparison of the ease of retrofitting for various CO_2 capture technologies was carried out, to make a selection of three feasible options. The technologies which have been considered for application in the context of cement industry were picked for making this comparison. The factors which formed the basis for the comparison include:

- Maturity of the technology
- Modifications required and
- Impact on cement production

The maturity of the technology can be understood from the Technology Readiness Level (TRL). TRL is a scale (on 1 to 9)[1] used to assign a value for the level of readiness for commercial large-scale implementation of a technology. A list of pilot projects and ongoing laboratory demonstrations for the chosen technologies were picked from literature and they are listed in table 3.1. The comparisons on the basis of the other two factors are listed in table 3.2.

3.2.2 CO_2 capture technologies selected for this thesis

The conclusions of the qualitative assessment made it possible to narrow down to three CO_2 capture technologies:

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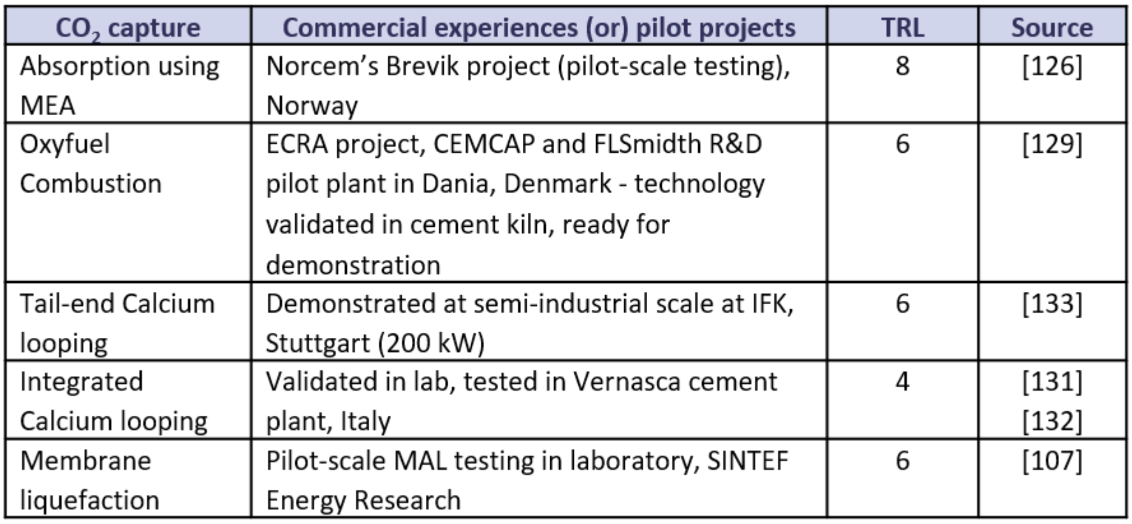
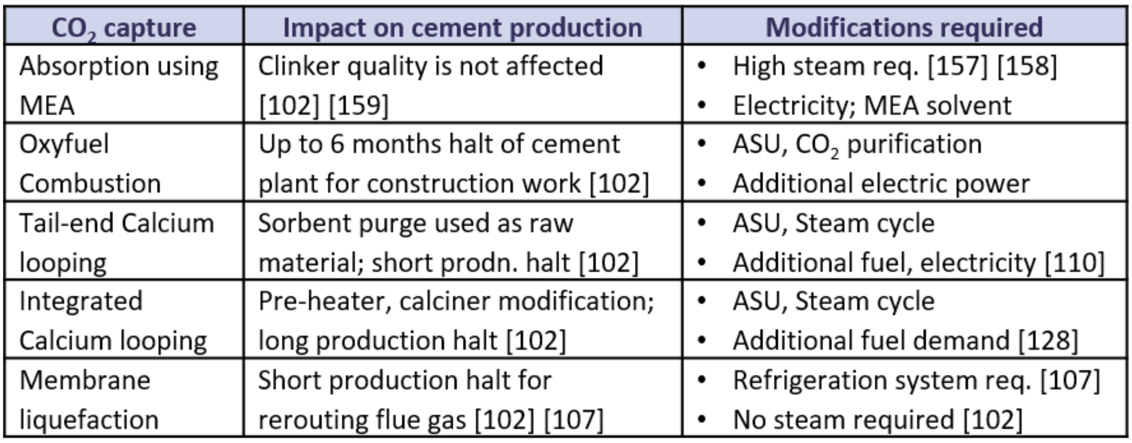
[1] TRL 1 - Idea of a technology and basic need described, but no testing/evidence yet; TRL 9 - Full commercial availability of a technology.

Table 3.1: Qualitative comparison of CO_2 capture processes based on their maturity level to assess retrofitability



CO_2 capture	Commercial experiences (or) pilot projects	TRL	Source
Absorption using MEA	Norcem's Brevik project (pilot-scale testing), Norway	8	[126]
Oxyfuel Combustion	ECRA project, CEMCAP and FLSmidth R&D pilot plant in Dania, Denmark - technology validated in cement kiln, ready for demonstration	6	[129]
Tail-end Calcium looping	Demonstrated at semi-industrial scale at IFK, Stuttgart (200 kW)	6	[133]
Integrated Calcium looping	Validated in lab, tested in Vernasca cement plant, Italy	4	[131] [132]
Membrane liquefaction	Pilot-scale MAL testing in laboratory, SINTEF Energy Research	6	[107]

Table 3.2: Qualitative comparison of the CO_2 capture processes on the basis of modifications and impact on cement production to assess retrofitability



CO_2 capture	Impact on cement production	Modifications required
Absorption using MEA	Clinker quality is not affected [102] [159]	• High steam req. [157] [158] • Electricity; MEA solvent
Oxyfuel Combustion	Up to 6 months halt of cement plant for construction work [102]	• ASU, CO_2 purification • Additional electric power
Tail-end Calcium looping	Sorbent purge used as raw material; short prodn. halt [102]	• ASU, Steam cycle • Additional fuel, electricity [110]
Integrated Calcium looping	Pre-heater, calciner modification; long production halt [102]	• ASU, Steam cycle • Additional fuel demand [128]
Membrane liquefaction	Short production halt for rerouting flue gas [102] [107]	• Refrigeration system req. [107] • No steam required [102]

1. **Post combustion capture using MEA** is suitable for retrofitting in spite of the few disadvantages which can be dealt with; for instance an option for energy supply can be utilizing waste heat from the cement exhaust gas to meet with the increased demands associated with this option. In addition to all these, amine based capture is considered to be closest to commercialization [125] [126] and hence scale-up will not be a critical issue [102].

2. With **oxyfuel combustion capture**, some modifications are required for retrofitting; but it is still considered cost-effective [127]. The mentioned modifications would take a few months to construct, during which time the cement production will have to be halted. However, the other benefits such as reduced CO_2 emissions and the relatively lower costs [127] [128] may compensate for the demerits [129]. Moreover, there is a possibility for oxyfuel CO_2 capture to outperform post combustion CO_2 capture technologies as a retrofit option in the mid-term future [130]. In addition to this, combustion in an O_2 rich environment has the added environmental benefits of reduced SO_2 and NO_x emissions [124].

3. **Tail-end calcium looping capture** is more suited for retrofitting [128]. The level of uncertainty is relatively better for tail-end CaL process when compared with the other options

considered [102]. It also has higher TRL than the integrated process (TRL of 6 for tail-end [131] compared to 4 for integrated CaL [132] [133] and 6 for membrane liquefaction [107]).

3.3 TECHNICAL ASSESSMENT

A typical kiln size in the EU region, as mentioned in the 'Best Available Techniques' document released by Industrial Emissions Directive, EU is about 3000 tonnes of clinker per day [7]. A clinker-cement ratio of 0.737[2] is considered [134] and the cement plant has a run time of 345 days per year. The quantity of raw meal required to get the desired amount of clinker was determined by assuming a raw meal-clinker ratio of 1.57 [7]. Following this, the composition of the raw mix employed was decided upon from literature [135] to be 78% $CaCO_3$, 21% additives (which include 14% SiO_2, 3.5% Al_2O_3, 2% Fe_2O_3, 1.5% $MgCO_3$) and 1% moisture (H_2O).

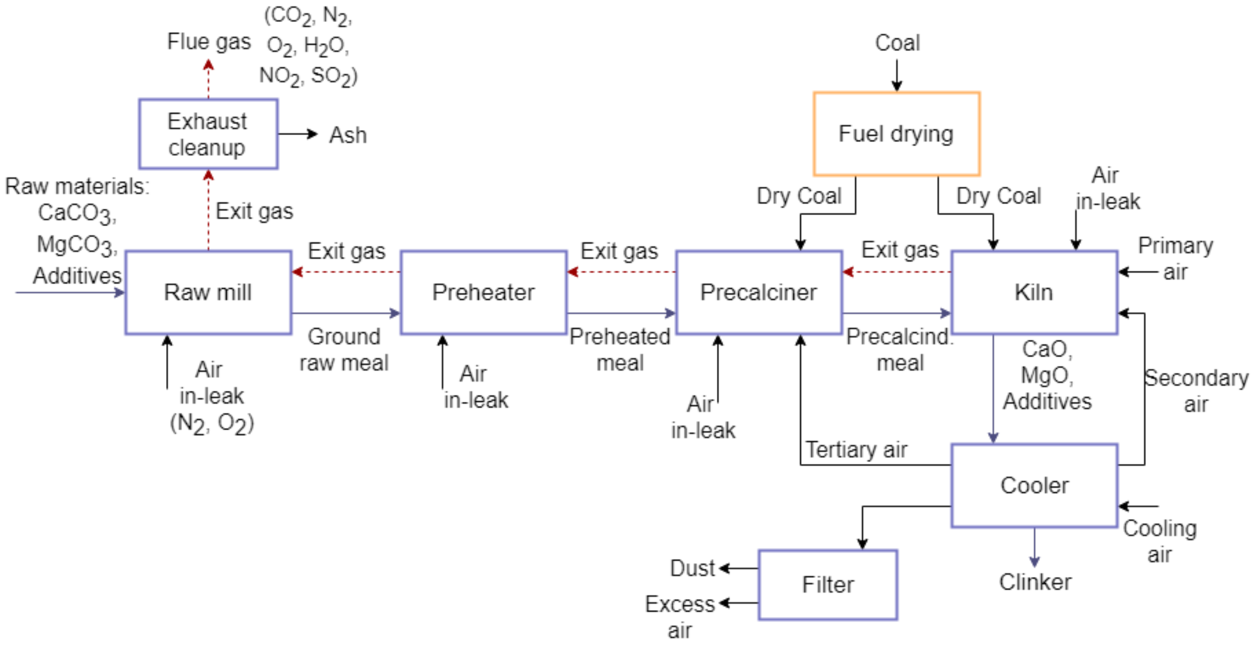


Figure 3.3: Process flow diagram for the base case clinker production process (fossil fuel without CCS)

A reference (base) case was set up. The base case scenario for this study involves using fossil fuel (coal) without CCS. The process flow diagram shown in 3.3 has been used for the reference scenario. The CO_2 capture plants in this study and the modifications pertaining to biomass usage have been retrofitted to this basic structure. Common assumptions used in the technical assessment for the base case and the BECCS cases are summarised in Table 3.3. Details on assumptions specific to the individual CO_2 capture technologies are presented in section 3.7.

The raw materials are ground by ball milling technique in the raw mill; in this stage, materials are dried and reduced in size before they are sent to the pre-heater. The hot exit gas from the pre-heater provides the heat required for drying. The dried raw meal reaches the pre-heater at a temperature of 60°C [136]. A five stage pre-heater is employed. During the pre-heating process, 18% of $CaCO_3$ and $MgCO_3$ are decomposed to form CaO and MgO. This assessment doesn't go into the details of how much of each of the components of clinker (C_3S, C_2S, C_3A, C_4AF) would be formed at each stage, but it can be safely assumed that the CaO formed would bond with an equivalent (molar) quantity of the additives (SiO_2, Al_2O_3, Fe_2O_3) to form some clinker. In the pre-calciner stage, 77% of the calcination takes place and more clinker is formed, and the remaining calcination occurs in the kiln [127]; a 100% calcination rate is assumed. The pre-heated

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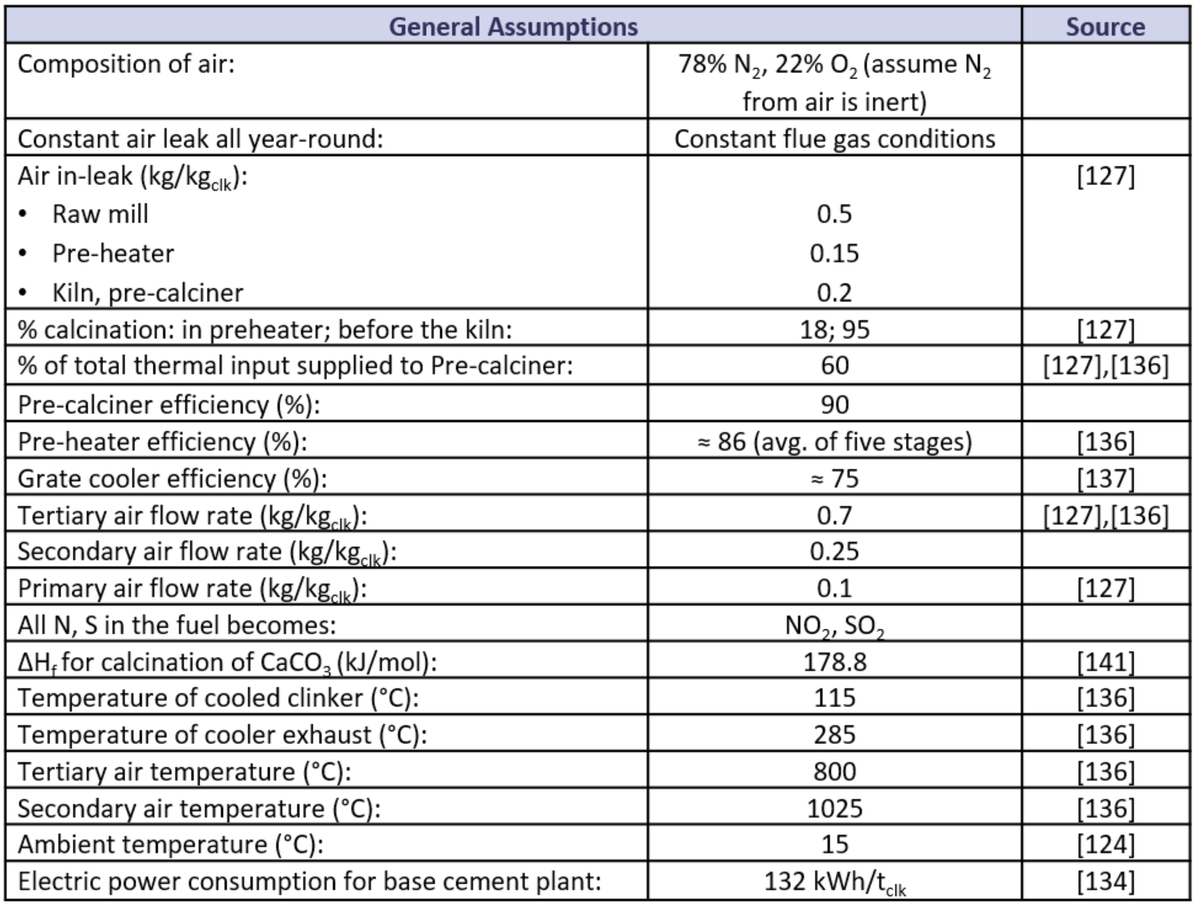
[2] The average share of clinker in the cement produced in Europe is 73.7%.

Table 3.3: Common assumptions used in technical assessment



General Assumptions		Source
Composition of air:	78% N_2, 22% O_2 (assume N_2 from air is inert)	
Constant air leak all year-round:	Constant flue gas conditions	
Air in-leak (kg/kg_{clk}):		[127]
• Raw mill	0.5	
• Pre-heater	0.15	
• Kiln, pre-calciner	0.2	
% calcination: in preheater; before the kiln:	18; 95	[127]
% of total thermal input supplied to Pre-calciner:	60	[127],[136]
Pre-calciner efficiency (%):	90	
Pre-heater efficiency (%):	≈ 86 (avg. of five stages)	[136]
Grate cooler efficiency (%):	≈ 75	[137]
Tertiary air flow rate (kg/kg_{clk}):	0.7	[127],[136]
Secondary air flow rate (kg/kg_{clk}):	0.25	
Primary air flow rate (kg/kg_{clk}):	0.1	[127]
All N, S in the fuel becomes:	NO_2, SO_2	
ΔH_f for calcination of $CaCO_3$ (kJ/mol):	178.8	[141]
Temperature of cooled clinker (°C):	115	[136]
Temperature of cooler exhaust (°C):	285	[136]
Tertiary air temperature (°C):	800	[136]
Secondary air temperature (°C):	1025	[136]
Ambient temperature (°C):	15	[124]
Electric power consumption for base cement plant:	132 kWh/t_{clk}	[134]

meal and the pre-calcined meal comprises of the clinker components formed due to the part of the raw meal that is calcined and also the part of the meal which remains to be calcined in the next stages. CO_2 is formed in the pre-heater, the pre-calciner and the kiln.

To reach the temperatures of 870°C and 1450°C in the pre-calciner and the kiln, coal is supplied for thermal energy. CO_2 formed by the combustion of coal is part of the exit gas. As illustrated in the process flow diagram (figure 3.3), the exit gas flows in the reverse direction. The outgoing hot flue gas at every stage pre-heats the incoming meal based on the counter-flow heat exchange principle. The flue gas is eventually removed from the exhaust filter placed near the raw mill. Dust (particulate matter) is produced in cement production process. In this model, it is assumed that the flow of dust is in the forward direction of mass flow, along with the products; this assumption is made for the reason that in this thesis, estimating the the rate of CO_2 emitted and energy consumption values are primary objectives and the the flow rates of dust do not affect any of these parameters. For the same reason, ash from the fuel is assumed to be part of the reverse direction of mass flow, that is, along with the exit (flue) gas.

The kiln exit (clinker) is sent to a cooler. A grate cooler is chosen to enhance the efficiency, as discussed in 2.2.1. Cool air input is sent to the cooler to cool the kiln exit. After taking heat from the clinker, part of the hot excess air is sent to the kiln and the pre-calciner as secondary and tertiary air respectively. These amounts are estimated based on the assumptions listed in Table 3.3; a cooler efficiency of about 75% (which is the average efficiency of a reciprocating grate cooler [137] [138]) is assumed. The excess hot air flows through an ESP (electrostatic precipitator) to remove dust and particulate matter.

Air in-leaks occur in the raw mill, pre-heater, pre-calciner and the kiln and they are unavoidable. The nitrogen in the air in-leaks forms part of the exit gas. This decreases the concentration of

CO_2 in the flue gas and increases volume flow rate of the flue gas [127]. Part of the oxygen in the air is consumed by the C, N, S and H in the fuel to form CO_2, NO_2, SO_2, and water vapor respectively; these gases along with the remaining oxygen and nitrogen from the air are also part of the exit (flue) gas. Primary air is fed into the kiln, along with the fuel injection.

Mass balance is set up for the base configuration described. A complete energy balance has not been performed (it is beyond the scope of this thesis). But for each unit, the total enthalpy values of the in-flows and out-flows are estimated; to meet the thermal energy demands of each process unit. The enthalpy values of the flows in and out of the units are estimated using the temperature, specific heat (C_p) and the mass flow rate. As mentioned in Table 2.1, when a preheater and pre-calciner are employed in a dry process, thermal energy of about 3.1 to 3.4 of MJ per kg of clinker (kg_{clk}) is required. The thermal energy consumption in the reference cement plant is in alignment with this value.

On estimating the rate of raw meal consumption and fuel (coal in the base case) consumption, the rate of CO_2 emitted from the cement plant has been estimated. **CO_2 emission intensity** is estimated as the amount of CO_2 emitted per tonne of the clinker produced. The value of electric power consumption (in kWh per tonne of clinker) has been taken from IEA's technical report based on which the configuration of the reference cement plant (without CCS) for this thesis has been set up [134].

3.4 ECONOMIC EVALUATION

An Excel model for estimation of the economic parameters was developed. The objective of the economic assessment was to estimate the levelised costs of clinker (LCOC). The geographical boundary considered in the economic assessment is Europe (average cost/price values in the EU region are used). The cost methodology employed is presented in this section. The evaluation comprised of estimating capital investment costs, operating costs (fixed and variable) of the cement plant without CO_2 capture and for all the BECCS scenarios (section 3.7). All economic assessments are reported on a 2018 basis. The costs of equipment were translated (equated) to 2018 basis using the Chemical Engineering Plant Cost Index (CEPCI) (presented in table 3.4) as indicated by equation 1. The economic assumptions common to all CO_2 capture scenarios are presented in Table 3.5.

Table 3.4: CEPCI values [139]

Year	CEPCI
2008	575.4
2010	550.8
2013	567.3
2014	576.1
2015	556.8
2016	541.7
2017	567.5
2018	603.1

3.4.1 Capital expenses (CapEx):

The total capital investment required is referred to as CapEx and it was determined by estimating the total plant costs (TPC). TPC for the BECCS technologies (TPC_{BECCS}) includes the cement

$$\mathrm{EC_{2018}} = \mathrm{EC_{year\ t}} * \left(\frac{603.1}{\mathrm{CEPCI_{year\ t}}}\right) \quad \text{.....Eqn. [1]}$$

$$\mathrm{EC_{scaled}} = \mathrm{EC_{base}} * \left(\frac{\mathrm{capacity_{scaled}}}{\mathrm{capacity_{base}}}\right)^{0.6} \quad \text{.....Eqn. [2]}$$

$$\mathrm{TDC} = \mathrm{EC} + \mathrm{IC} + \mathrm{C_{Process}} \quad \text{.....Eqn. [3]}$$

$$\mathrm{TPC} = \mathrm{TDC} + \text{Indirect Costs} + \text{Owner's Costs} + \mathrm{C_{Project}} \quad \text{.....Eqn. [4]}$$

$$\mathrm{CapEx} = \mathrm{TPC} + \text{Start-up Costs} \quad \text{.....Eqn. [5]}$$

plant costs (TPC_{base}) and the retrofit CO_2 capture plant costs ($TPC_{retrofit}$). Total plant costs are estimated by totalling the equipment costs (EC), installation costs (IC), process contingencies ($C_{Process}$), indirect costs, owner's costs and project contingencies ($C_{Project}$) as shown in equations 3 and 4.

- Equipment costs (EC): EC includes the sum of the costs of all equipment of the different processes involved. They were estimated using the parameters derived from the results of the technical assessment and based on expressions (or assumptions) obtained from literature (stated in section 3.7).

- Installation costs (IC): IC refers to the expenses incurred while integrating the equipment into the plant, such as civil works, erection, etc. The installation costs vary depending on the complexity of the equipment and they are calculated in techno-economic studies as a factor of the equipment costs (EC). In this thesis, for individual equipment in case of each of the CO_2 capture technologies, either installation costs are calculated using factors obtained from literature (or) the total value of equipment and installation costs (EC+IC) are directly obtained and scaled. The assumptions for individual equipment of the CO_2 capture plants are mentioned in section 3.7. For the base cement plant however, the total of equipment and installation costs are taken from IEA's technical report [134] and updated using CEPCI[3].

- Indirect costs: These include costs for yard improvement, building, service facilities, engineering/consultancy costs.

- Owner's costs: These include costs for planning, designing and commissioning the cement plant.

For the CO_2 capture equipment, the equipment costs were scaled on the basis of their capacity and CEPCI (as shown in equations 1 and 2[4]). A scaling factor was used to scale the equipment, which usually varies depending on the complexity of the equipment. In this thesis, a scaling factor of 0.6 was used for all the equipment [140]. For some equipment (such as ASU, CPU), the cost expressions were directly obtained from literature and they are stated in section 3.7.

Total direct costs (TDC) were calculated as the sum of equipment and installation costs, after including the process contingencies. Process contingencies ($C_{process}$) were included to reflect the variations in the level of maturity between the considered CO_2 capture technologies. They were calculated as a fraction of the sum of equipment and installation costs. Considering 'nth of a kind' estimate, the technology was assumed to be mature and commercially well-established. Therefore, additional costs due to first time setting up are neglected (excluded) for this kind of a situation. Even if CO_2 capture technologies are not mature enough in practice, this assumption was made as the assessment was carried out with the objective of enabling retrofitting of such technologies, once they attain a certain level of maturity, scaling up the TRL scale.

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[3] The size of the base cement plant in this thesis is the same as that in the stated reference, therefore there is no need for scaling based on the capacity.

[4] If the sum of equipment and installation costs were obtained directly from literature, then (EC+IC) was scaled and updated with CEPCI using the equations 1 and 2.

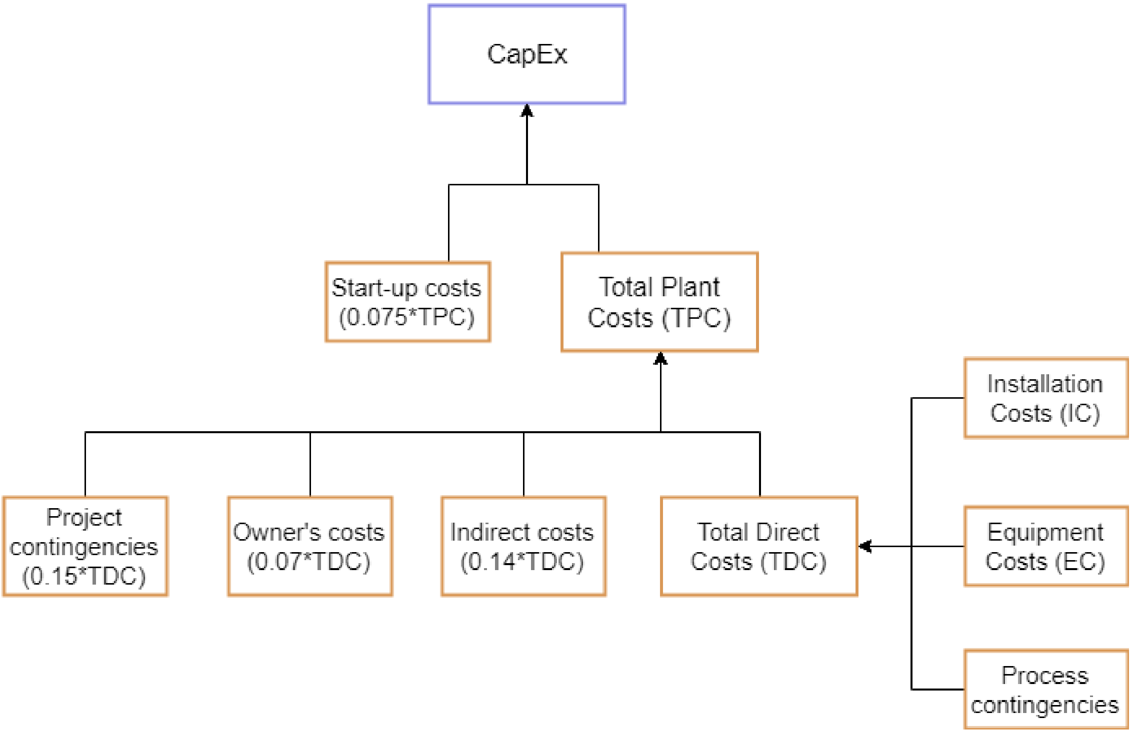

Figure 3.4: Elements of capital expenses (CapEx) in this evaluation

Start-up costs are incurred before the set up plants are actually in operation, but after installation of the equipment. A value of 7.5% of the total plant costs was assumed here [141]. To get CapEx, the total plant costs were added with the start-up costs. The capital expenses (CapEx) estimated for the base year were translated to a yearly basis while estimating the levelised costs. This is to account for depreciation[5]. A construction time of 2 years is assumed each for the cement plant and the CO_2 capture plant. Allocation of capital expenses across both the years is assumed to be 50% [142]. CapEx is determined using the equations numbered as 3, 4 and 5.

3.4.2 Operating expenses (OpEx):

Operating expenses include costs incurred due to utilities and consumables, labor, maintenance, insurance and local taxes. They are categorized further into variable operating expenses (variable OpEx) and fixed operating expenses (fixed OpEx). Variable OpEx refers to the costs of utilities and consumables (fuel (coal [143], biomass), raw materials, electricity, operation & maintenance) and are evaluated based on the results of the technical assessment; the costs are subject to change depending on the CO_2 capture technology and its process requirements. The capture technology specific consumables are included under variable OpEx; for instance, the price of MEA solvent in case of MEA based CO_2 capture. The costs incurred for CO_2 transportation and storage are estimated using the assumptions listed below and they are categorized under variable OpEx as they are dependant on the amount of CO_2 that is captured and compressed; therefore these costs are subject to change depending upon the biomass used and the CO_2 capture technology.

- Cost of CO_2 transport[6]: 6 €/t_{CO_2} [111].
- Cost of CO_2 storage[7]: 10 €/t_{CO_2} [118].

Fixed OpEx includes the following:

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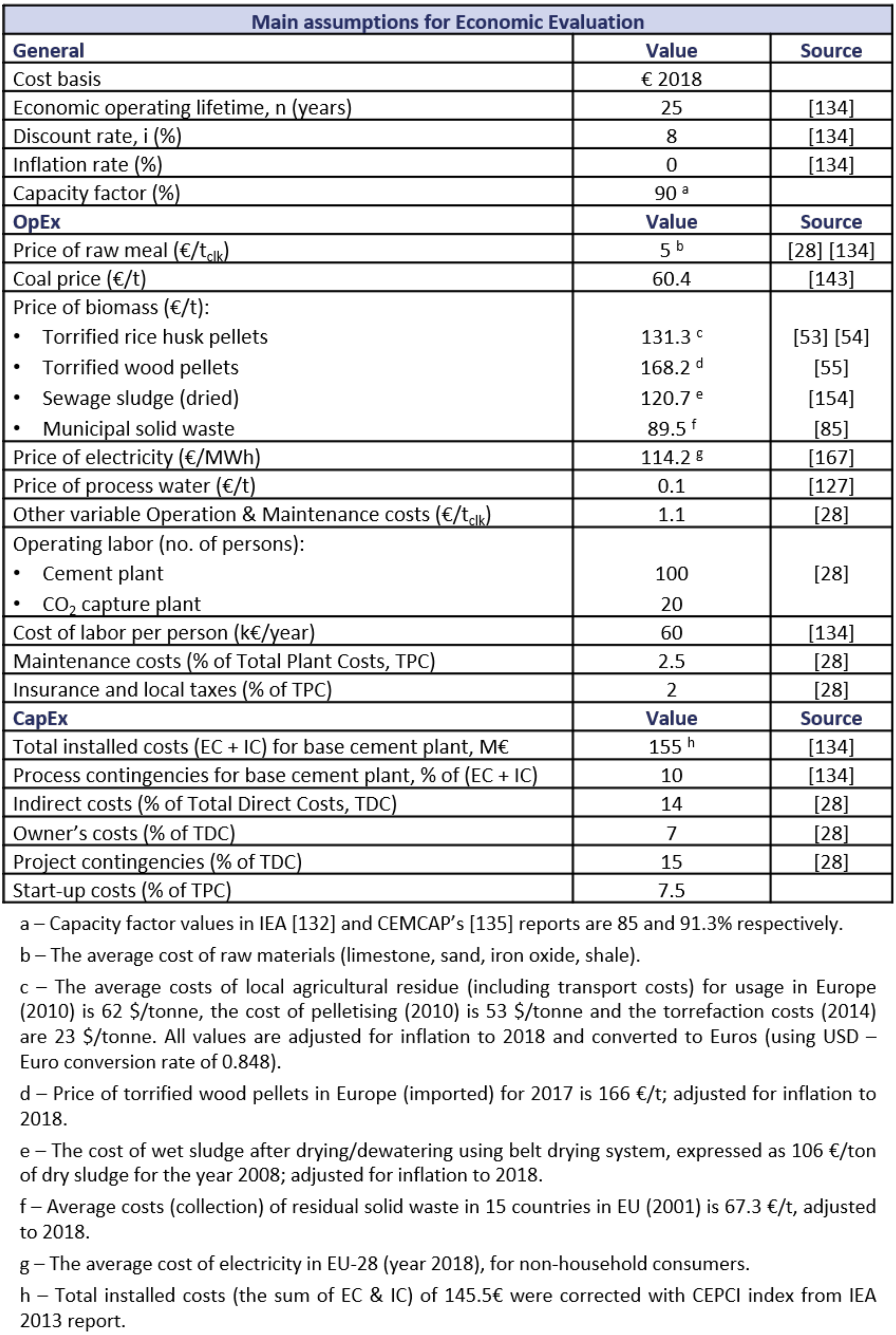
[5] Depreciation accounts for the equipment's loss of value over time.
[6] Unit transportation costs for offshore pipeline transportation (500 km).
[7] Storage cost in the medium cost scenario for offshore DOGF, with no possibility of re-using existing wells (NoLeg).

Table 3.5: Assumptions used in economic assessment (common to all CO_2 capture scenarios)



Main assumptions for Economic Evaluation		
General	**Value**	**Source**
Cost basis	€ 2018	
Economic operating lifetime, n (years)	25	[134]
Discount rate, i (%)	8	[134]
Inflation rate (%)	0	[134]
Capacity factor (%)	90 [a]	
OpEx	**Value**	**Source**
Price of raw meal (€/t_{clk})	5 [b]	[28] [134]
Coal price (€/t)	60.4	[143]
Price of biomass (€/t):		
- Torrified rice husk pellets	131.3 [c]	[53] [54]
- Torrified wood pellets	168.2 [d]	[55]
- Sewage sludge (dried)	120.7 [e]	[154]
- Municipal solid waste	89.5 [f]	[85]
Price of electricity (€/MWh)	114.2 [g]	[167]
Price of process water (€/t)	0.1	[127]
Other variable Operation & Maintenance costs (€/t_{clk})	1.1	[28]
Operating labor (no. of persons):		
- Cement plant	100	[28]
- CO_2 capture plant	20	
Cost of labor per person (k€/year)	60	[134]
Maintenance costs (% of Total Plant Costs, TPC)	2.5	[28]
Insurance and local taxes (% of TPC)	2	[28]
CapEx	**Value**	**Source**
Total installed costs (EC + IC) for base cement plant, M€	155 [h]	[134]
Process contingencies for base cement plant, % of (EC + IC)	10	[134]
Indirect costs (% of Total Direct Costs, TDC)	14	[28]
Owner's costs (% of TDC)	7	[28]
Project contingencies (% of TDC)	15	[28]
Start-up costs (% of TPC)	7.5	

a – Capacity factor values in IEA [132] and CEMCAP's [135] reports are 85 and 91.3% respectively.

b – The average cost of raw materials (limestone, sand, iron oxide, shale).

c – The average costs of local agricultural residue (including transport costs) for usage in Europe (2010) is 62 $/tonne, the cost of pelletising (2010) is 53 $/tonne and the torrefaction costs (2014) are 23 $/tonne. All values are adjusted for inflation to 2018 and converted to Euros (using USD – Euro conversion rate of 0.848).

d – Price of torrified wood pellets in Europe (imported) for 2017 is 166 €/t; adjusted for inflation to 2018.

e – The cost of wet sludge after drying/dewatering using belt drying system, expressed as 106 €/ton of dry sludge for the year 2008; adjusted for inflation to 2018.

f – Average costs (collection) of residual solid waste in 15 countries in EU (2001) is 67.3 €/t, adjusted to 2018.

g – The average cost of electricity in EU-28 (year 2018), for non-household consumers.

h – Total installed costs (the sum of EC & IC) of 145.5€ were corrected with CEPCI index from IEA 2013 report.

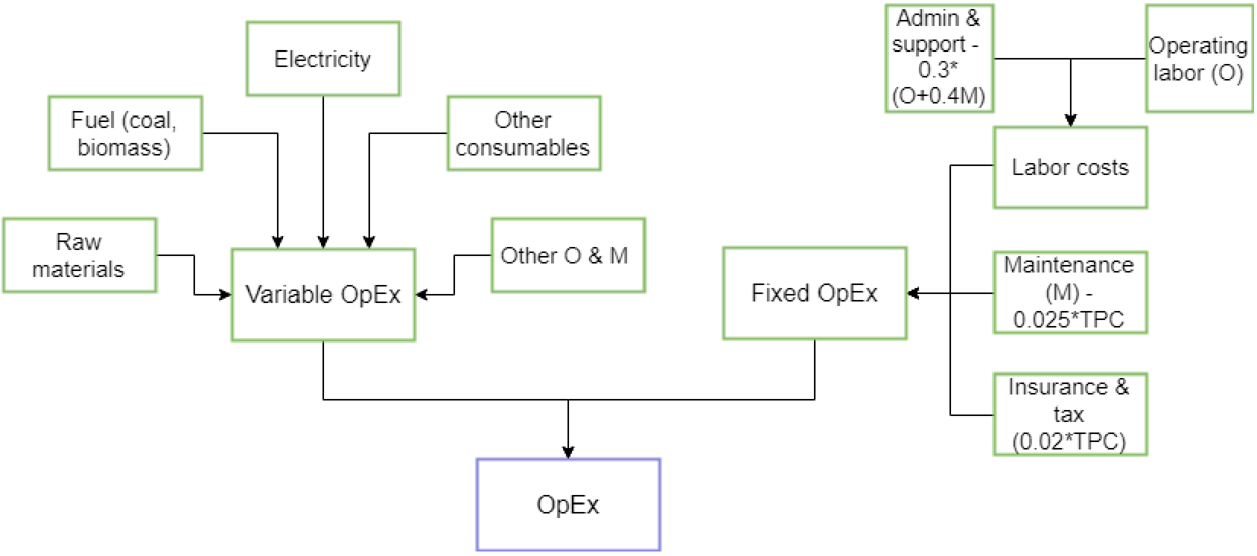


Figure 3.5: Elements of operating expenses (OpEx) in this evaluation

- Labor costs: this includes operating labor, administrative and support labor. Administrative and labor costs are assumed to be 30% of the operating labor and the maintenance labor costs [134].
- Maintenance costs: This includes the costs of preventive and corrective maintenance (replacing faulty components, materials). Maintenance labor costs are assumed to be 40% of the total value for maintenance.
- Total annual cost of insurance and local property taxes of 2% of the total plant costs is considered [141]. This also includes miscellaneous regulatory and overhead fees.

No CO_2 emission taxation is considered in the evaluation. CapEx and OpEx are estimated for the base year '2018', which is then used to estimate the costs over the entire lifetime, to obtain the levelised costs.

3.4.3 Levelised costs of clinker (LCOC):

The definition for levelised costs as stated by IEA/NEA is regarded as the broadest among other definitions: "the present value of the sum of discounted costs divided by total production adjusted for its economic time value" [144]. LCOC is calculated by estimating the total capital and operating expenses incurred over the entire lifetime defined for the economic assessment. It is given by the **ratio of the total lifetime costs to the total lifetime output** (output is clinker) [144]. LCOC is expressed in Euros per tonne of clinker, '$€/t_{clk}$' and is estimated using equation 6. The allocation of CapEx and OpEx over the economic operating lifetime of the cement plant is depicted in figure 3.6.

The cement plant is constructed over a period of two years post the base year of 2018 (that is, year 1 and 2), followed by which the operation of the cement plant is assumed to begin (that is, starting from year 3 until year 27). The CO_2 capture plant can be retrofitted at any stage during the operating lifetime of the cement plant - it has been assumed in this thesis that the CO_2 capture plant is retrofitted during the 10th year of operation (that is, year 12) and constructed over a two year period (that is, year 12 and 13). However this was subjected to a sensitivity analysis by estimating the cost variations when the CO_2 capture plants are retrofitted at different stages of operation.

The capital and operating expenses (related to the cement plant and the CO_2 capture plant) are first estimated for the base year 2018. Using the base year expenses, the yearly expenses

LCOC – levelised cost of clinker (in $€/t_{clk}$): .....Eqn. [6]

$$\mathrm{LCOC} = \frac{\sum_{t=1}^{n+2} \frac{\frac{\mathrm{CapEx}_t}{c_f} + \mathrm{Fixed\ OpEx}_t + \mathrm{Variable\ OpEx}_t}{(1+i)^t}}{\sum_{t=1}^{n+2} \frac{A,\mathrm{clk}_t}{(1+i)^t}}$$

CapEx_t = capital expenses in year ‘t’ (in €)

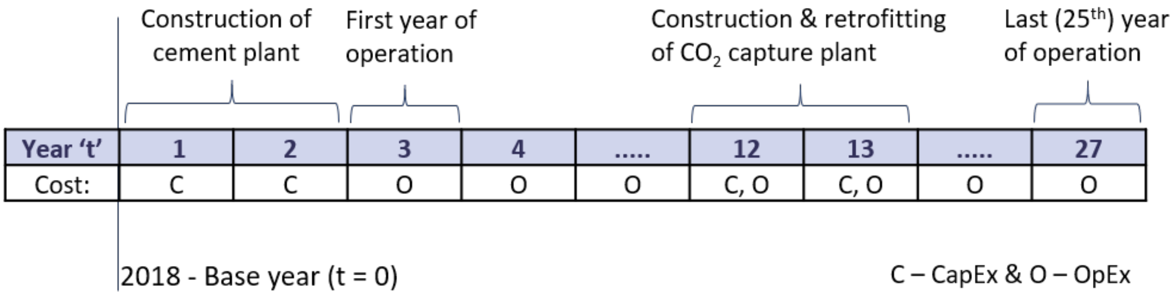
Fixed OpEx_t and Variable OpEx_t = fixed and variable operating expenses in year ‘t’ (in €)

i = discount rate

n = economic plant lifetime

c_f = capacity factor

A,clk_t – annual clinker production in year ‘t’ (in tonnes)



Year ‘t’	1	2	3	4	.....	12	13	.....	27
Cost:	C	C	O	O	O	C, O	C, O	O	O

Figure 3.6: Allocation of capital expenses (CapEx) and operating expenses (OpEx) over the entire lifetime of the cement plant’s operation.

as stated in equation 6 are estimated (CapEx_t, fixed OpEx_t and variable OpEx_t) for t = 1 to t = 27. The capital expenses for the cement plant are estimated for the years t = 1 and t = 2 by estimating the TPC_{base}. Similarly the capital expenses associated with the retrofitted CO_2 capture plant are estimated by first calculating the retrofit plant costs ($\mathrm{TPC}_{retrofit}$). CapEx associated with the retrofit are then estimated for the years t = 12 and t = 13 using $\mathrm{TPC}_{retrofit}$. The operating expenses associated with the CO_2 capture technology are included post year 12, until year 27. Partial substitution of coal with biomass however, is considered to be implemented from year 1, in the BECCS scenarios.

During the construction of the CO_2 capture plant, the operation of the cement plant may be affected depending on the capture technology. It has been mentioned in literature for oxyfuel combustion capture that it entails a shut down of the cement plant for a six month period - in this thesis, this period of 6 months is assumed to be during the second year of construction of the capture plant (that is, the last 6 months of year 13). However, for the other two CO_2 capture technologies (MEA and CaL), this information was not explicitly available in literature. Therefore an assumption was made that three months of operation of the cement plant will be affected during the construction and setting up of MEA and CaL based CO_2 capture technologies (that is, last three months of year 13).

Levelised costs are standardized on the basis of unit of clinker in this thesis; this is because the direct CO_2 emissions in a cement plant are associated with the production of clinker only. Furthermore, the CO_2 emission intensity and the technical key performance indicators chosen (defined in section 3.5) are also represented per tonne of clinker. However, in the LCOC calculations, the costs pertaining to the cement grinding stage are also included (price of electric power consumed for grinding, price of additives, equipment costs for grinding, etc.); it is just that the standardization of these terms is per tonne of clinker, instead of cement.

3.5 KEY PERFORMANCE INDICATORS

A comparative assessment has been carried out with the case scenarios evaluated, the five key performance indicators (KPIs) listed in this section are compared with the estimated base case values. The first three indicators are defined to compare the technical performance of the BECCS technologies.

KPI 1 - Rate of clinker produced:

This indicator refers to quantity of clinker produced (in tonnes per day) on substituting a portion of the coal with biomass. The reduction in thermal input (due to lower heating value of biomass) implies a reduction in the clinker output. The amount of annual cement production (in mega tonnes per year) as a result of reduced clinker, is estimated from this value.

KPI 2 - Total CO_2 avoided:

CO_2 avoided is defined as the amount of emissions that are avoided on co-firing coal with biomass and retrofitting the CO_2 capture plant, with respect to the initial value of emissions in the reference case (coal without the CO_2 capture plant). Direct ($\mathbf{e_d}$) and indirect emissions ($\mathbf{e_i}$) are included. Direct emissions refer to emissions due to calcination and fuel combustion at the cement plant. Indirect emissions refer to the emissions due to generation of the electric power consumed by the cement plant. In the reference cement plant, the amount of CO_2 emissions per unit of product is estimated as the **CO_2 emission intensity** (in kg_{CO_2}/t_{clk}). The CO_2 capture plant consumes additional fuel and electricity, which further increases the direct emissions. A fraction of the direct emissions are captured and the net direct emissions in the BECCS case are therefore reduced. The difference between the net direct emissions in the BECCS case[8] and the net direct emissions in the base case are calculated (as illustrated by the diagram in 3.7).

Similarly, the difference in indirect emissions between the BECCS and base case per unit of clinker are estimated using the equation depicted for $\mathbf{e_i}$ in figure 3.7. Indirect CO_2 emissions, are calculated using an electricity generation efficiency of 45% and specific CO_2 emissions ($Em_{sp,elec}$) of 295.8 kg CO_2 per MWh or 0.082 kg CO_2 per MJ. This is based on the contribution of different fuels to electricity generation in the European Union in 2016 [145]. The power consumption in MJ per tonne of clinker is used to estimate the indirect primary energy consumption using the stated efficiency value; and then the specific emission factor is used to estimate the indirect emissions.

A fraction of CO_2 in the BECCS cases is the CO_2 generated by the combustion of biomass in the fuel mix used. It is assumed in the calculations that CO_2 emitted by the combustion of biomass implies an equivalent amount of CO_2 removed from the atmosphere ($\mathbf{r_{bio}}$). Therefore the CO_2 removed from the atmosphere is included in the term 'total CO_2 avoided'. Different biomass types have varied biogenic content, particularly solid wastes. The extent of carbon neturality (as assumed in this thesis) for each of the biomass types chosen is explained under the methodology for carbon accounting in section 3.6.

The total CO_2 avoided is obtained as the difference in total CO_2 emission intensities - direct and indirect, to which the CO_2 removed from the atmosphere is added, as illustrated by the formula in figure 3.7.

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[8] Note that the direct CO_2 emissions in the BECCS case refers to the CO_2 emitted after a fraction of the total emissions is captured by the CO_2 capture technology used.

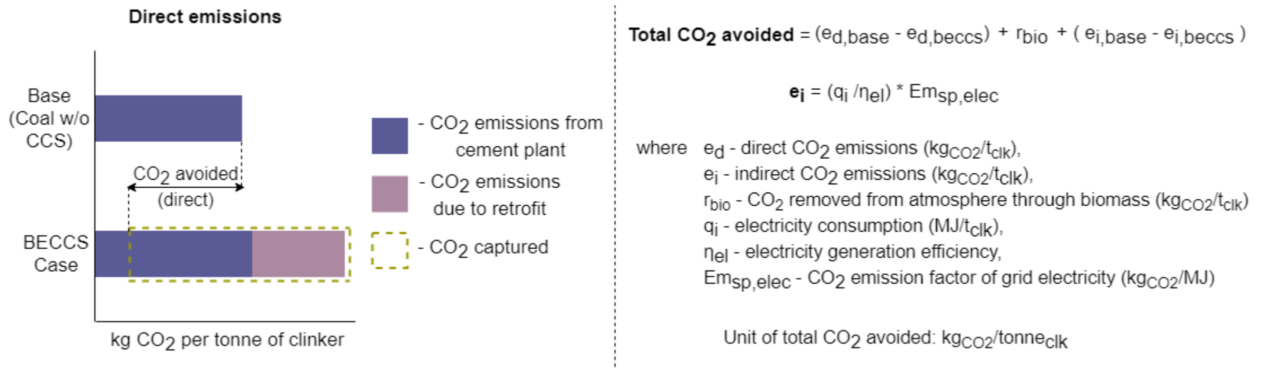

Figure 3.7: Diagram to illustrate direct CO_2 avoided (left) and the formula to estimate 'total CO_2 avoided' (right)

KPI 3 - Specific primary energy consumption per CO_2 avoided (SPECCA):

SPECCA is defined as the incremental primary energy required to avoid CO_2 emissions to the atmosphere [110] [146]. The reference plant consumes thermal energy (in the form of coal) and electric power; when the CO_2 capture plant is retrofitted, additional energy (thermal and electrical) is consumed. This additional primary energy consumption per unit of avoided CO_2 is termed as SPECCA (formula used is mentioned in figure 3.8). To understand 'primary energy consumption', the terms 'direct' and 'indirect' fuel consumption are defined:

- Direct fuel consumption (q_d): This indicates the primary energy consumed in the cement plant or the CO_2 capture plant, through combustion of the fuel employed per unit of clinker produced (MJ/t_{clk}).
- Indirect fuel consumption: This indicates the primary energy consumption associated with the electric power consumption (q_i) in the cement plant or the CO_2 capture plant. By defining a reference electric efficiency (45%), the energy consumed (in the form of fuel) to generate the electric power that is required for the cement plant (or the CO_2 capture plant) has been calculated as 'q_i/efficiency'.

The total of direct and indirect fuel consumption is referred to as the **total primary energy consumption** and is expressed in MJ/t_{clk}. The difference in the total primary energy consumption for the BECCS case and the base case is calculated. The ratio of this difference to the total CO_2 avoided (KPI 2) is expressed in MJ/kg_{CO_2} as SPECCA.

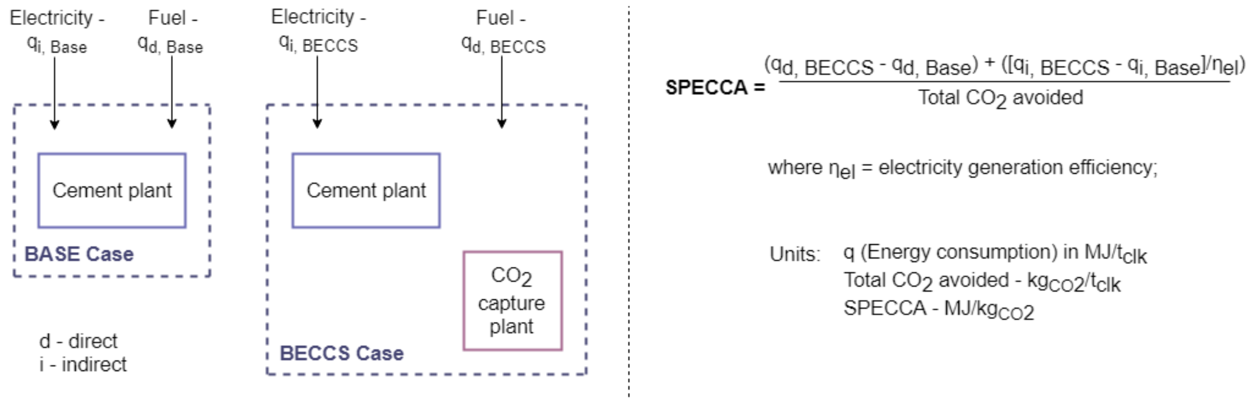

Figure 3.8: Diagram to illustrate direct and indirect primary energy consumption (left) and the formula to estimate 'SPECCA' (right)

The following two indicators are defined to compare the economic performance of the BECCS technologies.

KPI 4 - Cement production cost (CPC)[9]:

CPC is estimated by first obtaining the levelised costs of clinker (LCOC). The cement production costs are calculated from the levelised costs of clinker by using the clinker-cement factor of 0.737. CPC is obtained using equation 7 and is expressed in '€/t_{cement}'.

$$\text{CPC } (€/t_{cement}) = 0.737 * \text{LCOC} \qquad \text{.....Eqn. [7]}$$

$$\text{Cost of } CO_2 \text{ avoided} = \frac{(\text{LCOC}_{\text{BECCS}} - \text{LCOC}_{\text{Base}})}{\text{Total } CO_2 \text{ avoided}} \qquad \text{.....Eqn. [8]}$$

KPI 5 - Cost of CO_2 avoided:

The cost per unit of avoided CO_2 incurred for the BECCS technology used for a cement plant is estimated in accordance with the **exhaustive** method as described in [147]. The paper describes three methods - exhaustive, net present value and annualisation methods to calculate CO_2 avoidance costs of CCS from industry. It has been stated that, when the production of industrial plant is affected by the implementation of CCS, only the exhaustive method is valid. Therefore, of the three methods, only the 'exhaustive' method can be applied in the context of this thesis, as the production rate of cement is affected due to the BECCS technologies. In the exhaustive method, the cost of CO_2 avoided is calculated as the ratio of the difference between the levelised costs for the BECCS and the base case to the total CO_2 avoided due to the BECCS technology. It is calculated using equation 8 and expressed in '€/t_{CO_2}'.

3.6 CARBON ACCOUNTING

In this section, a 'gate-to-gate' accounting of the CO_2 emissions are estimated also by taking into consideration the carbon dioxide that the biomass consumed (the extent to which biomass is C-neutral). Also indirect emissions generated due to cement grinding (outside of the clinker production process) are taken into account. The amount of CO_2 emissions and all other quantities in this section are standardized on the basis of cement produced (per tonne of cement) instead of clinker produced.

Direct emissions are from the results of the technical assessment. For indirect emissions (emissions due to electric power consumption), the electric power consumption for the base cement plant is taken as 97 kWh per tonne of cement [134]. This is the value for the electric power consumption in the clinker production phases (raw material grinding in the raw mill, units where calcination takes place) and the cement grinding (milling) stage, storage, packaging and dispatch of end product (cement).

Factors such as the type of biomass, time horizon, land use change and rotation period determine the extent to which the biomass actually removes biomass [148]. In this thesis, however, rice husk and wood are to be carbon-neutral, that is, they absorb as much CO_2 as they emit when they're burnt. The biogenic content in sewage sludge is assumed to be 100% [134]. Municipal solid waste (MSW) is only partly organic (biogenic). The biogenic content in MSW is assumed to be 35%. 35% biogenic content in MSW is assumed on the basis of a study carried out by EEA

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[9] CPC does not include costs for land property, permits, raw material deposits and freight costs for cement delivery as high uncertainty of influencing parameters makes it harder to estimate these terms; moreover, they are unaffected by CO_2 capture [134]

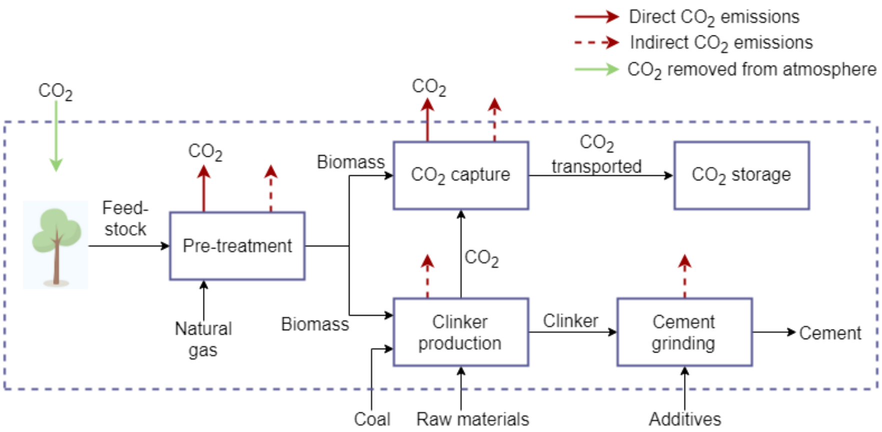
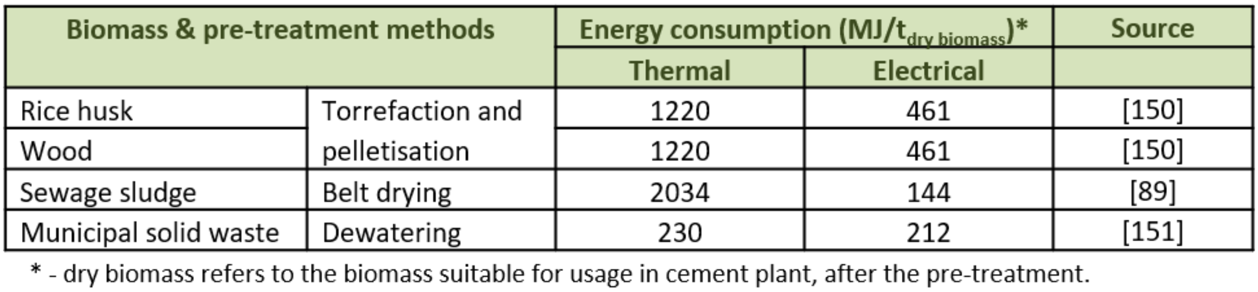


Figure 3.9: System boundary defined for carbon accounting

Table 3.6: Thermal and energy consumption values for the pre-treatment of biomass feedstock



Biomass & pre-treatment methods		Energy consumption ($MJ/t_{dry\ biomass}$)*		Source
		Thermal	Electrical	
Rice husk	Torrefaction and pelletisation	1220	461	[150]
Wood		1220	461	[150]
Sewage sludge	Belt drying	2034	144	[89]
Municipal solid waste	Dewatering	230	212	[151]

* - dry biomass refers to the biomass suitable for usage in cement plant, after the pre-treatment.

(European Environmental Agency) which reported the average share of biogenic content in the various samples of municipal solid waste studied across the EU-28 region[10] [149].

The system boundary defined for this section is depicted in figure 3.9. The following are included in the boundary defined for the CO_2 accounting - cement manufacture process, with the retrofitted CO_2 capture plant, storage of the captured CO_2, pre-treatment of the biomass and the CO_2 removed from the atmosphere through the biomass. Performing a life-cycle assessment (LCA) was not part of the objectives of this thesis. Therefore a detailed inventory of the upstream process emissions was not prepared. However, the direct and indirect CO_2 emissions associated with the pre-treatment of biomass was included. For rice husk and wood, torrefaction and pelletisation are considered [150], belt drying for sewage sludge [89] and de-watering for municipal solid waste [151]. For estimating the CO_2 emissions associated with these processes, the thermal and electrical energy requirements for different types of pre-treatment are assumed from literature, and they are listed in table 3.6. To provide the thermal energy, it was assumed that natural gas (NG) is the fuel used in all the cases and a specific CO_2 emissions factor of 2.75 kg_{CO_2}/kg_{NG} is assumed [152].

3.7 BECCS SCENARIOS ASSESSED

This section discusses the BECCS scenarios which are the main focus of this thesis. Process flow diagrams are depicted, the CO_2 capture technologies are explained and the assumptions used in the assessment are tabulated for each of the CO_2 capture technologies. The following case scenarios are evaluated:

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[10] The share of bio-waste in total MSW in Europe (on an average) is between 30 and 40%, as per a study by the European Environment Agency.

- Co-firing biomass with coal, the CO_2 capture technology here is post combustion using mono-ethanol amine by the principle of chemical absorption; referred to as **MEA**.
- Co-firing biomass with coal, the CO_2 capture technology involved is post combustion using tail-end calcium looping; referred to as **CaL**.
- Co-firing biomass with coal, the CO_2 capture technology involved is oxyfuel combustion; referred to as **Oxyfuel**.
- Using the ash obtained from biomass co-firing as a raw material for clinker production or an additive in the cement grinding process.

The four biomass options chosen for direct co-firing with coal are: torrified rice husk pellets (RHP), torrified wood pellets (WP), dry sewage sludge (SS) and municipal solid waste (MSW). In the fourth BECCS scenario, using the ash obtained as a result of direct co-firing of coal with biomass in the raw meal or as an additive for cement grinding is explored for all of the CO_2 capture technologies assessed. The composition of the fuels are depicted in Table 3.7.

Table 3.7: Composition (mass fraction in %) of coal [135] and biomass [153] as used in this thesis, with their heating values

	Coal	RHP	WP	SS	MSW
Ash	16.5	16.12	0.5	32.3	16.82
C	69	47.85	50.15	31	49.23
O	9	26.47	43.18	26.5	23.73
H	4	4.01	6.07	4.6	8.15
N	0.5	0.43	0.09	4.5	1.82
S	0.5	0.05	0.01	1.1	0.25
Moisture	0.5	5.07	-	-	-
LHV (MJ/kg)	27.2	16.16	21	10.97	18.7

RHP and WP are purchased directly in their torrified and pelletised forms. RHP, WP and MSW are obtained such that they can be directly fed for co-firing with coal. Sewage sludge is also purchased in its dry (dewatered) form; it was discussed in section 2.2.4 that sludge is best suited for co-firing after pre-drying. It is therefore assumed that dried sludge is sourced for usage in the cement plant [154].

A co-firing rate of 30% was decided for the four chosen biomass options to enable a fair comparison. This is in accordance with the average substitution rate of alternative fuels (including biomass and wastes) in cement plants across Europe - 30.5% on thermal-basis [134]. In this thesis, however, substitution on mass-basis has been considered. Another basis for deciding 30% as the co-firing rate is that there are no major negative environmental impacts for this value in all the four alternative fuel options. This was discussed in chapter 2.

Owing to the emphasis on retrofitting in this thesis, the capacity of the furnace is held constant constant while replacing a portion of the heating fuel used in the base cement plant (coal). Due to the low energy of biomass, it is expected to alter the output flow rate of clinker. To estimate this, and thereby the reduced annual cement production, the net thermal energy consumption in the base cement plant has been used to estimate the fraction of the thermal input that is consumed for the formation of clinker. The clinker formation energy (in kcal/kg_{clk}) is estimated as [155]:

Eqn [9]: $\text{Formation energy} = 7.646[CaO] + 6.48[MgO] + 4.11[Al_2O_3] - 5.116[SiO_2] - 0.59[Fe_2O_3]$

where [X] represents the percentage of component 'X' in the clinker produced.

A CO_2 capture rate of 90% is assumed in this thesis for all the CO_2 capture technologies. This refers to the fraction of CO_2 avoided from the flue gas in the cement plant.

3.7.1 Scenario 1: Post combustion CO_2 capture using MEA

Mono-ethanol amine (C_2H_7NO) - based CO_2 capture is an end-of-pipe option. The flue gas from the raw mill is sent through a filter to remove the particulate matter (ash, dust); the capture units are retrofitted post the filter as shown in the process flow diagram in figure 3.10. For effective absorption by MEA, it is imperative to have very minimal SO_2 and NO_2 in the flue gas [127]. The flue gas stream from the filter is taken through a Selective Non-Catalytic Reduction (SNCR) process to reduce the NO_2. Vaporized ammonia (NH_3) is supplied as a reducing agent; the quantity of this is calculated on the basis of the molar quantity of NO_2 present in the incoming flue gas stream. Part of the NH_3 exits the unit, which leads to lower reduction rates (this is referred to as NH_3 slip). To deal with this and ensure higher reduction rates, increasing the rate of NH_3 supplied is considered; it has been assumed that 1.5 times the stoichiometric amount is fed to achieve a reduction of NO_2 to a concentration suitable for MEA absorption[11] [135] [156]. The corresponding equation for NO_2 reduction is:

$$4\,NH_3 + 2\,NO_2 + O_2 \longrightarrow 3\,N_2 + 6\,H_2O$$

The flue gas stream exiting the SNCR unit is subject to flue gas desulphurization (FGD), to remove the SO_2 from the flue gas. Limestone and water are sent in as inputs and gypsum is formed, which is then removed from the unit. The equation involved is:

$$CaCO_3 + SO_2 + 2\,H_2O + 0.5\,O_2 \longrightarrow CaSO_4 \cdot 2\,H_2O + CO_2$$

The remaining $CaCO_3$ is removed as the effluent out of the FGD unit. The wet limestone slurry cools the gas and the flue gas released from the FGD unit will have a temperature of 50°C, which is the temperature suitable for MEA absorption [127]. Flue gas is then blown to the absorption unit. The incoming flue gas stream comes into contact with the CO_2-lean MEA which is recirculated from the desorber and the make-up MEA. CO_2 is absorbed by the MEA and the CO_2-rich MEA is sent to the desorber for regeneration. The absorber-desorber system should ideally be a closed-loop system where the MEA is recirculated to the absorber[12] once the CO_2 has been stripped off in the desorber. However some components of the flue gas react with MEA to form amine salts[13]. It is to compensate this, that the make-up MEA is sent in to the absorber. The corresponding equation of the absorption process is:

$$OH-C_2H_4-NH_2 + H_2O + CO_2 \longrightarrow OH-C_2H_4-NH_3{}^+ + HCO_3{}^-$$

Low pressure steam is required for the desorber [157] [158] [159]. A biomass-fired boiler is installed on-site to generate steam for the desorber. The emissions from the boiler are not captured[14]. The biomass chosen for co-firing is also used to fire the steam boiler and an efficiency of 90% is assumed [160].

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[11] NO_x concentration at absorber inlet for MEA absorption should be limited to 410 mg/Nm^3 [127]

[12] There is exchange of heat on the counterflow principle. The recirculation loop b/w the absorber and desorber is completed by a heat exchanger, which is not shown in the process flow diagram; However its costs have been accounted for.

[13] Thermal reclaiming of MEA solvent to remove the heat stable salts or amine degradation products is not considered in this thesis

[14] The steam requirement for desorption is estimated based on the amount of CO_2 captured (check assumptions in Table 3.8). Using the thermal energy value, the rate of fuel (NG) consumption in the boiler is estimated. If emissions from the steam boiler were to be captured, steam requirement would further increase and hence this hasn't been considered in this thesis.

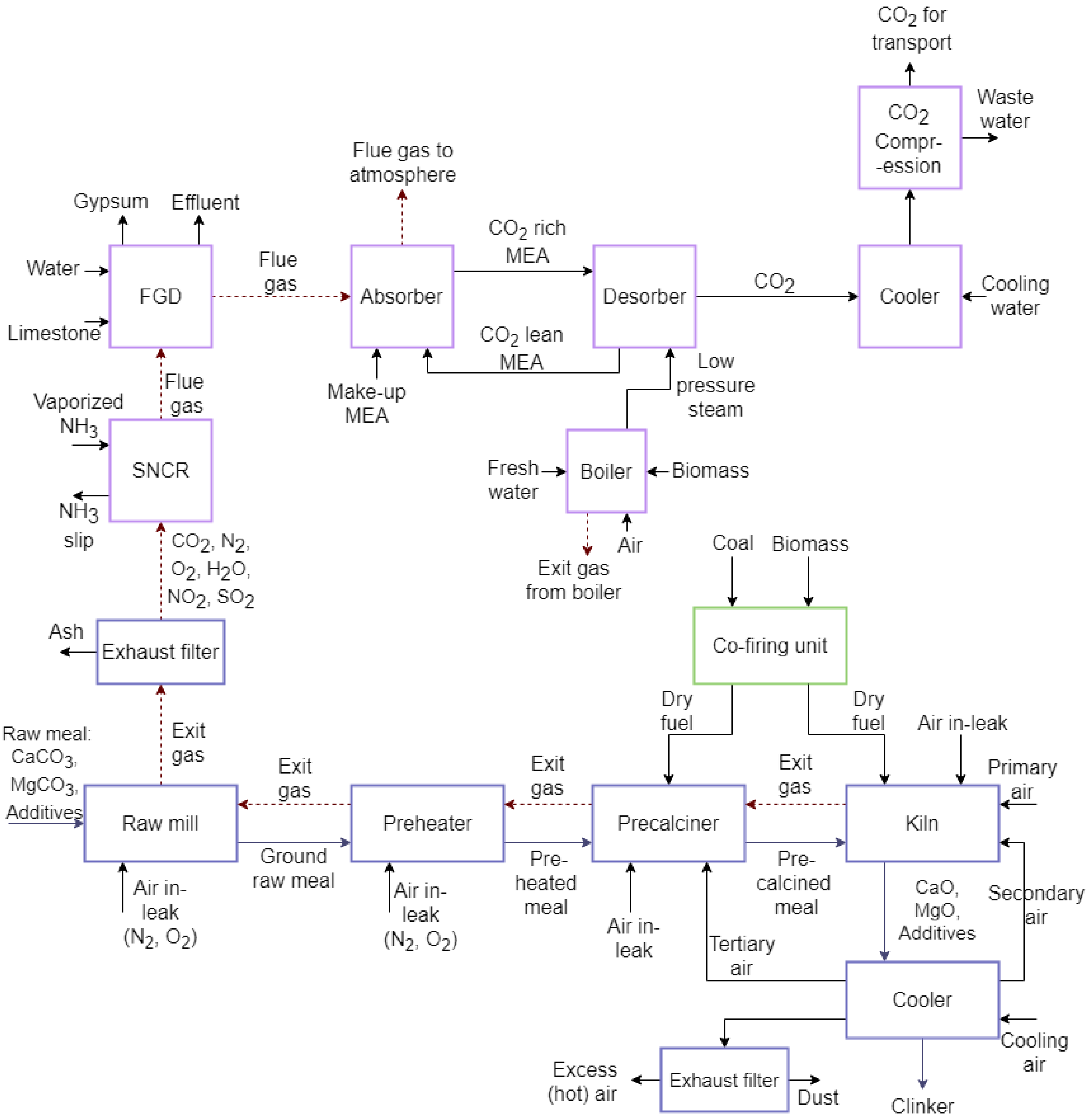
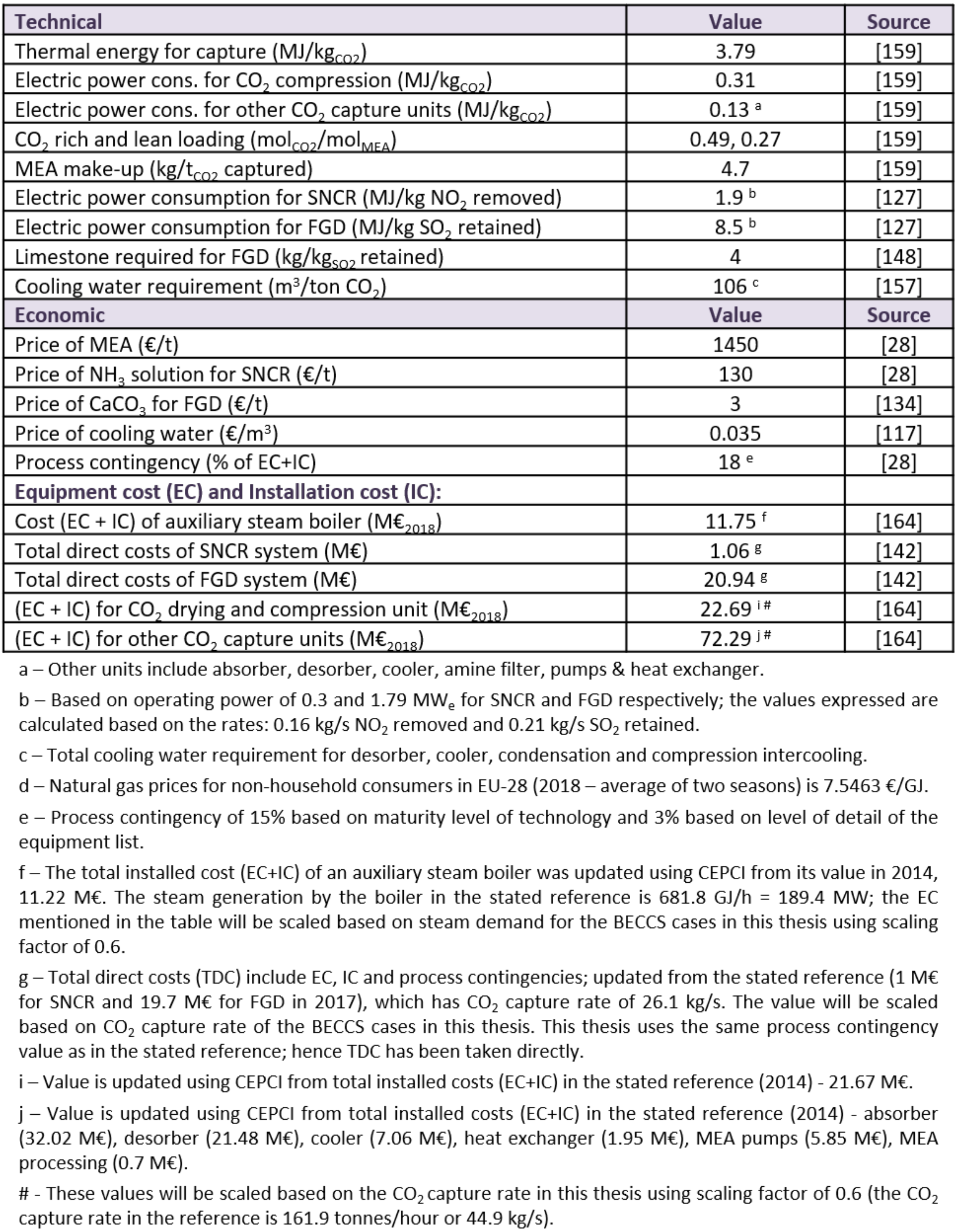


Figure 3.10: Process flow diagram for clinker production process with (partial) biomass and CO_2 capture using MEA scrubbing

Table 3.8: Assumptions specific to MEA scrubbing based CO_2 capture



Technical	**Value**	**Source**
Thermal energy for capture (MJ/kg_{CO2})	3.79	[159]
Electric power cons. for CO_2 compression (MJ/kg_{CO2})	0.31	[159]
Electric power cons. for other CO_2 capture units (MJ/kg_{CO2})	0.13 [a]	[159]
CO_2 rich and lean loading (mol_{CO2}/mol_{MEA})	0.49, 0.27	[159]
MEA make-up (kg/t_{CO2} captured)	4.7	[159]
Electric power consumption for SNCR (MJ/kg NO_2 removed)	1.9 [b]	[127]
Electric power consumption for FGD (MJ/kg SO_2 retained)	8.5 [b]	[127]
Limestone required for FGD (kg/kg_{SO2} retained)	4	[148]
Cooling water requirement (m^3/ton CO_2)	106 [c]	[157]
Economic	**Value**	**Source**
Price of MEA (€/t)	1450	[28]
Price of NH_3 solution for SNCR (€/t)	130	[28]
Price of $CaCO_3$ for FGD (€/t)	3	[134]
Price of cooling water (€/m^3)	0.035	[117]
Process contingency (% of EC+IC)	18 [e]	[28]
Equipment cost (EC) and Installation cost (IC):		
Cost (EC + IC) of auxiliary steam boiler ($M€_{2018}$)	11.75 [f]	[164]
Total direct costs of SNCR system (M€)	1.06 [g]	[142]
Total direct costs of FGD system (M€)	20.94 [g]	[142]
(EC + IC) for CO_2 drying and compression unit ($M€_{2018}$)	22.69 [i #]	[164]
(EC + IC) for other CO_2 capture units ($M€_{2018}$)	72.29 [j #]	[164]

a – Other units include absorber, desorber, cooler, amine filter, pumps & heat exchanger.

b – Based on operating power of 0.3 and 1.79 MW_e for SNCR and FGD respectively; the values expressed are calculated based on the rates: 0.16 kg/s NO_2 removed and 0.21 kg/s SO_2 retained.

c – Total cooling water requirement for desorber, cooler, condensation and compression intercooling.

d – Natural gas prices for non-household consumers in EU-28 (2018 – average of two seasons) is 7.5463 €/GJ.

e – Process contingency of 15% based on maturity level of technology and 3% based on level of detail of the equipment list.

f – The total installed cost (EC+IC) of an auxiliary steam boiler was updated using CEPCI from its value in 2014, 11.22 M€. The steam generation by the boiler in the stated reference is 681.8 GJ/h = 189.4 MW; the EC mentioned in the table will be scaled based on steam demand for the BECCS cases in this thesis using scaling factor of 0.6.

g – Total direct costs (TDC) include EC, IC and process contingencies; updated from the stated reference (1 M€ for SNCR and 19.7 M€ for FGD in 2017), which has CO_2 capture rate of 26.1 kg/s. The value will be scaled based on CO_2 capture rate of the BECCS cases in this thesis. This thesis uses the same process contingency value as in the stated reference; hence TDC has been taken directly.

i – Value is updated using CEPCI from total installed costs (EC+IC) in the stated reference (2014) - 21.67 M€.

j – Value is updated using CEPCI from total installed costs (EC+IC) in the stated reference (2014) - absorber (32.02 M€), desorber (21.48 M€), cooler (7.06 M€), heat exchanger (1.95 M€), MEA pumps (5.85 M€), MEA processing (0.7 M€).

- These values will be scaled based on the CO_2 capture rate in this thesis using scaling factor of 0.6 (the CO_2 capture rate in the reference is 161.9 tonnes/hour or 44.9 kg/s).

After the regeneration, CO_2 is cooled using water. Cooling water requirements are stated in table 3.8 [157] [117]. Cooled CO_2 is then dried and compressed to 110 bar pressure in a compression unit [159] and sent for further transportation via pipelines.

3.7.2 Scenario 2: Tail-end Calcium Looping process for CO_2 capture

In a calcium looping (CaL) process, integration level is defined as the ratio of limestone fed for the CaL process to the total limestone fed to the cement plant with the CaL capture unit. This parameter decides the extent to which the CaL unit is integrated into the cement plant, in a tail-end scenario. Integration level of 25% is considered here[15]. This means that, only 3/4th of the $CaCO_3$ in the raw meal is fed to the raw mill; the other 1/4th of the $CaCO_3$ is fed to the new calciner unit which is part of the retrofitted capture plant.

The process flow diagram for tail-end CaL process retrofitted to the base cement plant is shown in figure 3.11. The flue gas from the pre-heater exit is taken to the CaL process for CO_2 capture as high temperature in the flue gas stream is required for the carbonation process [109]. Another reason is to evade high air infiltration in the raw mill that would reduce the CO_2 concentration in the flue gas (thereby increasing the size and cost of the CaL reactors[16] [110]). CaL process is based on the reversible carbonation reaction which uses a calcium oxide (CaO) sorbent to capture the CO_2. The process is carried out in two interconnected reactors - carbonator and calciner. The CO_2 in the flue gas stream reacts with the CaO sorbent in the carbonator to form $CaCO_3$, which is transferred to the calciner. Fuel (biomass), limestone and oxygen (O_2 rich air) are fed into the calciner; oxy-combustion of fuel is carried out in the calciner to provide thermal energy for the CaO sorbent regeneration. Reverse calcination occurs (100% calcination is assumed in the oxyfired calciner [110] [109]) and a CO_2-rich gaseous stream is produced which is sent to a CO_2 compression and purification unit (CPU).

$CaSO_4$ is unavoidably formed in the calciner by the reaction of CaO with SO_2 generated from fuel combustion [110] [109]. $CaSO_4$ concentrations for varied integration levels (from 15 to 80%) are within the 2.6%wt limit specified for Portland cement clinker [110]. Still, part of the CaO sorbent is continuously purged to avoid excessive build-up of $CaSO_4$ and ash as they reduce the average activity of the solids for CO_2 capture [128]. This is why the calciner is compensated with make-up $CaCO_3$[17]. The CaO-rich solid purge extracted (which also contains $CaSO_4$ and ash) is cooled to nearly ambient temperature [110] and joins the raw meal in the base plant, before the raw milling stage. Calciner operates at a temperature of 950°C and therefore cooling is necessary before feeding to the raw mill. The rate of clinker produced increases as a result of the purge stream[18].

The limestone fed to the CaL process is milled in a dedicated limestone crusher. In spite of this, the CaO-rich solid purge is sent to the raw mill. This is because, in the configuration, the reactors (carbonator and calciner) are circulating fluidized beds (CFB). An average particle size in the range of 100 to 300 µm is suitable for fluidized beds. Therefore, the dedicated limestone crusher (mill) installed for the CaL process prepares it for fludized operation. The purge stream, when taken to the raw mill is milled to an average particle size of 10 to 20 µm, which is suitable for clinker production [110] [128].

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[15] Integration levels ranging from 15 to 80% are assessed in techno-economic studies for CaL and it has been reported that retrofitability is more feasible in case of lower integration levels [110].

[16] If flue gas stream is taken from the raw mill instead, that would necessitate modifications in the raw mill operation to reduce air infiltration, which is not desirable for retrofitting [24] [110]. Furthermore it has been reported that the raw mill must not operate under air-tight conditions [134].

[17] Repeated looping cycles will lead to deterioration of CO_2 absorption capacity [109], hence the need for make-up $CaCO_3$.

[18] There is also a possibility to adjust the amount of additives fed to the raw mill taking into account the SiO_2, Fe_2O_3 and Al_2O_3 in the ash contained in the CaL purge [110]. However this is not considered here as this possibility is being studied later in Scenario 4.

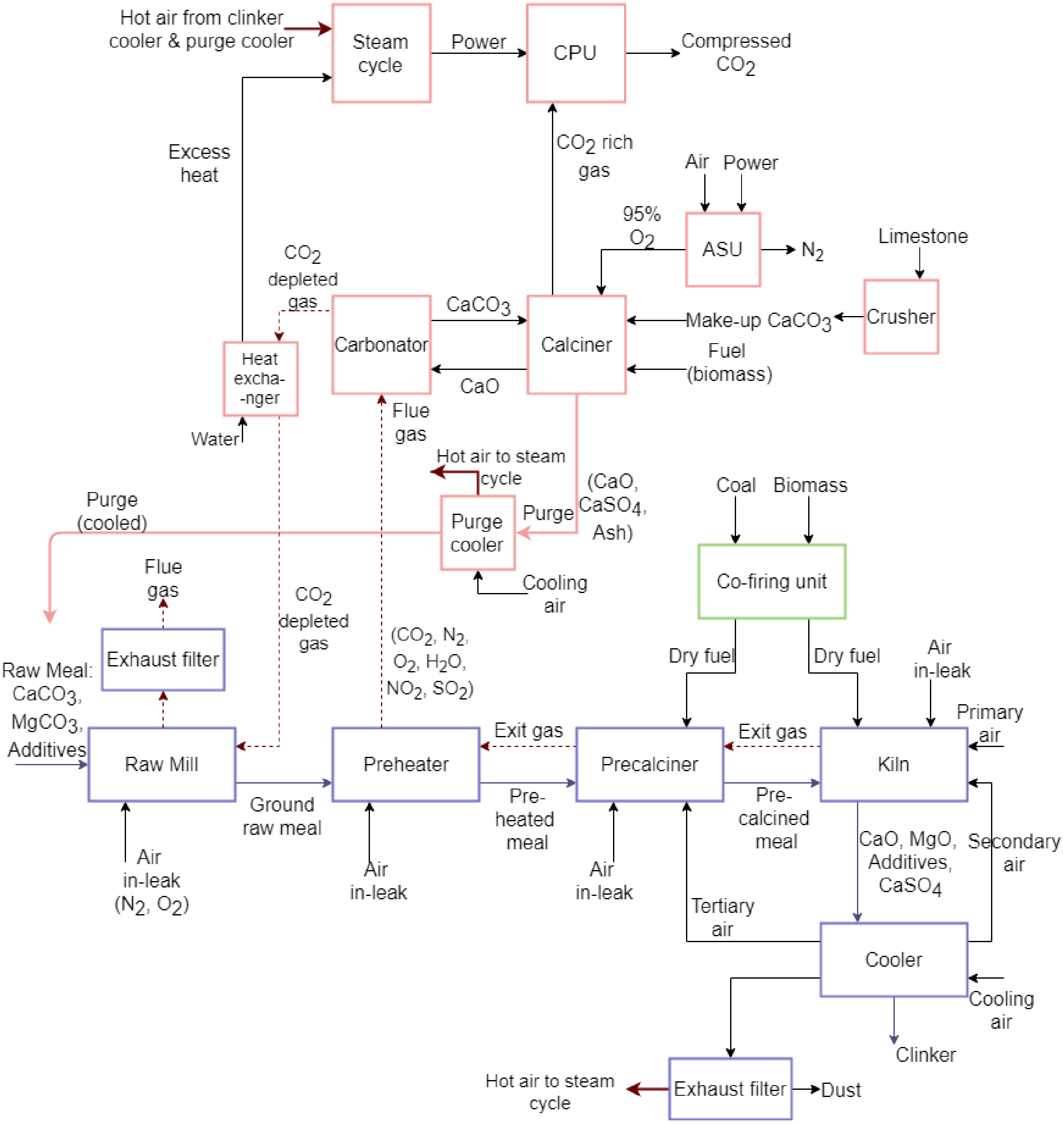
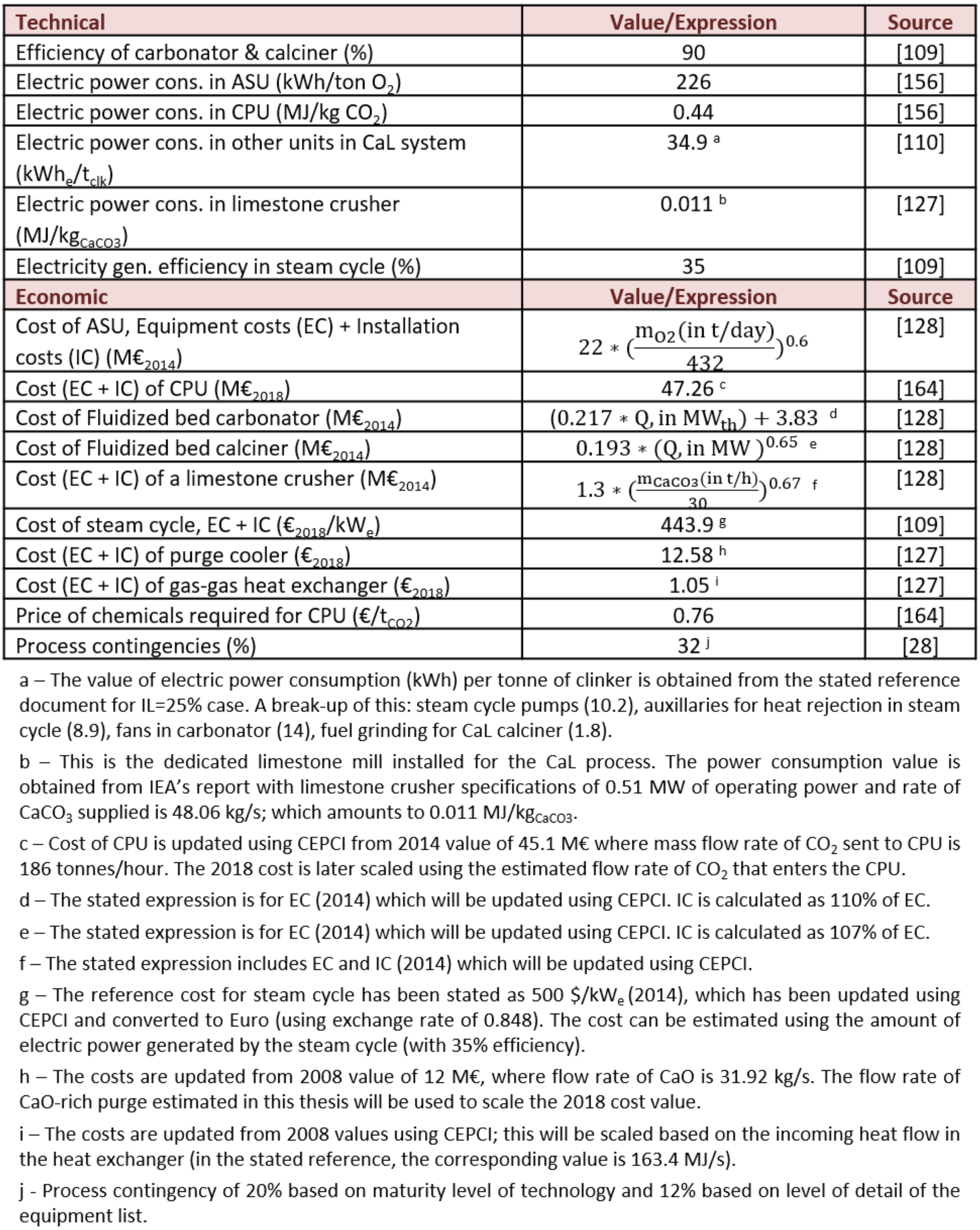


Figure 3.11: Process flow diagram for clinker production process with (partial) biomass and calcium looping (tail-end) CO_2 capture

Table 3.9: Assumptions specific to Calcium looping process for CO_2 capture



Technical	**Value/Expression**	**Source**
Efficiency of carbonator & calciner (%)	90	[109]
Electric power cons. in ASU (kWh/ton O_2)	226	[156]
Electric power cons. in CPU (MJ/kg CO_2)	0.44	[156]
Electric power cons. in other units in CaL system (kWh_e/t_{clk})	34.9 [a]	[110]
Electric power cons. in limestone crusher (MJ/kg_{CaCO3})	0.011 [b]	[127]
Electricity gen. efficiency in steam cycle (%)	35	[109]
Economic	**Value/Expression**	**Source**
Cost of ASU, Equipment costs (EC) + Installation costs (IC) ($M€_{2014}$)	$22 * (\frac{m_{O2}(\text{in t/day})}{432})^{0.6}$	[128]
Cost (EC + IC) of CPU ($M€_{2018}$)	47.26 [c]	[164]
Cost of Fluidized bed carbonator ($M€_{2014}$)	$(0.217 * Q, \text{in } MW_{th}) + 3.83$ [d]	[128]
Cost of Fluidized bed calciner ($M€_{2014}$)	$0.193 * (Q, \text{in MW})^{0.65}$ [e]	[128]
Cost (EC + IC) of a limestone crusher ($M€_{2014}$)	$1.3 * (\frac{m_{CaCO3}(\text{in t/h})}{30})^{0.67}$ [f]	[128]
Cost of steam cycle, EC + IC ($€_{2018}/kW_e$)	443.9 [g]	[109]
Cost (EC + IC) of purge cooler ($€_{2018}$)	12.58 [h]	[127]
Cost (EC + IC) of gas-gas heat exchanger ($€_{2018}$)	1.05 [i]	[127]
Price of chemicals required for CPU ($€/t_{CO2}$)	0.76	[164]
Process contingencies (%)	32 [j]	[28]

a – The value of electric power consumption (kWh) per tonne of clinker is obtained from the stated reference document for IL=25% case. A break-up of this: steam cycle pumps (10.2), auxillaries for heat rejection in steam cycle (8.9), fans in carbonator (14), fuel grinding for CaL calciner (1.8).

b – This is the dedicated limestone mill installed for the CaL process. The power consumption value is obtained from IEA's report with limestone crusher specifications of 0.51 MW of operating power and rate of $CaCO_3$ supplied is 48.06 kg/s; which amounts to 0.011 MJ/kg_{CaCO3}.

c – Cost of CPU is updated using CEPCI from 2014 value of 45.1 M€ where mass flow rate of CO_2 sent to CPU is 186 tonnes/hour. The 2018 cost is later scaled using the estimated flow rate of CO_2 that enters the CPU.

d – The stated expression is for EC (2014) which will be updated using CEPCI. IC is calculated as 110% of EC.

e – The stated expression is for EC (2014) which will be updated using CEPCI. IC is calculated as 107% of EC.

f – The stated expression includes EC and IC (2014) which will be updated using CEPCI.

g – The reference cost for steam cycle has been stated as 500 $\$/kW_e$ (2014), which has been updated using CEPCI and converted to Euro (using exchange rate of 0.848). The cost can be estimated using the amount of electric power generated by the steam cycle (with 35% efficiency).

h – The costs are updated from 2008 value of 12 M€, where flow rate of CaO is 31.92 kg/s. The flow rate of CaO-rich purge estimated in this thesis will be used to scale the 2018 cost value.

i – The costs are updated from 2008 values using CEPCI; this will be scaled based on the incoming heat flow in the heat exchanger (in the stated reference, the corresponding value is 163.4 MJ/s).

j - Process contingency of 20% based on maturity level of technology and 12% based on level of detail of the equipment list.

Reduced limestone for calcination in the base cement plant leads to a corresponding decrease in fuel consumption in the pre-calciner, but not to a great extent in the kiln; this is to maintain a temperature of 1450°C in the kiln [109]. In this thesis, it is assumed that the rate of fuel supplied to the kiln is the same as in the base cement plant without CO_2 capture. Rate of fuel supplied to the CaL calciner is calculated based on the quantity of limestone calcined, heating value of the fuel used and the heat of reaction of calcination process (178.8 kJ/mol). Biomass considered for co-firing in the base cement plant is used as the fuel for this CaL calciner as well. An air separator unit (ASU) is installed on-site to produce an O_2-rich air for the CaL process; the rate of O_2 supplied is estimated based on the fuel consumption rate and the requirements of oxygen for combustion process within the calciner, which varies depending on the fuel composition of the biomass used [161].

For pipeline transport, CO_2 compression and purification unit (CPU) is designed as a self-refrigerated unit which delivers compressed CO_2 at 110 bar. The CPU includes multi-stage intercooling, drying of the CO_2 stream in molecular sieves, purification of CO_2 by cryogenic distillation[19], followed by compression [24] [128]. Assumptions specific to CaL capture scenario are listed in table 3.9.

Waste heat recovery is possible in this configuration. There is additional electric power consumption in ASU and CPU; but electric power is also generated by a steam cycle that utilizes waste heat from the process. Sources of waste heat recovery include the clinker cooler, the purge cooler and the carbonator. Excess hot air streams from the grate cooler (clinker cooler) and the purge cooler are taken to the steam cycle. The CO_2 depleted flue gas exits the carbonator at a temperature of 650°C and it has a heat content that exceeds the heat requirement for raw meal drying in the raw mill[20]. Therefore, a heat exchanger is used to cool the CO_2 depleted flue gas to a temperature that is sufficient to meet the thermal demand for raw meal drying (estimated in this thesis to be around 330°C). The excess heat is recovered and sent to the steam cycle. Also the heat in the carbonated solids (at temperature of 650°C) can help reduce the total heat introduced in the CaL system [162]. The dehydration heat in CPU and ASU are assumed to be provided by the waste heat from the cement plant [156] and are not accounted for in this thesis.

3.7.3 Scenario 3: Oxyfuel combustion CO_2 capture

In oxyfuel combustion capture, the air inputs to the pre-calciner and the kiln are rich in oxygen. To achieve this, an air separator unit (ASU) is installed on-site to strip the air input off its nitrogen and feed O_2 rich air (95% O_2 and 5% N_2) to the pre-calciner and kiln units. Combustion in an oxygen-rich environment will ensure higher CO_2 concentration in the flue gas stream and reduced N_2 concentration (compared to other capture scenarios). This enables easier CO_2 separation by cryogenic (physical) process rather than a chemical process (as in the case of MEA-based capture) [163].

Designing an oxy-combustion process requires minimal air-leaks, hence appropriate sealing is needed [127] [164]. In spite of the sealing, there is still a small amount of air in-leak, however the portion of false air in the flue gas can be lowered (than in the other capture scenarios) with the sealing. It has been assumed that about 5% of the exit gas from the kiln and pre-calciner comprise of false air. A portion of the flue gas is recycled to the cement plant to maintain a moderate temperature profile in the combustion process [24]. Otherwise, increased temperature profile in the kiln in case of oxyfuel combustion causes structural damage to equipment [164]. Clinker

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[19] CO_2 rich gaseous stream released in the calciner might still have some impurities in the O_2 produced in the ASU, hence purification is required.

[20] The thermal energy requirement for drying the raw meal varies depending on the moisture content in the raw meal. The lower the moisture content, lesser the energy required. From the energy requirements stated in the BAT document [7] for different shares of moisture (%wt), the thermal energy required to dry the raw meal with 1% moisture is roughly estimated as 16 MJ.

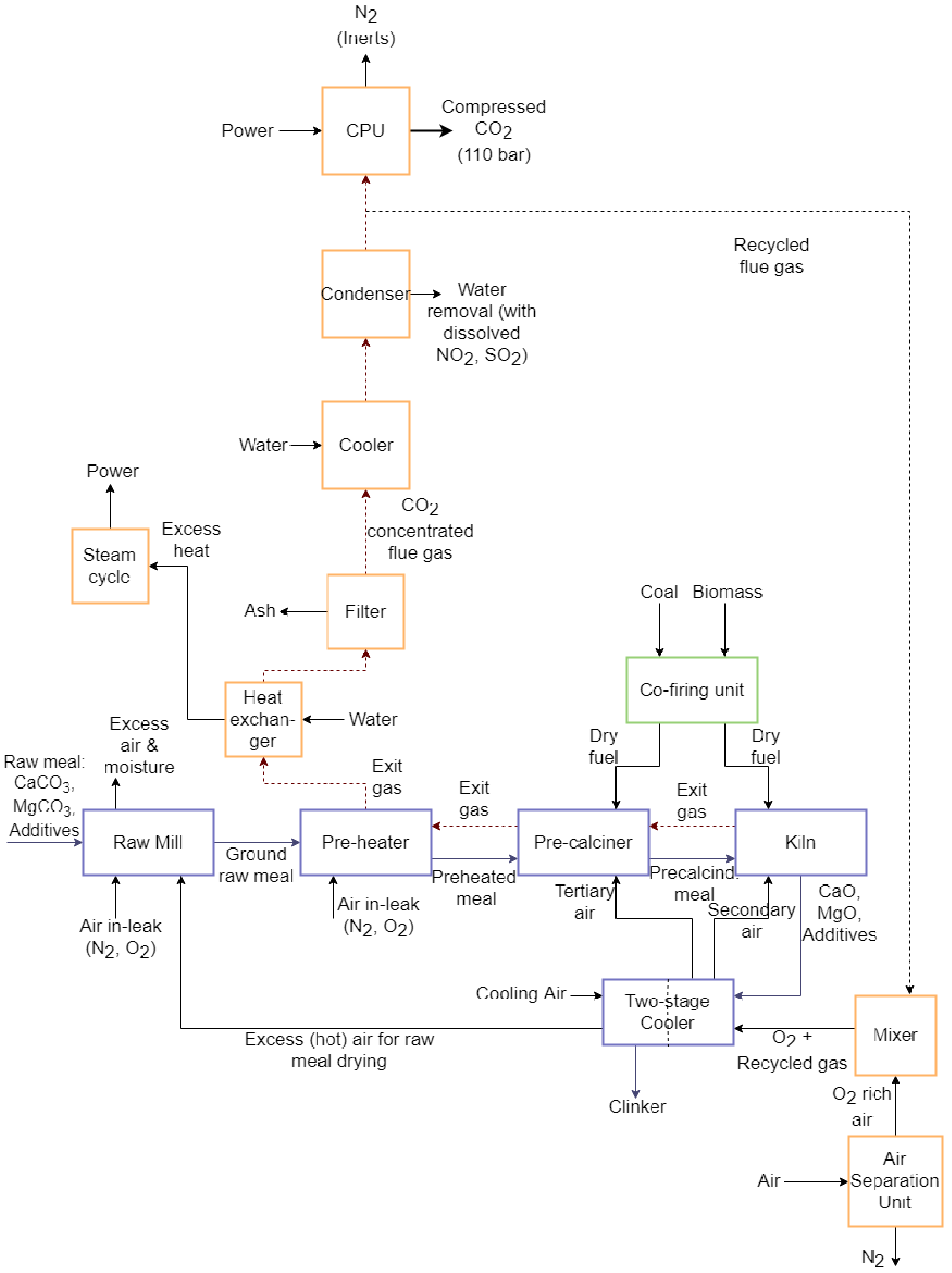
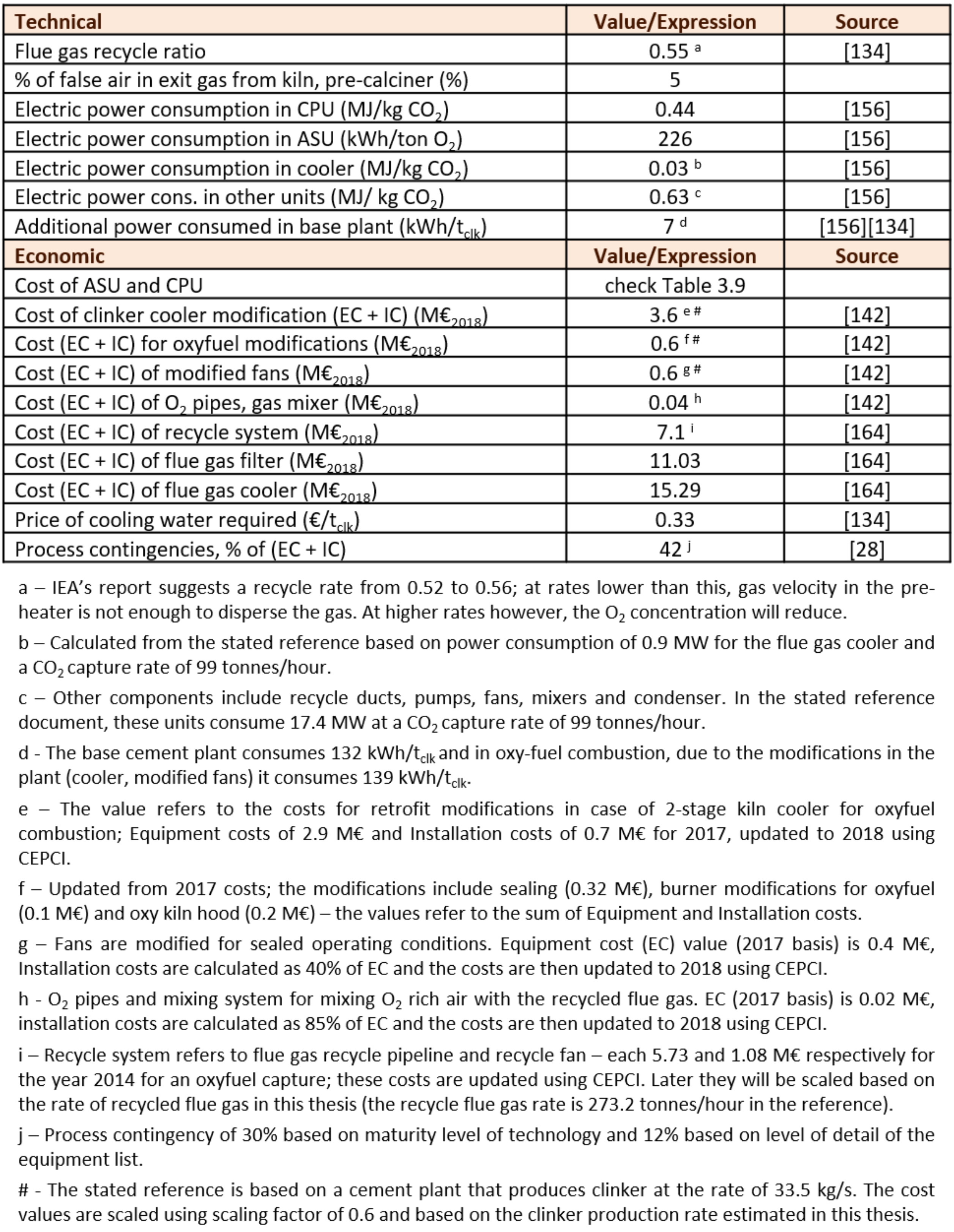


Figure 3.12: Process flow diagram for clinker production process with (partial) biomass and oxyfuel combustion CO_2 capture

Table 3.10: Assumptions specific to Oxyfuel scenario



Technical	**Value/Expression**	**Source**
Flue gas recycle ratio	0.55 [a]	[134]
% of false air in exit gas from kiln, pre-calciner (%)	5	
Electric power consumption in CPU (MJ/kg CO_2)	0.44	[156]
Electric power consumption in ASU (kWh/ton O_2)	226	[156]
Electric power consumption in cooler (MJ/kg CO_2)	0.03 [b]	[156]
Electric power cons. in other units (MJ/ kg CO_2)	0.63 [c]	[156]
Additional power consumed in base plant (kWh/t_{clk})	7 [d]	[156][134]
Economic	**Value/Expression**	**Source**
Cost of ASU and CPU	check Table 3.9	
Cost of clinker cooler modification (EC + IC) (M€$_{2018}$)	3.6 [e #]	[142]
Cost (EC + IC) for oxyfuel modifications (M€$_{2018}$)	0.6 [f #]	[142]
Cost (EC + IC) of modified fans (M€$_{2018}$)	0.6 [g #]	[142]
Cost (EC + IC) of O_2 pipes, gas mixer (M€$_{2018}$)	0.04 [h]	[142]
Cost (EC + IC) of recycle system (M€$_{2018}$)	7.1 [i]	[164]
Cost (EC + IC) of flue gas filter (M€$_{2018}$)	11.03	[164]
Cost (EC + IC) of flue gas cooler (M€$_{2018}$)	15.29	[164]
Price of cooling water required (€/t_{clk})	0.33	[134]
Process contingencies, % of (EC + IC)	42 [j]	[28]

a – IEA's report suggests a recycle rate from 0.52 to 0.56; at rates lower than this, gas velocity in the pre-heater is not enough to disperse the gas. At higher rates however, the O_2 concentration will reduce.

b – Calculated from the stated reference based on power consumption of 0.9 MW for the flue gas cooler and a CO_2 capture rate of 99 tonnes/hour.

c – Other components include recycle ducts, pumps, fans, mixers and condenser. In the stated reference document, these units consume 17.4 MW at a CO_2 capture rate of 99 tonnes/hour.

d - The base cement plant consumes 132 kWh/t_{clk} and in oxy-fuel combustion, due to the modifications in the plant (cooler, modified fans) it consumes 139 kWh/t_{clk}.

e – The value refers to the costs for retrofit modifications in case of 2-stage kiln cooler for oxyfuel combustion; Equipment costs of 2.9 M€ and Installation costs of 0.7 M€ for 2017, updated to 2018 using CEPCI.

f – Updated from 2017 costs; the modifications include sealing (0.32 M€), burner modifications for oxyfuel (0.1 M€) and oxy kiln hood (0.2 M€) – the values refer to the sum of Equipment and Installation costs.

g – Fans are modified for sealed operating conditions. Equipment cost (EC) value (2017 basis) is 0.4 M€, Installation costs are calculated as 40% of EC and the costs are then updated to 2018 using CEPCI.

h - O_2 pipes and mixing system for mixing O_2 rich air with the recycled flue gas. EC (2017 basis) is 0.02 M€, installation costs are calculated as 85% of EC and the costs are then updated to 2018 using CEPCI.

i – Recycle system refers to flue gas recycle pipeline and recycle fan – each 5.73 and 1.08 M€ respectively for the year 2014 for an oxyfuel capture; these costs are updated using CEPCI. Later they will be scaled based on the rate of recycled flue gas in this thesis (the recycle flue gas rate is 273.2 tonnes/hour in the reference).

j – Process contingency of 30% based on maturity level of technology and 12% based on level of detail of the equipment list.

\# - The stated reference is based on a cement plant that produces clinker at the rate of 33.5 kg/s. The cost values are scaled using scaling factor of 0.6 and based on the clinker production rate estimated in this thesis.

cooler is modified; a two-stage cooler that separately operates in two different atmospheres is designed. This is to ensure that one part of the cooler comprises of the flue gas and O_2 mixture from the ASU, to be able to possess minimal N_2 content, so that the secondary and tertiary air sent to the kiln and calciner remain unaffected by the cooling air input (which is high in N_2). The other part of the cooler comprises of the cooling air[21] - the excess hot air from this part of the cooler is sent to the raw mill for moisture drying; the flue gas is taken out from the pre-heater in the oxyfuel combustion capture[22]. The pre-heater exit gas is taken to a heat exchanger where the thermal energy content in the flue gas is recovered for electricity generation using a steam cycle.

The flue gas, on exchanging heat with water in the heat exchanger, is stripped off the particulate matter in a filter [165]. Followed by this, flue gas is cooled and water content is removed in a condenser; the acidic gases are removed on dissolving in the water [24] (it is assumed that all of NO_2 and SO_2 exit with the water removed [127] [166]). Post the condenser, a portion of the flue gas is recycled to the cement plant. The recycled stream (which is rich in CO_2) is mixed with the O_2 rich air from the ASU before being fed to the cooler. The remaining fraction of the flue gas after condensation is passed to the CO_2 compression and purification unit (CPU). In the CPU, drying of the CO_2-rich flue gas takes place, where thermal energy is consumed for the dehydration. After drying, inerts (in this thesis, only N_2) are removed[23] (purification). This is followed by compression of CO_2 to 110 bar, suitable for pipeline transport. It has been assumed that the leftover oxygen in the CO_2 stream needn't be removed [127]. The process flow diagram for oxyfuel combustion capture is shown in figure 3.12 and the assumptions specific to this capture technology are listed in table 3.10.

3.7.4 Using ash from co-firing as a raw material or an additive

When the ash from biomass co-firing is utilized as a raw material to produce clinker or as an additive while grinding cement, it has potential to further avoid some CO_2 emissions (this was discussed earlier in section 2.2.5). The objective in this scenario is to assess the total CO_2 emissions avoided per tonne of cement as a result of this addition. The ash obtained will have the composition of the blend of both coal ash and the ash of the biomass used (based on the co-firing rate used) (composition of ash is listed in table 3.11). Rice husk ash (RHA) and municipal solid waste ash (MSWA) are incorporated as additives during the cement grinding stage; and on using them, the clinker requirement correspondingly reduces, thereby reducing the CO_2 emissions also, due to reduced raw material and fuel consumption. Sewage sludge ash (SSA) is considered as part of the raw meal; as discussed earlier, they have certain limitations in terms of substitution rates.

The following cases have been assessed:

a) SSA as part of the raw meal in clinker production:

When SSA is incorporated into the raw meal, the share of the other raw materials employed can be decreased in order to receive the same amount of clinker. This implies a reduction in $CaCO_3$ as well, which has been adjusted based on the share of CaO in the co-fired SSA used in the raw meal. It was discussed in section 2.2.5 that up to 5% of the raw meal can be substituted with SSA (section 2.2.5) and it was also seen that availability of ash is an important parameter to take into consideration. The amount of ash generated for 30% co-firing of sewage sludge with coal was

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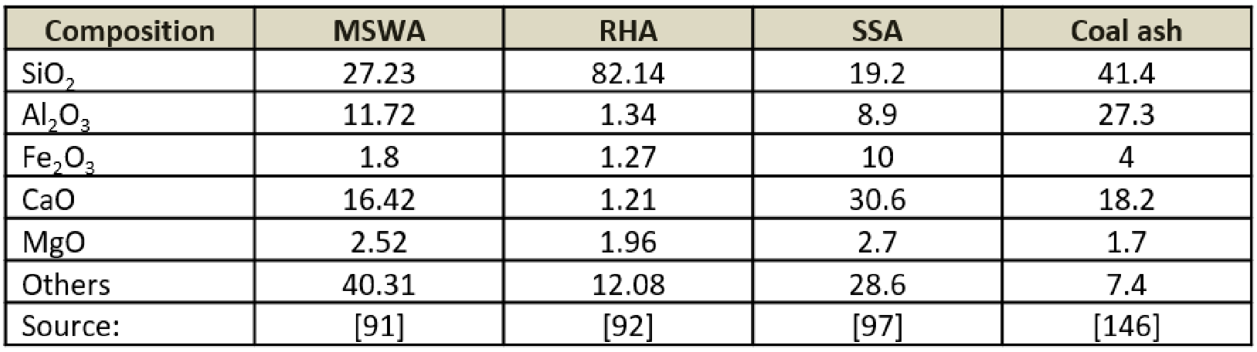
[21] Taking the recycled gas stream into the cooler will further increase the temperature; which is why a second cooler stage with cool ambient air is preferred [134].

[22] High air in-leaks in the raw mill will further decrease the CO_2 concentration if flue gas is taken from its exit.

[23] Inert removal in the CPU is based on the principle of cryogenic distillation

Table 3.11: Composition of ash (mass fraction in %) as considered in this study



Composition	MSWA	RHA	SSA	Coal ash
SiO_2	27.23	82.14	19.2	41.4
Al_2O_3	11.72	1.34	8.9	27.3
Fe_2O_3	1.8	1.27	10	4
CaO	16.42	1.21	30.6	18.2
MgO	2.52	1.96	2.7	1.7
Others	40.31	12.08	28.6	7.4
Source:	[91]	[92]	[97]	[146]

estimated. It was assumed that 90% of the ash generated was available for usage after recovery, following removal from the filter and appropriate washing[24].

The corresponding increase in CO_2 emissions avoided due to SSA (co-fired) usage in the raw meal was estimated for all the 3 CO_2 capture technologies.

b) RHA and MSWA as additives during cement grinding:

In the earlier BECCS scenarios, a clinker-cement factor of 0.737 was used. This means that 73.7% of the cement is comprised of clinker; the other 26.3% consists of additives, primarily gypsum. These additives will also consist of any one of (or a mix of) fly ash, blast furnace slag, pozzolana or limestone. The clinker proportion implies that the cement topology considered is CEM II type; and in this section the objective is to replace clinker to assess the CO_2 reduction potential; therefore the composition of the additives was fixed at 26.3%. And based on the amount of ash recovered from the cement plant co-firing and steam boilers, a fraction of clinker was replaced with the ash; this leads to a corresponding decrease in clinker percentage from 73.7. On substituting clinker with the ash obtained from co-firing at the cement grinding stage, it still possess sufficient clinker (higher than 65%) to fulfil the standard of CEM II type cements (section 2.2.2). The ash from co-firing coal with RHP and MSW were considered for usage as additives in cement grinding.

In case of ash used as additives and raw materials, the amount of total CO_2 emissions avoided (per tonne of cement) was calculated for all the three CO_2 capture technologies and will be compared with emissions avoided in the earlier BECCS scenarios (before incorporating the bio-based ash). It must be noted that from here-on, the notations SSA, RHA and MSWA would refer to the ash obtained from co-firing the respective biomass fuels with coal.

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[24] This is to ensure that there is enough ash available even when the input flow rate of the raw materials are reduced later on.

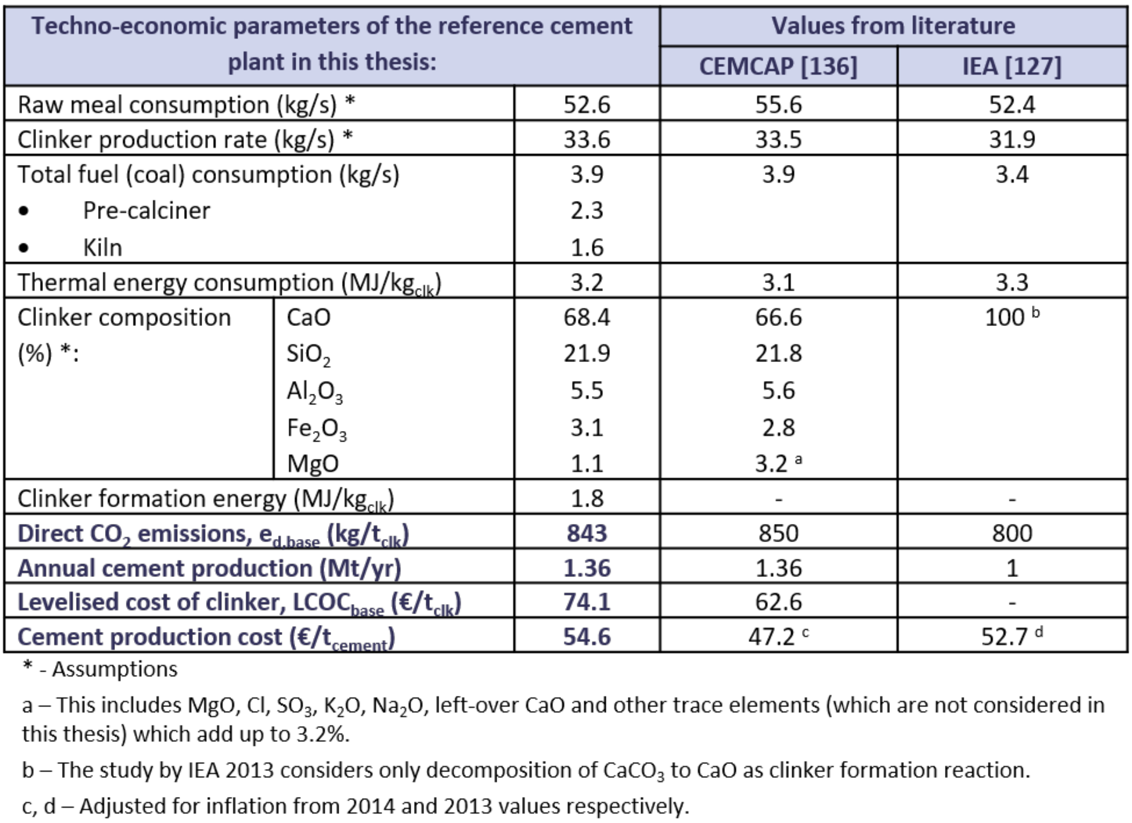
4 RESULTS AND DISCUSSIONS

In this chapter, the results of the techno-economic assessment are presented and discussed individually for each of the BECCS technologies (in section 4.2). The techno-economic parameters (key performance indicators) are then compared in section 4.3 with each other and with the techno-economic parameters of the base cement plant (listed in section 4.1). The results of carbon accounting are presented in section 4.4 and the sensitivity of the key technical and economic parameters to uncertainties is presented in section 4.5.

4.1 REFERENCE CASE SCENARIO

The techno-economic parameters for the base (reference) cement plant (100% coal, without CO_2 capture) are tabulated here:

Table 4.1: Key technical and economic values of the reference cement plant



Techno-economic parameters of the reference cement plant in this thesis:			Values from literature	
			CEMCAP [136]	IEA [127]
Raw meal consumption (kg/s) *		52.6	55.6	52.4
Clinker production rate (kg/s) *		33.6	33.5	31.9
Total fuel (coal) consumption (kg/s)		3.9	3.9	3.4
• Pre-calciner		2.3		
• Kiln		1.6		
Thermal energy consumption (MJ/kg_{clk})		3.2	3.1	3.3
Clinker composition (%) *:	CaO	68.4	66.6	100 [b]
	SiO_2	21.9	21.8	
	Al_2O_3	5.5	5.6	
	Fe_2O_3	3.1	2.8	
	MgO	1.1	3.2 [a]	
Clinker formation energy (MJ/kg_{clk})		1.8	-	-
Direct CO_2 emissions, $e_{d,base}$ (kg/t_{clk})		**843**	850	800
Annual cement production (Mt/yr)		**1.36**	1.36	1
Levelised cost of clinker, $LCOC_{base}$ (€/t_{clk})		**74.1**	62.6	-
Cement production cost (€/t_{cement})		**54.6**	47.2 [c]	52.7 [d]

* - Assumptions

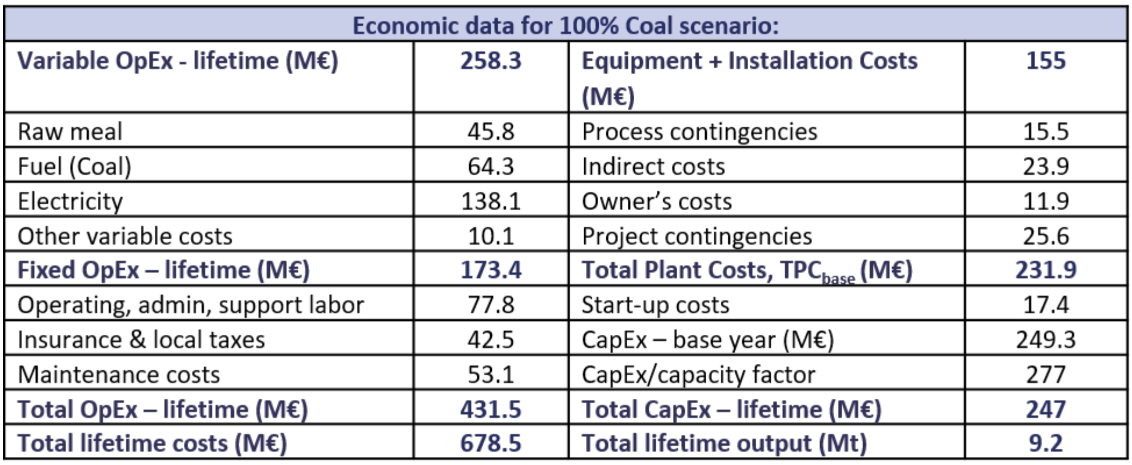
a – This includes MgO, Cl, SO_3, K_2O, Na_2O, left-over CaO and other trace elements (which are not considered in this thesis) which add up to 3.2%.

b – The study by IEA 2013 considers only decomposition of $CaCO_3$ to CaO as clinker formation reaction.

c, d – Adjusted for inflation from 2014 and 2013 values respectively.

100% calcination of $CaCO_3$ was assumed, hence there is no left-over CaO in the product; although in practice, this wouldn't be entirely possible. For a raw meal flow rate of 52.6 kg/s, a clinker output flow rate of 33.6 kg/s can be obtained. And this amounts to 1 Mt of clinker production per year, which is the equivalent of 1.36 Mt of cement production per year. The thermal energy consumption is 3.2 MJ/kg_{clk} and this is in the range mentioned in section 2.2.1 (3.1 to 3.4 MJ/kg_{clk}). The clinker composition listed in table 4.1 was used to calculate the clinker formation

Table 4.2: Break-up of the economic parameters of the reference (base) cement plant



Economic data for 100% Coal scenario:			
Variable OpEx - lifetime (M€)	**258.3**	**Equipment + Installation Costs (M€)**	**155**
Raw meal	45.8	Process contingencies	15.5
Fuel (Coal)	64.3	Indirect costs	23.9
Electricity	138.1	Owner's costs	11.9
Other variable costs	10.1	Project contingencies	25.6
Fixed OpEx – lifetime (M€)	**173.4**	**Total Plant Costs, TPC_{base} (M€)**	**231.9**
Operating, admin, support labor	77.8	Start-up costs	17.4
Insurance & local taxes	42.5	CapEx – base year (M€)	249.3
Maintenance costs	53.1	CapEx/capacity factor	277
Total OpEx – lifetime (M€)	**431.5**	**Total CapEx – lifetime (M€)**	**247**
Total lifetime costs (M€)	**678.5**	**Total lifetime output (Mt)**	**9.2**

energy using equation [9] mentioned in section 3.7. The CO_2 emission intensity for the reference cement plant (the heating fuel is 100% coal) is 843 kg CO_2 per tonne of clinker, which is within the range specified in literature (800 to 850 kg/t_{clk}). This value was later used to estimate the CO_2 avoided in the BECCS cases. The cement production costs (CPC) were estimated as 54.6 €/t_{cement}. The corresponding values of the main parameters in two reference documents from literature are listed in table 4.1 alongside the results of the technical assessment for the base case cement plant in this thesis.

A break-up of the levelised costs of clinker is listed in Table 4.2. The components of operating expenses (OpEx) - variable and fixed are listed. The operating expenses listed are lifetime cost values for all the components. The base year capital expenses are also listed. On estimating the total lifetime costs and the total lifetime output, the levelised costs of clinker for the base value was estimated as 74.6 €/t_{clk}. This value was used to estimate the CO_2 avoidance costs later. CPC evaluated for the reference cement plant in this thesis was observed to be roughly 4% and 16% higher than the production costs in IEA and CEMCAP's reports respectively. This significant variation can be attributed to the different electricity prices used (different year of cost basis) and the capacity factor (90% in this thesis, while IEA and CEMCAP have used 80% and 91.3% respectively). The electricity price assumption used in this thesis was 114.2 €/MWh and the values used in the reports of CEMCAP and IEA were 58.1 and 80 €/MWh respectively. The assumption for electricity price in this study was roughly 97% and 43% higher than CEMCAP and IEA respectively; and the lifetime electricity costs constitute about 32% of the total lifetime operating expenses, and this significant share could be a reason for the impact of varied electricity prices on the cement production costs.

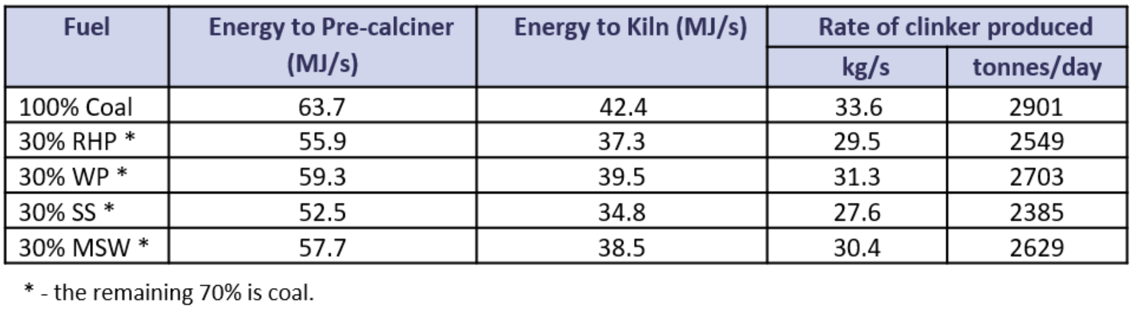
4.2 PROCESS YIELDS AND ECONOMIC MODELING RESULTS

The results of the techno-economic assessment for the BECCS technologies are presented in this section. The impact of direct co-firing of biomass with coal on the clinker production is discussed first; followed by this, the technical and economic results after the retrofitting of the CO_2 capture technologies are discussed.

Reduction in the rate of clinker on co-firing with biomass:

The clinker formation energy for the estimated clinker composition has been calculated as: 62 MJ/kg; and this accounts for 58% of the total thermal input supplied to the cement plant for

Table 4.3: Reduced thermal energy flows into the cement plant and the reduced clinker output due to biomass co-firing



Fuel	Energy to Pre-calciner (MJ/s)	Energy to Kiln (MJ/s)	Rate of clinker produced	
			kg/s	tonnes/day
100% Coal	63.7	42.4	33.6	2901
30% RHP *	55.9	37.3	29.5	2549
30% WP *	59.3	39.5	31.3	2703
30% SS *	52.5	34.8	27.6	2385
30% MSW *	57.7	38.5	30.4	2629

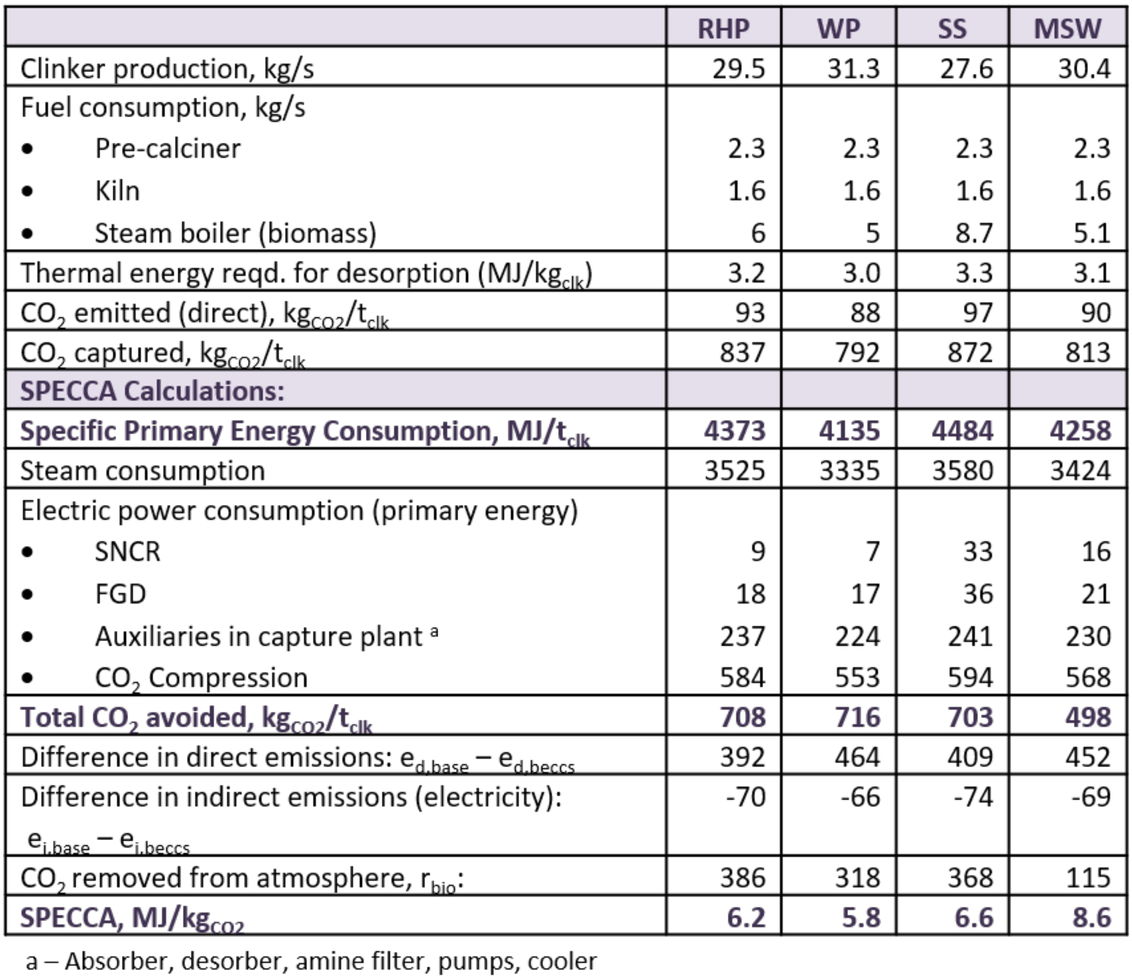
* - the remaining 70% is coal.

the base case (in the form of coal). The reduced thermal energy input flows to the pre-calciner and kiln units individually in case of 30% co-firing (on a mass-basis) of the chosen biomass options with coal are shown in Table 4.3. The corresponding flow rate of the clinker produced are indicated as well. There is a reduction in the rate owing to the lower heating value (LHV) of the fuel; if 30% of the coal is replaced on a mass basis, then the corresponding mass fraction is substituted by a low energy biomass fuel. Therefore, the net energy content in the co-fired fuel will have 70% of the energy content of coal and the rest of the energy content corresponds to that of biomass. The LHV of the chosen biomass options are the only determining factor in estimating the reduced rate of clinker as a result of the co-firing. Sewage sludge has the least LHV (10.97 MJ/kg) among the chosen biomass types; hence the **least rate of clinker produced** is observed when **sewage sludge** is co-fired with coal (27.6 kg/s, which is roughly 18% lower than the rate of clinker produced in the cement plant without biomass co-firing). Consequently, **wood pellets** (the biomass type among the four chosen options with highest LHV, 21 MJ/kg) entail the **highest rate of clinker produced** on co-firing with coal; the rate obtained with wood pellets is 31.3 kg/s, which is still roughly 7% lower than the reference cement plant (however, the reduction in the output rate is the least).

4.2.1 MEA Scenario

The MEA capture plant is retrofitted to the cement plant, with no modifications to the clinker production process. All the operating conditions, the assumptions pertaining to the base case scenario are relevant in the MEA scenario as well. Therefore, the rate of thermal energy supplied and the output rate of clinker is the same as mentioned in Table 4.3. The total CO_2 avoided is specified in table 4.4, along with other key parameters. A break-up of the avoided CO_2 is presented in the table as part of the SPECCA calculations. There is additional fuel consumption in the capture plant - in the biomass-fired boiler installed for steam generation (for the desorber unit to regenerate the CO_2 from MEA). The total CO_2 avoided includes the indirect emissions due to the electric power consumption in the retrofitted capture plant units. CO_2 emissions from the biomass-fired boiler also contribute to an increase in the CO_2 emissions on-site; however in this thesis, it was assumed that the CO_2 emissions from the combustion of biogenic fuel are offset by an equivalent amount of CO_2 absorbed from the atmosphere by the biogenic fraction in the fuel. Hence the CO_2 emitted from the fraction of the co-fired fuel which comprises of biomass does not result in any net positive CO_2 emissions, and there is no impact on the term total CO_2 avoided, and thereby SPECCA calculations. This is the reason for the partial biogenic nature of municipal solid waste (MSW) resulting in lower CO_2 avoidance rates. The CO_2 avoidance rates in the other three biomass fuels (RHP, WP, SS) are very similar (there is only a variation of maximum 2%); this was because these fuels were assumed to be 100% biogenic (that is, carbon neutral).

Table 4.4: Results of technical assessment for MEA scenario and SPECCA calculations



	RHP	**WP**	**SS**	**MSW**
Clinker production, kg/s	29.5	31.3	27.6	30.4
Fuel consumption, kg/s				
• Pre-calciner	2.3	2.3	2.3	2.3
• Kiln	1.6	1.6	1.6	1.6
• Steam boiler (biomass)	6	5	8.7	5.1
Thermal energy reqd. for desorption (MJ/kg_{clk})	3.2	3.0	3.3	3.1
CO_2 emitted (direct), kg_{CO2}/t_{clk}	93	88	97	90
CO_2 captured, kg_{CO2}/t_{clk}	837	792	872	813
SPECCA Calculations:				
Specific Primary Energy Consumption, MJ/t_{clk}	**4373**	**4135**	**4484**	**4258**
Steam consumption	3525	3335	3580	3424
Electric power consumption (primary energy)				
• SNCR	9	7	33	16
• FGD	18	17	36	21
• Auxiliaries in capture plant [a]	237	224	241	230
• CO_2 Compression	584	553	594	568
Total CO_2 avoided, kg_{CO2}/t_{clk}	**708**	**716**	**703**	**498**
Difference in direct emissions: $e_{d,base} - e_{d,beccs}$	392	464	409	452
Difference in indirect emissions (electricity): $e_{i,base} - e_{i,beccs}$	-70	-66	-74	-69
CO_2 removed from atmosphere, r_{bio}:	386	318	368	115
SPECCA, MJ/kg_{CO2}	**6.2**	**5.8**	**6.6**	**8.6**

a – Absorber, desorber, amine filter, pumps, cooler

SPECCA for MEA scenario:

Specific primary energy consumption for the avoided CO_2 is estimated by accounting for the retrofitted units pertaining to the CO_2 capture technology. This includes steam consumption, electric power consumption in the SNCR (NO_2 reduction unit), FGD (desulphurization unit), CO_2 capture units[1] and the CO_2 compression work post capture. It can be inferred that the largest contributor to SPECCA in MEA scenario is the consumption of steam for the desorption of CO_2 from the MEA solvent; it amounts to about 80% of the specific primary energy consumption, in all of the four biomass types. Steam consumption is the largest contributor in terms of both added energy consumption and the associated CO_2 emissions. Of the total electric power consumption in the CO_2 capture plant, the CO_2 compression consumes about 66% to 69% of the power. The compression unit includes drying of the regenerated and cooled CO_2 stream as well, prior to compression. The electric power consumption in the base cement plant, equated to primary energy value is 1056 MJ/t_{clk}, and the power consumption in the retrofitted CO_2 capture plant ranges from 800 to 904 MJ/t_{clk}. This amounts to an increase in electricity demand ranging from 76% to 86% when MEA absorption-based CO_2 capture units are retrofitted to the cement plant. In comparison with the increase in electric power consumption when RHP, WP and MSW are used, there was additional power consumed in the case of sewage sludge (about 111 to 350 MJ/t_{clk} higher than the other three fuels). This can be attributed to the high nitrogen and sulphur content in sewage sludge, which necessitates additional power in the De-NO_x and FGD units respectively.

SPECCA values are in the range of 5.8 to 8.6 MJ/kg_{CO_2}, the highest for municipal solid waste and the least value for wood pellets. Rice husk pellets, wood pellets and sewage sludge have SPECCA values in the range of 5.8 to 6.6 MJ/kg_{CO_2}, but the value shoots up to 8.6 MJ/kg_{CO_2} in the case of municipal solid waste. The reason for the deviation in the SPECCA for MSW is the 65% non-biogenic fraction assumed. As 65% of the CO_2 emitted is still from the non-biogenic content in the MSW, these CO_2 emissions lead to a relatively lower value of the total CO_2 avoided. Also this variation in the values of CO_2 avoided when MSW is used as a fuel is only visible in case of MEA capture technology as the emissions from the biomass-fired steam boiler are not captured by the capture technology.

Economic assessment for MEA scenario:

The results of the economic evaluation for MEA scenario for all the four biomass types are presented in table 4.5. The total lifetime operating expenses (variable and fixed OpEx) and capital expenses are depicted. A break up of the lifetime OpEx components is given; for CapEx, the retrofit costs in the base year (2018) are listed. From the break up of variable OpEx, it can be inferred that the largest contributor is electricity consumption (for the cement plant + CO_2 capture plant). The second biggest contributor to variable OpEx is the biomass fuel prices, the highest value of biomass costs being observed for sewage sludge where it amounts to roughly 30% of the variable OpEx. With regards to the price of NH_3 for the SNCR unit, there is a deviation observed in the case of sewage sludge, where the costs are much higher than with the other biomass types. This can be attributed to the increased share of nitrogen in the sludge composition, which leads to increased need for De-NO_x. Apart from this one deviation, there is no other major difference in cost components among the four biomass types.

Cement production costs range from 89 (MSW) to 104 (SS) €/t_{cement} and the costs of CO_2 avoided range from 71 (WP) to 96 (SS) €/t_{CO_2}. The avoidance costs for MSW are high in spite of the least levelised costs obtained. This is the result of the low CO_2 avoided in case of MSW. With

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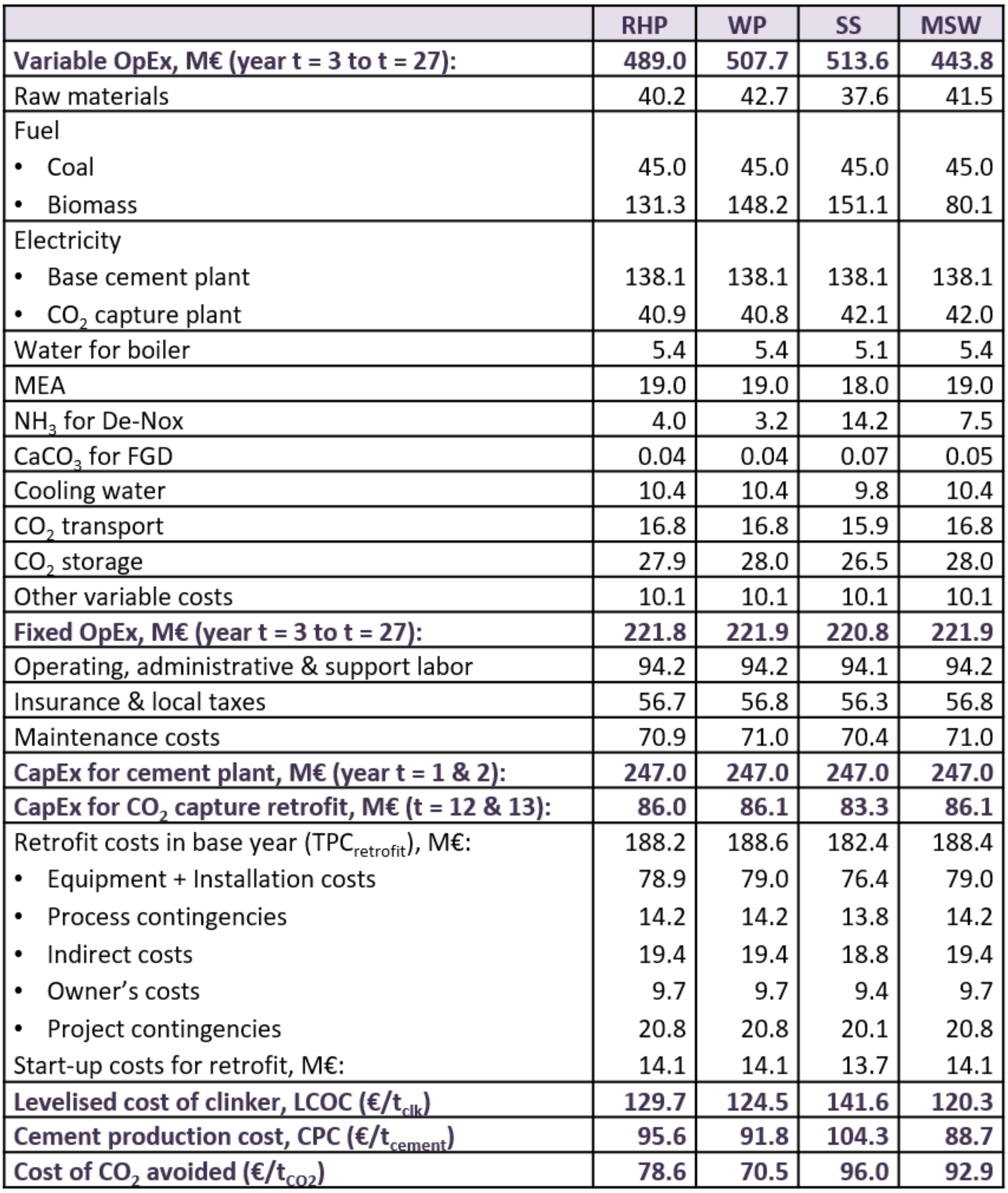
[1] Include absorber, desorber, heat exchanger, MEA pumps, MEA processing and cooler.

Table 4.5: Economic evaluation results for MEA scenario



	RHP	WP	SS	MSW
Variable OpEx, M€ (year t = 3 to t = 27):	**489.0**	**507.7**	**513.6**	**443.8**
Raw materials	40.2	42.7	37.6	41.5
Fuel				
• Coal	45.0	45.0	45.0	45.0
• Biomass	131.3	148.2	151.1	80.1
Electricity				
• Base cement plant	138.1	138.1	138.1	138.1
• CO_2 capture plant	40.9	40.8	42.1	42.0
Water for boiler	5.4	5.4	5.1	5.4
MEA	19.0	19.0	18.0	19.0
NH_3 for De-Nox	4.0	3.2	14.2	7.5
$CaCO_3$ for FGD	0.04	0.04	0.07	0.05
Cooling water	10.4	10.4	9.8	10.4
CO_2 transport	16.8	16.8	15.9	16.8
CO_2 storage	27.9	28.0	26.5	28.0
Other variable costs	10.1	10.1	10.1	10.1
Fixed OpEx, M€ (year t = 3 to t = 27):	**221.8**	**221.9**	**220.8**	**221.9**
Operating, administrative & support labor	94.2	94.2	94.1	94.2
Insurance & local taxes	56.7	56.8	56.3	56.8
Maintenance costs	70.9	71.0	70.4	71.0
CapEx for cement plant, M€ (year t = 1 & 2):	**247.0**	**247.0**	**247.0**	**247.0**
CapEx for CO_2 capture retrofit, M€ (t = 12 & 13):	**86.0**	**86.1**	**83.3**	**86.1**
Retrofit costs in base year ($TPC_{retrofit}$), M€:	188.2	188.6	182.4	188.4
• Equipment + Installation costs	78.9	79.0	76.4	79.0
• Process contingencies	14.2	14.2	13.8	14.2
• Indirect costs	19.4	19.4	18.8	19.4
• Owner's costs	9.7	9.7	9.4	9.7
• Project contingencies	20.8	20.8	20.1	20.8
Start-up costs for retrofit, M€:	14.1	14.1	13.7	14.1
Levelised cost of clinker, LCOC (€/t_{clk})	**129.7**	**124.5**	**141.6**	**120.3**
Cement production cost, CPC (€/t_{cement})	**95.6**	**91.8**	**104.3**	**88.7**
Cost of CO_2 avoided (€/t_{CO2})	**78.6**	**70.5**	**96.0**	**92.9**

the retrofitting of MEA capture technology, an increase in the cement production costs ranging from 62% (MSW) to 90% (SS) was observed.

4.2.2 CaL (tail-end) Scenario

Integration level of 25% was considered for the calcium looping (CaL) based CO_2 capture. This corresponds to the initial limestone flow rate in the cement plant being split into two fractions - of which 1/4th is fed as the make-up limestone solution (92% w/w $CaCO_3$, 8% water) for the CaL process. The technical assessment results for the CaL scenario are presented in table 4.6. The oxygen requirements for CaL process have been estimated using stoichiometry and mass balance in the CaL calciner. It was observed that depending on the composition of the biomass fuel, the oxygen requirement varies. The mentioned oxygen supply rates comprise of 95% O_2 and 5% N_2.

The estimated rate of fuel supplied is also presented in table 4.6. The fuel consumption rate was observed to vary depending on the calorific value of the fuel. Sewage sludge consumes the highest amount of fuel for the CaL process owing to its least calorific value among the four biomass types (10.97 MJ/kg). In the pre-calciner of the base cement plant (coal w/o CCS), there is a decrease in the rate of fuel consumption as only 75% of the limestone supplied in the base case scenario is supplied through the raw mill in the CaL scenario (the other 25% is fed to CaL process as make-up limestone). It was assumed that the fuel consumption in the kiln is the same, however (this was discussed in the methodology in section 3.7.2).

The rate of (CaO-rich) purge stream expelled from the CaL calciner was also observed to be varying depending on the composition of the fuel; this is because, the purge stream comprises of ash and $CaSO_4$, in addition to CaO. The quantity of the ash and $CaSO_4$ are directly impacted by the composition of the biomass used; the sulphur content in the biomass affects the rate of $CaSO_4$ formed. The ash composition in the biomass affects the clinker composition; there is also an increase in the output rate of clinker obtained as a result of the purge stream being incorporated[2]. The reason for the change in clinker composition/flow rate is because the ash in the purge stream (from the combustion of biomass in the CaL calciner) comprises of SiO_2, Al_2O_3, Fe_2O_3, MgO and CaO - which increase the quantity of additives in the clinker that is formed in the cement plant. The rate of clinker produced and the variation in clinker composition obtained for each of the four biomass types are presented in table 4.6. There was observed to be a significant variation in the increase in the rate of clinker production, among different biomass types. With wood pellets, for instance, there is a negligible increase; however there is an 8% increase in the clinker production rate observed with sewage sludge. This high variation when sewage sludge is used for CaL process can be attributed to the increased share of sulphur in the fuel, thereby relatively higher share of $CaSO_4$ in the purge stream; another possible reason is the higher rate of fuel consumption (due to low LHV) that leads to increased share of ash, and hence increased share of additives.

SPECCA for CaL scenario:

The largest contributor to SPECCA in CaL-based capture is the consumption of fuel associated with the calcination in the CaL process. Fuel consumption amounts to about 73 to 78% of the total specific primary energy consumption. The other components in SPECCA pertain to electricity consumption. An increase in (primary) electricity consumption (relative to the base cement plant without CO_2 capture) ranging from 159 to 181% was observed in CaL based capture (note that this refers to increase in the power demand, not the electric power generated). This results in increased indirect CO_2 emissions in CaL based capture. The electric power consumption in the

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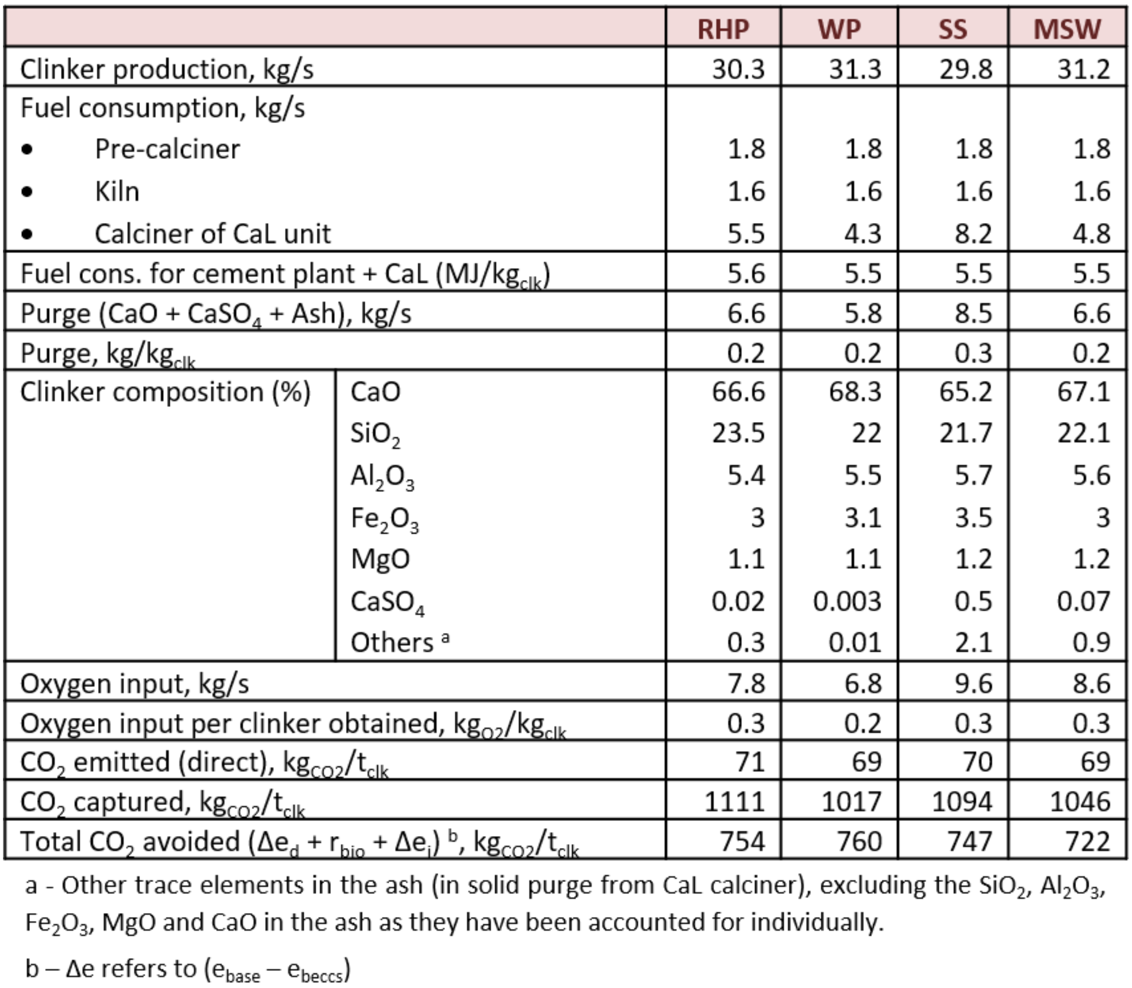
[2] There is also a possibility to adjust the additives in the raw meal to get the same output rate of clinker, which hasn't been considered in this section as this is being studied in the fourth scenario (section 4.2.4).

Table 4.6: Results of technical assessment for CaL scenario

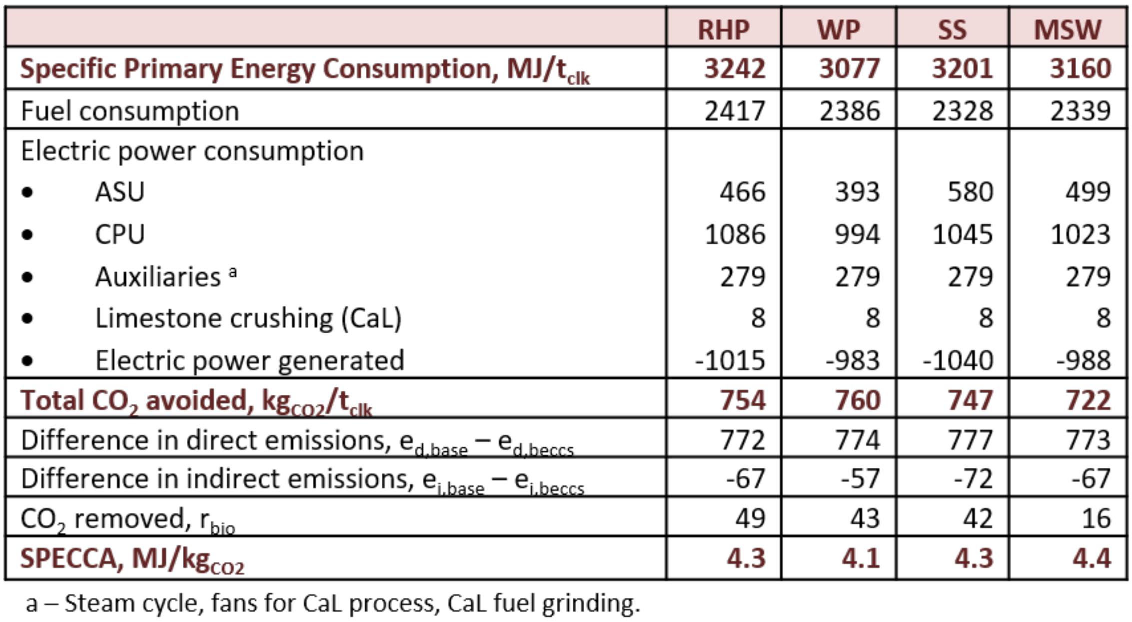


		RHP	WP	SS	MSW
Clinker production, kg/s		30.3	31.3	29.8	31.2
Fuel consumption, kg/s					
• Pre-calciner		1.8	1.8	1.8	1.8
• Kiln		1.6	1.6	1.6	1.6
• Calciner of CaL unit		5.5	4.3	8.2	4.8
Fuel cons. for cement plant + CaL (MJ/kg_{clk})		5.6	5.5	5.5	5.5
Purge ($CaO + CaSO_4$ + Ash), kg/s		6.6	5.8	8.5	6.6
Purge, kg/kg_{clk}		0.2	0.2	0.3	0.2
Clinker composition (%)	CaO	66.6	68.3	65.2	67.1
	SiO_2	23.5	22	21.7	22.1
	Al_2O_3	5.4	5.5	5.7	5.6
	Fe_2O_3	3	3.1	3.5	3
	MgO	1.1	1.1	1.2	1.2
	$CaSO_4$	0.02	0.003	0.5	0.07
	Others [a]	0.3	0.01	2.1	0.9
Oxygen input, kg/s		7.8	6.8	9.6	8.6
Oxygen input per clinker obtained, kg_{O2}/kg_{clk}		0.3	0.2	0.3	0.3
CO_2 emitted (direct), kg_{CO2}/t_{clk}		71	69	70	69
CO_2 captured, kg_{CO2}/t_{clk}		1111	1017	1094	1046
Total CO_2 avoided ($\Delta e_d + r_{bio} + \Delta e_i$) [b], kg_{CO2}/t_{clk}		754	760	747	722

a - Other trace elements in the ash (in solid purge from CaL calciner), excluding the SiO_2, Al_2O_3, Fe_2O_3, MgO and CaO in the ash as they have been accounted for individually.

b – Δe refers to ($e_{base} - e_{beccs}$)

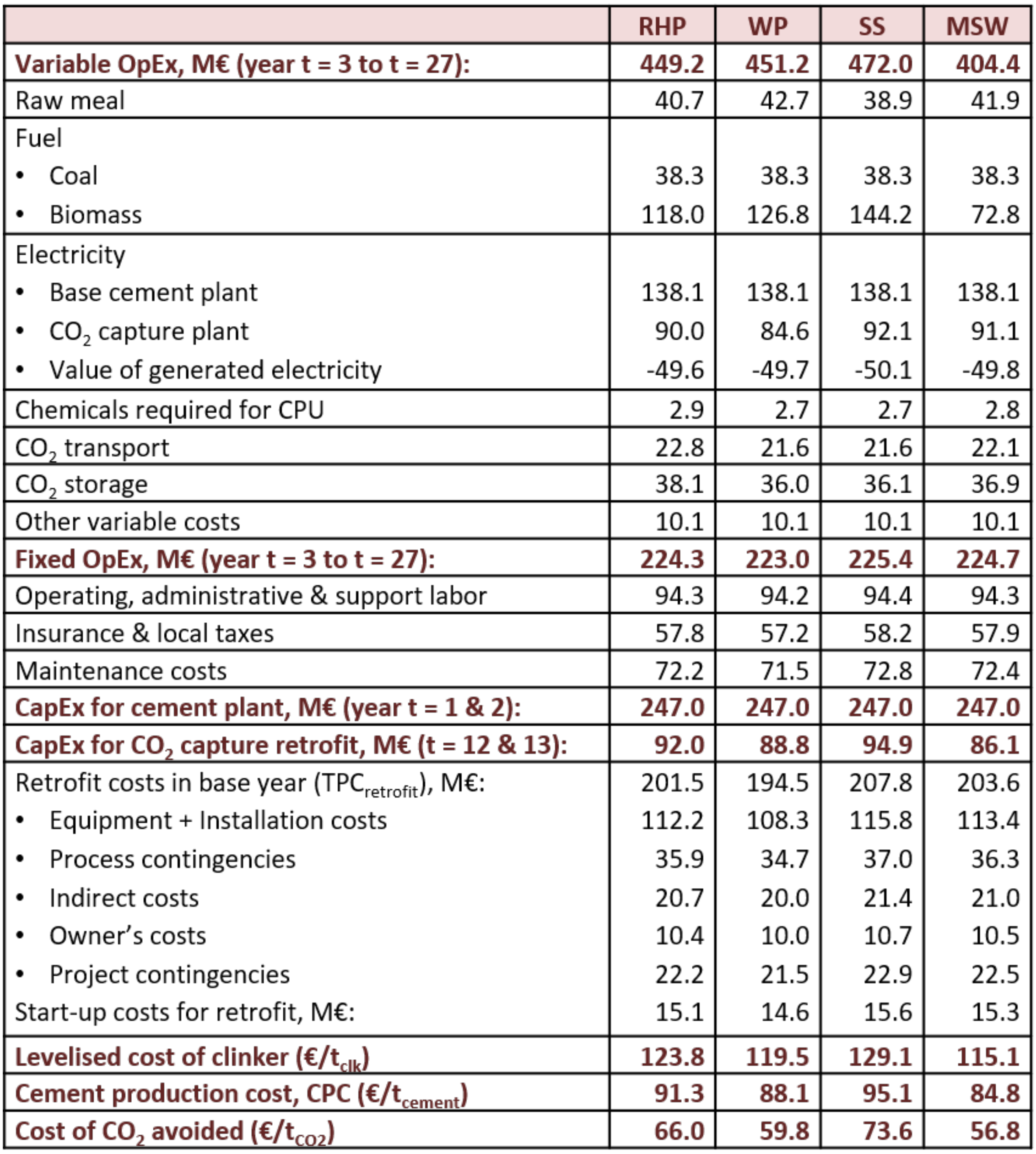
Table 4.7: SPECCA calculations for CaL scenario



	RHP	WP	SS	MSW
Specific Primary Energy Consumption, MJ/t_{clk}	**3242**	**3077**	**3201**	**3160**
Fuel consumption	2417	2386	2328	2339
Electric power consumption				
• ASU	466	393	580	499
• CPU	1086	994	1045	1023
• Auxiliaries [a]	279	279	279	279
• Limestone crushing (CaL)	8	8	8	8
• Electric power generated	-1015	-983	-1040	-988
Total CO_2 avoided, kg_{CO2}/t_{clk}	**754**	**760**	**747**	**722**
Difference in direct emissions, $e_{d,base} - e_{d,beccs}$	772	774	777	773
Difference in indirect emissions, $e_{i,base} - e_{i,beccs}$	-67	-57	-72	-67
CO_2 removed, r_{bio}	49	43	42	16
SPECCA, MJ/kg_{CO2}	**4.3**	**4.1**	**4.3**	**4.4**

a – Steam cycle, fans for CaL process, CaL fuel grinding.

Table 4.8: Economic evaluation results for CaL scenario



	RHP	WP	SS	MSW
Variable OpEx, M€ (year t = 3 to t = 27):	**449.2**	**451.2**	**472.0**	**404.4**
Raw meal	40.7	42.7	38.9	41.9
Fuel				
• Coal	38.3	38.3	38.3	38.3
• Biomass	118.0	126.8	144.2	72.8
Electricity				
• Base cement plant	138.1	138.1	138.1	138.1
• CO_2 capture plant	90.0	84.6	92.1	91.1
• Value of generated electricity	-49.6	-49.7	-50.1	-49.8
Chemicals required for CPU	2.9	2.7	2.7	2.8
CO_2 transport	22.8	21.6	21.6	22.1
CO_2 storage	38.1	36.0	36.1	36.9
Other variable costs	10.1	10.1	10.1	10.1
Fixed OpEx, M€ (year t = 3 to t = 27):	**224.3**	**223.0**	**225.4**	**224.7**
Operating, administrative & support labor	94.3	94.2	94.4	94.3
Insurance & local taxes	57.8	57.2	58.2	57.9
Maintenance costs	72.2	71.5	72.8	72.4
CapEx for cement plant, M€ (year t = 1 & 2):	**247.0**	**247.0**	**247.0**	**247.0**
CapEx for CO_2 capture retrofit, M€ (t = 12 & 13):	**92.0**	**88.8**	**94.9**	**86.1**
Retrofit costs in base year ($TPC_{retrofit}$), M€:	201.5	194.5	207.8	203.6
• Equipment + Installation costs	112.2	108.3	115.8	113.4
• Process contingencies	35.9	34.7	37.0	36.3
• Indirect costs	20.7	20.0	21.4	21.0
• Owner’s costs	10.4	10.0	10.7	10.5
• Project contingencies	22.2	21.5	22.9	22.5
Start-up costs for retrofit, M€:	15.1	14.6	15.6	15.3
Levelised cost of clinker (€/t_{clk})	**123.8**	**119.5**	**129.1**	**115.1**
Cement production cost, CPC (€/t_{cement})	**91.3**	**88.1**	**95.1**	**84.8**
Cost of CO_2 avoided (€/t_{CO2})	**66.0**	**59.8**	**73.6**	**56.8**

CaL process is very high in comparison with MEA capture, mainly due to the CPU and ASU. With MEA capture technology, an increase in electricity consumption ranging from 76% to 86% of the base cement plant was only witnessed. Of the electric power consumption in the retrofitted units of the CaL capture technology, the share of the CPU's power demands ranges from 55 to 59% while that of the ASU ranges from 23 to 30%. Part of this power consumption was compensated with on-site electric power generation using recovered waste heat. The estimated values of electric power generation are displayed in Table 4.7. However, the electric power generation results in further CO_2 avoidance; although to a very small extent, it still is able to offset almost all (about 93 to 99%) of the indirect emissions associated with the electric power consumption in the CPU.

SPECCA ranges from 4.1 to 4.4 MJ/kg_{CO_2} for the CaL-based capture. The SPECCA value in case of MSW used as fuel is 4.4 MJ/kg_{CO_2} and it doesn't deviate drastically as it did in the case of MEA based CO_2 capture, even though there is an additional calciner which consumes MSW exclusively. This is because, most of the CO_2 emitted in the calciner of the CaL is captured and sent to the CPU.

Economic assessment for CaL scenario:

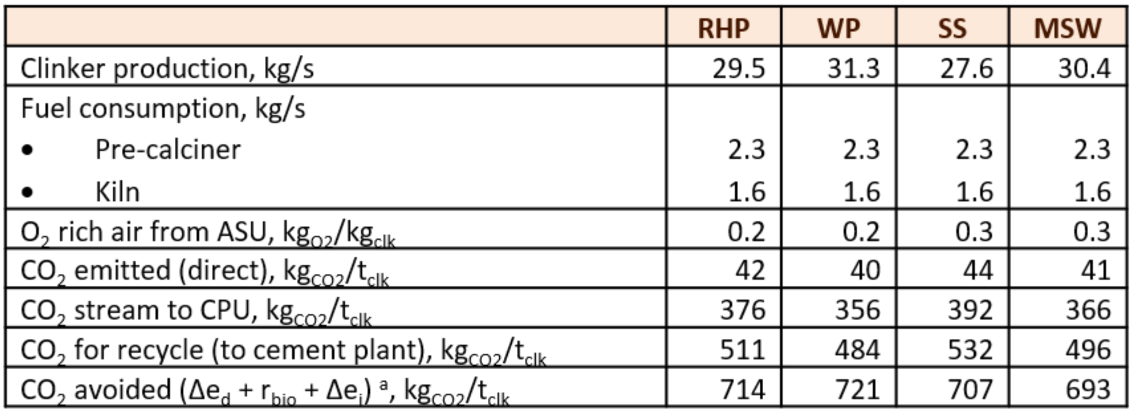
The results of economic assessment for CaL-based CO_2 capture are tabulated in Table 4.8. In the table, the lifetime CapEx and OpEx (fixed and variable) are presented. The estimation of capital expenses in the base year 2018 are also specified in the table. For the estimation of OpEx, a break up of the lifetime cost values estimated are presented. As observed in the MEA scenario, the price of biomass accounts for a large fraction of the variable OpEx (ranging from 18 to 29%). Costs are highest when sewage sludge is used; this result is not just a direct relation to the biomass price assumptions used in this thesis, but it is also the high value of sludge consumption for the CaL process (as discussed in the technical results). The costs associated with electricity requirements for the retrofitted CO_2 capture units are significantly higher than the corresponding values in MEA scenario (almost twice the value in MEA). This is a direct result of the increased electric power requirements in the CaL when compared with MEA. However, the benefits accrued due to electricity generation on-site offset a fraction (roughly 38 to 40%) of the electricity costs.

CaL based CO_2 capture entails the highest capture rates among the three CO_2 capture technologies because the emissions from CaL process are also captured in this scenario; this is the reason for the high values of CO_2 transport and storage costs incurred in CaL scenario. The transport and storage costs are estimated based on a direct relation to the amount of CO_2 that is captured and sent through the CCS chain. Also the equipment and installation costs are roughly 40% higher than that of MEA based capture. Cement production costs in CaL capture technology range from 85 to 95 $€/t_{cement}$ and the costs of avoided CO_2 range from 57 to 74 $€/t_{CO_2}$.

4.2.3 Oxyfuel Scenario

In oxyfuel combustion capture, the rate of clinker is unaffected (same as the values in table 4.3), the modifications presented in the methodology are taken into consideration while estimating the energy consumption parameters. The rate of fuel consumption is also unaltered therefore. There was a variation in assumptions of the temperature of the cooler exit gas streams (to maintain the temperature profile); there is no variation in the mass balance results. The total CO_2 avoided is shown in table 4.9 along with other technical parameters; a break-up of the avoided CO_2 for oxyfuel combustion capture is shown under the SPECCA calculations in table 4.10.

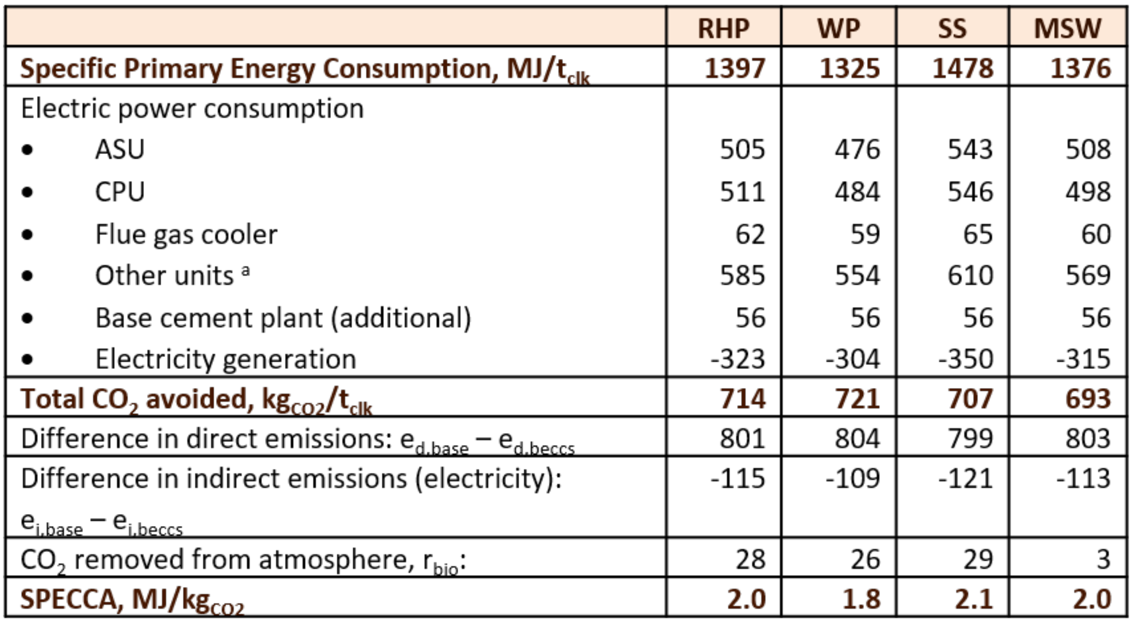
Table 4.9: Results of technical assessment for Oxyfuel scenario



	RHP	WP	SS	MSW
Clinker production, kg/s	29.5	31.3	27.6	30.4
Fuel consumption, kg/s				
• Pre-calciner	2.3	2.3	2.3	2.3
• Kiln	1.6	1.6	1.6	1.6
O_2 rich air from ASU, kg_{O2}/kg_{clk}	0.2	0.2	0.3	0.3
CO_2 emitted (direct), kg_{CO2}/t_{clk}	42	40	44	41
CO_2 stream to CPU, kg_{CO2}/t_{clk}	376	356	392	366
CO_2 for recycle (to cement plant), kg_{CO2}/t_{clk}	511	484	532	496
CO_2 avoided ($\Delta e_d + r_{bio} + \Delta e_i$) ^{a}, kg_{CO2}/t_{clk}	714	721	707	693

a – Δe refers to ($e_{base} - e_{beccs}$).

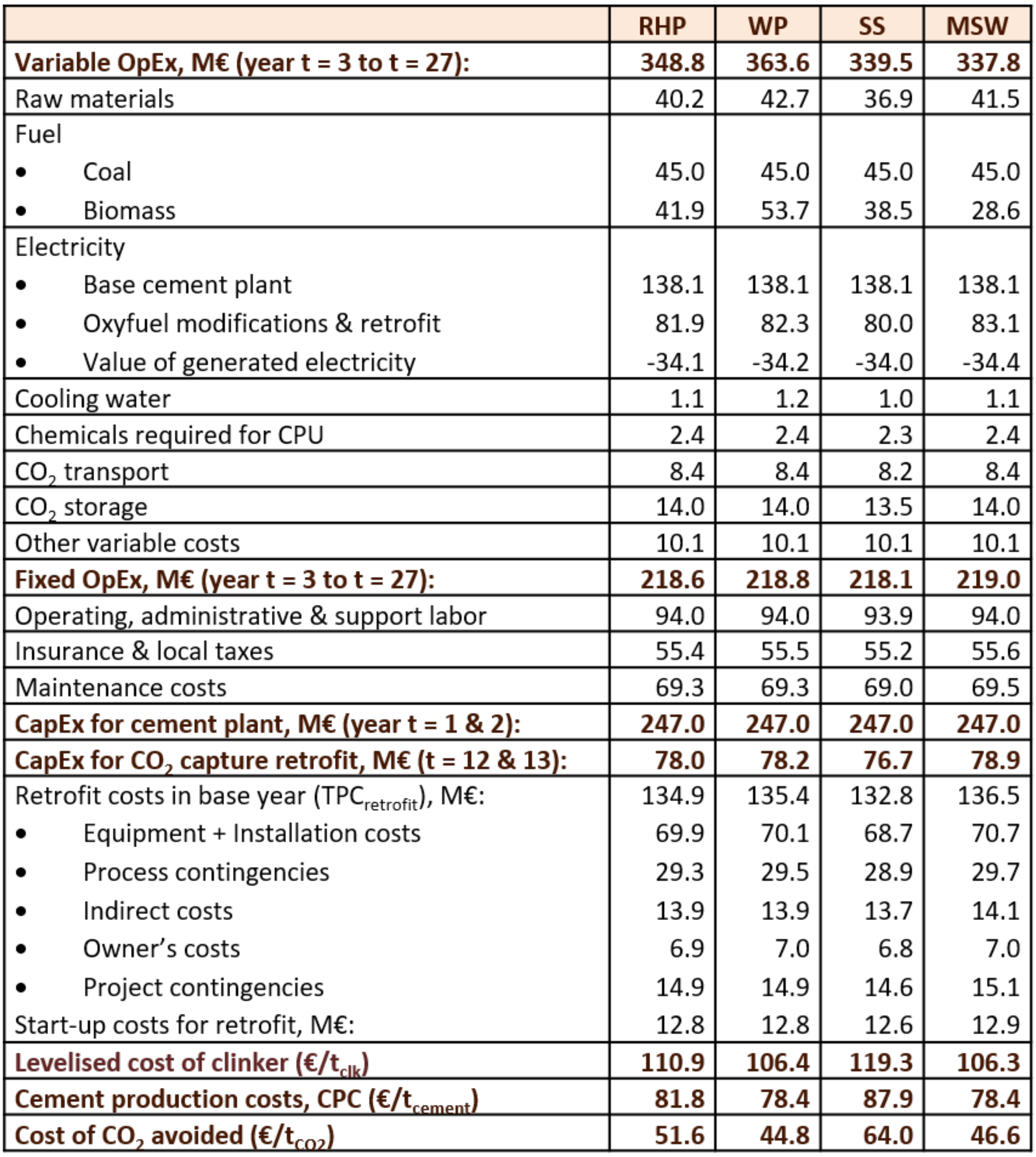
Table 4.10: SPECCA calculations for Oxyfuel scenario



	RHP	WP	SS	MSW
Specific Primary Energy Consumption, MJ/t_{clk}	**1397**	**1325**	**1478**	**1376**
Electric power consumption				
• ASU	505	476	543	508
• CPU	511	484	546	498
• Flue gas cooler	62	59	65	60
• Other units ^{a}	585	554	610	569
• Base cement plant (additional)	56	56	56	56
• Electricity generation	-323	-304	-350	-315
Total CO_2 avoided, kg_{CO2}/t_{clk}	**714**	**721**	**707**	**693**
Difference in direct emissions: $e_{d,base} - e_{d,beccs}$	801	804	799	803
Difference in indirect emissions (electricity): $e_{i,base} - e_{i,beccs}$	-115	-109	-121	-113
CO_2 removed from atmosphere, r_{bio}:	28	26	29	3
SPECCA, MJ/kg_{CO2}	**2.0**	**1.8**	**2.1**	**2.0**

a – Other units include fans, recycle, condenser, filter and pumps.

Table 4.11: Economic evaluation results for Oxyfuel scenario



	RHP	WP	SS	MSW
Variable OpEx, M€ (year t = 3 to t = 27):	**348.8**	**363.6**	**339.5**	**337.8**
Raw materials	40.2	42.7	36.9	41.5
Fuel				
• Coal	45.0	45.0	45.0	45.0
• Biomass	41.9	53.7	38.5	28.6
Electricity				
• Base cement plant	138.1	138.1	138.1	138.1
• Oxyfuel modifications & retrofit	81.9	82.3	80.0	83.1
• Value of generated electricity	-34.1	-34.2	-34.0	-34.4
Cooling water	1.1	1.2	1.0	1.1
Chemicals required for CPU	2.4	2.4	2.3	2.4
CO_2 transport	8.4	8.4	8.2	8.4
CO_2 storage	14.0	14.0	13.5	14.0
Other variable costs	10.1	10.1	10.1	10.1
Fixed OpEx, M€ (year t = 3 to t = 27):	**218.6**	**218.8**	**218.1**	**219.0**
Operating, administrative & support labor	94.0	94.0	93.9	94.0
Insurance & local taxes	55.4	55.5	55.2	55.6
Maintenance costs	69.3	69.3	69.0	69.5
CapEx for cement plant, M€ (year t = 1 & 2):	**247.0**	**247.0**	**247.0**	**247.0**
CapEx for CO_2 capture retrofit, M€ (t = 12 & 13):	**78.0**	**78.2**	**76.7**	**78.9**
Retrofit costs in base year ($TPC_{retrofit}$), M€:	134.9	135.4	132.8	136.5
• Equipment + Installation costs	69.9	70.1	68.7	70.7
• Process contingencies	29.3	29.5	28.9	29.7
• Indirect costs	13.9	13.9	13.7	14.1
• Owner's costs	6.9	7.0	6.8	7.0
• Project contingencies	14.9	14.9	14.6	15.1
Start-up costs for retrofit, M€:	12.8	12.8	12.6	12.9
Levelised cost of clinker (€/t_{clk})	**110.9**	**106.4**	**119.3**	**106.3**
Cement production costs, CPC (€/t_{cement})	**81.8**	**78.4**	**87.9**	**78.4**
Cost of CO_2 avoided (€/t_{CO2})	**51.6**	**44.8**	**64.0**	**46.6**

SPECCA for Oxyfuel scenario:

Energy consumption in the CPU and ASU are the highest contributors to SPECCA, as can be seen from the break up in SPECCA calculations in Table 4.11. SPECCA values in the range of 1.8 to 2.1 MJ/kg$_{CO_2}$ are obtained in the case of oxyfuel combustion capture, estimated to be the least among all the assessed CO_2 capture technologies. CO_2 capture rates are the least in this type of capture (owing to the recycle flue gas stream). The increase in (primary) electric energy consumption (relative to the base cement plant without oxyfuel combustion) ranges from 154 to 173%, which is about 5 to 11% lower than the corresponding values observed in CaL process. Of the additional electric power consumption, the share of CPU's power demands ranges from 29 to 30% and that of the ASU also ranges from 29 to 30%. Moreover, an additional electric power consumption value for the cement plant has been mentioned, 56 MJ/t$_{clk}$; this is on account of the modifications made in the base cement plant units (cooler, for instance). Although, it contributes to only roughly 3% the total electricity consumption pertaining to the retrofitted CO_2 capture units. As discussed earlier, the CO_2 capture rates are least in oxyfuel combustion capture, therefore a lower amount of CO_2 is captured and sent to CPU. The amount of captured CO_2 is about 35 and 45% of the captured CO_2 in MEA and CaL technologies respectively. This is the reason for the relatively lower value of electric power consumption in the CPU than CaL scenario (about 48 to 53% lower than the value in CPU of CaL technology). As with the CaL scenario, the electricity generation using waste heat recovered is able to offset a fraction of the power consumed in the CPU (about two-thirds).

Economic assessment for oxyfuel scenario:

The results of economic evaluation for oxyfuel combustion CO_2 capture are tabulated in Table 4.11. The break up of lifetime variable and fixed OpEx are presented. It can be inferred that price of biomass is the least and has no significant impact as it did in the other two capture technologies. This is due to the low share of biomass used for the process; while in CaL and MEA capture technologies, there were additional boilers for the retrofits that were fed with biomass in addition to the 30% biomass co-fired in the cement plant. However, in oxyfuel combustion capture, there is no such additional biomass consumption for the retrofitted units; the only requirement for biomass is for 30% co-firing in the cement plant. Electricity costs incurred due to oxyfuel modifications are the highest among the three CO_2 capture technologies. There are not as many sources available for waste heat recovery as in the case of CaL; this is the reason why the generated electricity values are not as high for oxyfuel as in the case of CaL. As the CO_2 capture rates in oxyfuel combustion capture are the least among the three CO_2 capture technologies assessed in this thesis, the costs for CO_2 transport and storage are the least among the three CO_2 capture technologies. This is on account of the low capture rates, as part of the CO_2 is recycled to the cement plant. There is no cost parameter that shows a significant variation among the four biomass types, which is again a direct result of the low share of biomass involved.

Cement production costs in oxyfuel combustion capture range from 78 (WP, MSW) to 88 (SS) €/t$_{cement}$ and the costs of CO_2 avoided range from 45 (WP) to 64 (SS) €/t$_{CO_2}$.

4.2.4 Using ash as raw material or additive

Firstly, the amount of ash obtained from co-firing RHP, SS, MSW have been estimated for the chosen co-firing rate of 30%; wood ash was excluded for this section (discussed in 2.2.5). In case of MEA and CaL capture technologies, there is increased amount of ash recovered (as there are additional biomass-fired boilers) relative to oxyfuel combustion. In the Oxyfuel scenario, it is possible to substitute only 1.1% of the raw meal with the ash from sludge co-firing, even if all

Table 4.12: Substitution rates of bio-based ash in cement grinding

Additive	CO_2 Capture technology	Qty. of ash obt. per year (Mt/yr)	Cement prodn. per year (Mt/yr)	Max. Substitution rate (%)
RHA + Coal ash	MEA	0.02	1.2	1.4
	CaL	0.04	1.2	3.1
	Oxyfuel	0.02	1.2	1.4
MSWA + Coal ash	MEA	0.02	1.3	1.3
	CaL	0.03	1.3	2.6
	Oxyfuel	0.02	1.3	1.3

Table 4.13: Change in CO_2 avoided per tonne of cement after incorporating bio-based ash.

BECCS Scenario		Usage of Ash	CO_2 avoided before & after ash usage (kg/t_{cement})		Raw meal (kg/s)	ΔCO_2 avoided (kg/t_{cement})
SS + SSA	MEA	5% of raw meal	513	518	52.6	5
	CaL	4.9% of raw meal	505	508	52.6	3
	Oxyfuel	1.1% of raw meal	528	530	52.6	2
RHP + RHA	MEA	1.4% of cement	522	527	51.6	5
	CaL	3.1% of cement	514	518	47.4	4
	Oxyfuel	1.4% of cement	531	533	51.3	2
MSW + MSWA	MEA	1.3% of cement	367	369	52.1	2
	CaL	2.6% of cement	507	511	48.6	4
	Oxyfuel	1.3% of cement	513	514	52.3	1

the recovered ash were to be used. Incorporating SSA into the raw meal has an upper limit of 5% which was decided upon from literature. However in case of RHA and MSWA, in order to determine the maximum substitution rate possible (to ensure availability of ash) to be used as an additive during cement grinding, the quantity of ash recovered annually has been calculated and the annual cement production for both RHP and MSW are used to determine this substitution rate. Table 4.12 contains these values.

In case of RHA and MSWA, the substitution rates considered are in accordance with the estimated values from Table 4.12. To get the same amount of cement, with ash mixed as additives, reduced clinker would imply a reduction in raw material consumption. The change in raw material consumption to get a clinker output in accordance with the substitution rates from Table 4.12 have been estimated and listed in Table 4.13.

Table 4.13 shows the difference in (or the additional) CO_2 avoided (per tonne of cement) when ash is incorporated into the BECCS scenarios assessed earlier. With MEA and CaL technologies, the higher quantity of ash obtained results in a relatively higher avoidance rates in comparison with oxyfuel combustion; however it was observed that in all the 9 cases, there was less than 1% increase in the CO_2 avoidance rates, when it is standardized per tonne of cement. With oxyfuel combustion, low share of biomass results in less than 0.4% increase in CO_2 avoidance rates. It can be concluded that the availability of ash is therefore a crucial factor in increasing the CO_2 avoidance potential; It can be noted that increased share of biomass may not directly imply increased CO_2 avoidance rates; this is because, the fuel requirement in oxyfuel combustion is itself lower than MEA and CaL; it is not just the low share of biomass in oxyfuel combustion that results in low CO_2 avoidance rates.

4.3 COMPARATIVE ANALYSIS

The Key Performance Indicators (KPIs) were compared for all the BECCS scenarios assessed.

KPI 1 - Rate of clinker produced:

30% of the heating fuel in the cement plant (coal) is substituted on a mass-basis with biomass in the existing burners. Hence the rate of clinker produced per day is lower than the base value of about 2901 tonnes. As biomass has lower calorific value than coal, it is less efficient. The rate of clinker produced is dependant on the calorific value of the fuel. Sewage sludge (least LHV of 10.97 MJ/kg) on co-firing with coal gives the least rate of clinker output, 2385 tonnes per day; this rate of production is 22% lower than the BAT reference value of 2901 tonnes. When wood pellets are used for co-firing in the cement plant, the rate of clinker produced is 2703 tonnes per day (7% lower than the BAT reference clinker output). Figure 4.1 illustrates the amount of clinker produced (in tonnes/day) for all the biomass options considered. The corresponding annual cement production has also been depicted in the same figure.

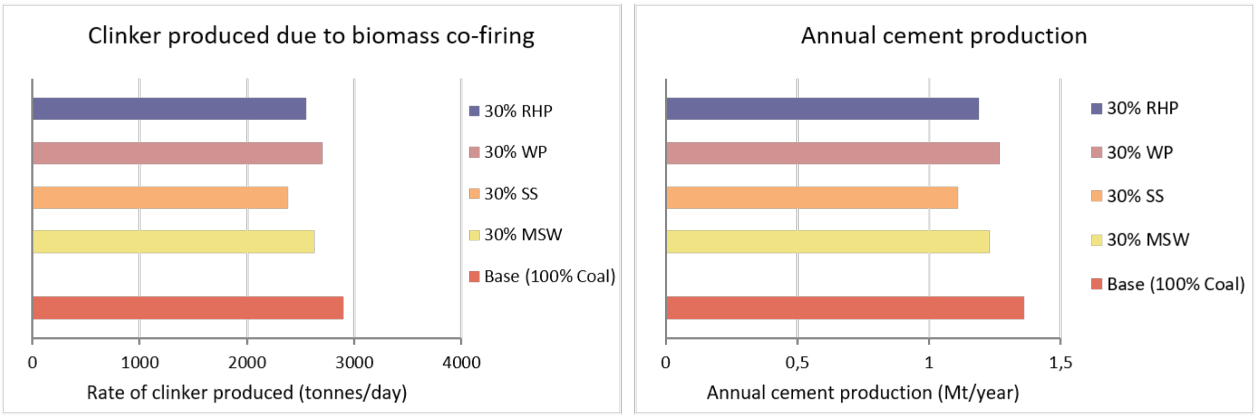


Figure 4.1: Reduced clinker production per day (left) and reduced annual cement production (right) when 30% of the coal in a cement plant is substituted with biomass

KPI 2 - CO_2 avoided:

CO_2 emission intensity when 100% coal was used to provide thermal energy for the calcination process in a cement plant amounted to 930 kg/t_{clk} (direct and indirect). This value was before the CO_2 capture plants were retrofitted. The CO_2 emission intensity values for all the BECCS cases are presented in figure 4.2, where the break-up of the emissions (direct, indirect) is illustrated along with the CO_2 removed from atmosphere and the net CO_2 emissions. The total CO_2 avoided has been estimated as the difference between the net CO_2 emission intensity values for the base case and the BECCS case. The total CO_2 avoided for all BECCS technologies are illustrated in the graph in figure 4.3.

From the graph, it can be inferred that with the exception of MSW used in case of MEA capture, the avoidance rate is in the range of 688 to 760 kg_{CO_2}/t_{clk} for all the BECCS cases. In MEA capture technology, the steam boiler emits CO_2 and these CO_2 emissions were not captured. Biomass was selected as the fuel for the steam boiler, and RHP, WP, and SS were assumed to possess 100% biogenic content. Therefore the CO_2 emissions from the steam boiler when those three biomass fuels were employed (RHP, WP, SS) did not affect the total CO_2 avoided in this thesis. But when MSW was used as fuel, 65% of the boiler CO_2 emissions are non-biogenic; therefore these CO_2 emissions offset a large part of the emissions avoided. Hence the least value of total CO_2 avoided

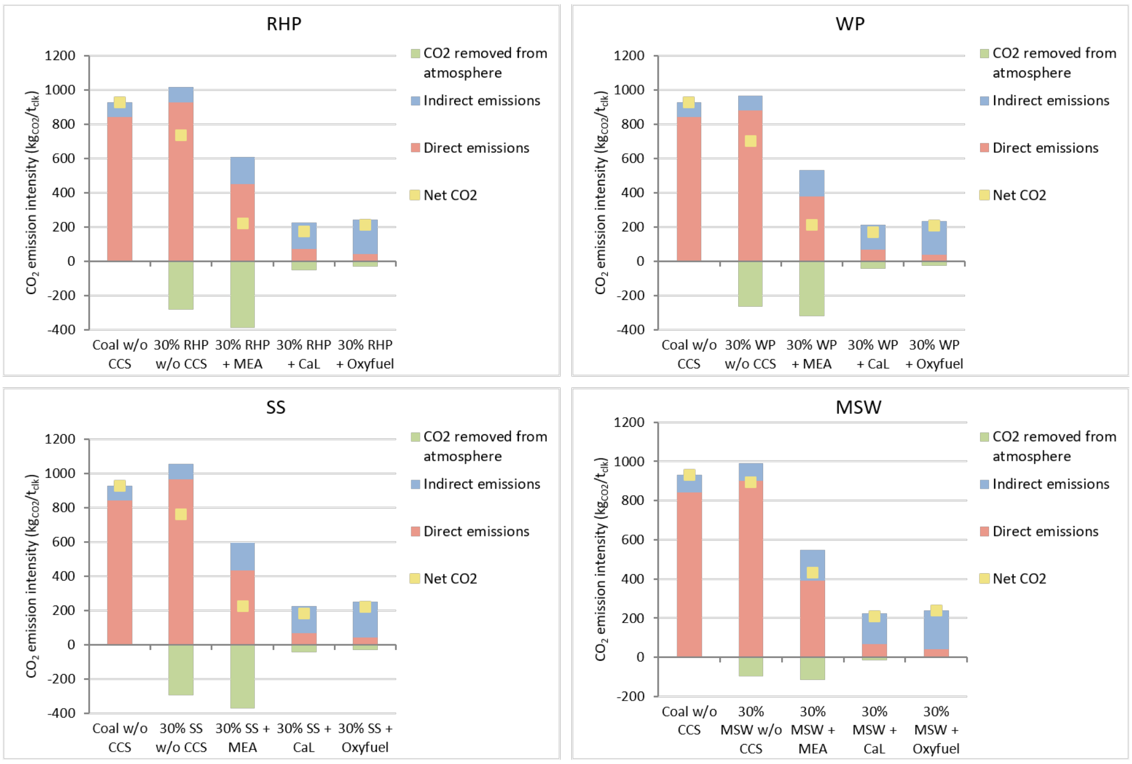


Figure 4.2: CO_2 emission intensity for all the BECCS technologies. The difference between the values indicated by the yellow mark for the base and BECCS cases is the value of the total CO_2 avoided.

(498 kg_{CO_2}/t_{clk}) was observed in that scenario (MSW + MEA capture). In CaL based CO_2 capture, there is an additional calciner that consumes biomass and there are increased CO_2 emissions. However unlike the steam boiler in MEA, the CO_2 emissions from the CaL calciner are captured and sent to the CPU.

It can be inferred from the graph in figure 4.3 that CaL capture technology entails the highest avoidance rates (722 to 760 kg_{CO_2}/t_{clk}). The avoidance rates in CaL technology are roughly 5% higher than the rates observed in MEA and oxyfuel capture technologies (with the excpetion of MSW in MEA capture technology).

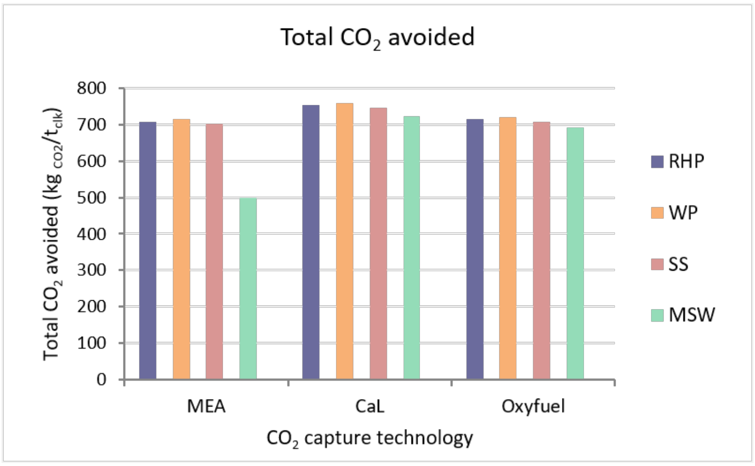


Figure 4.3: Total CO_2 avoided for all the BECCS technologies.

KPI 3 - SPECCA:

The graph in figure 4.4 illustrates the SPECCA values (in MJ/kg$_{CO_2}$) for all the BECCS cases assessed. MEA capture technology has the highest primary energy consumption per CO_2 avoided (ranging from 5.8 to 8.6 MJ/kg$_{CO_2}$). And oxyfuel has the least SPECCA (1.8 to 2.1 MJ/kg$_{CO_2}$) among the three CO_2 capture technologies assessed. It can be inferred from the graph that in MEA-based CO_2 capture, the highest value of 8.6 MJ/kg$_{CO_2}$ is observed in case of MSW. This does not imply any major difference in the primary energy consumption involved when MSW is used; it is a direct result of the low CO_2 avoided. As discussed in the comparative analysis of KPI 2, the low CO_2 avoidance and consequently the high SPECCA for MSW can be attributed to the additional non-biogenic CO_2 emissions from the steam boiler. The other biomass types (RHP, WP and SS) have SPECCA values in the range of 5.8 to 6.4 MJ/kg$_{CO_2}$ for MEA capture technology.

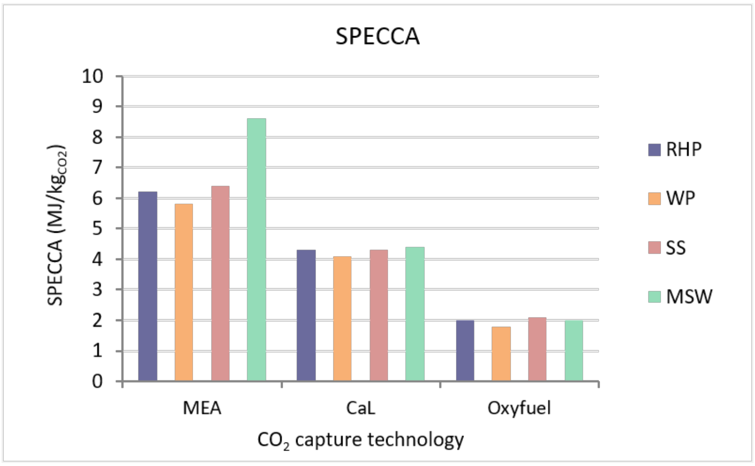


Figure 4.4: Specific primary energy consumption per CO_2 avoided (SPECCA) for all the BECCS technologies

A breakdown of the primary energy consumption (in MJ/t$_{clk}$) for the three CO_2 capture technologies retrofitted to a cement plant is illustrated for one biomass type (rice husk pellets) in figure 4.5. In terms of the specific primary energy consumption, MEA based capture involves the highest energy requirements - a large fraction of it (about 80%) is associated with the low pressure steam requirement for the regeneration of CO_2 from the MEA solvent. The energy requirements for CaL capture technology is only about 3% lower than the energy requirement for MEA capture technology. However, owing to on-site electricity generation using recovered waste heat, the net primary energy consumption for CaL capture technology reduces. The electric power generated in case of CaL process meets close to 24% of the energy requirements. Oxyfuel combustion capture also entails on-site electricity generation using the recovered waste heat. The generated electric power is able to offset a large fraction of the high electric power consumption in the CPU in both the capture technologies (CaL and oxyfuel). Between oxyfuel and CaL capture technologies, CaL has higher SPECCA than oxyfuel capture. This increased energy consumption for CaL in comparison with oxyfuel is a result of the fuel requirements for the additional calciner in the CaL process. From the breakdown indicated in figure 4.5 for rice husk pellets, it can be seen that the additional fuel consumption in CaL process accounts for 75% of the specific (net) primary energy consumption. Another observation that can be made is the relatively lower fraction of the electric power generated in case of oxyfuel capture, in comparison with CaL process. CaL process is observed to generate about 197 to 223% higher amount of electric power than oxyfuel combustion. This is because of more available sources for waste heat recovery in CaL technology. However, with SPECCA in the range of 4.1 to 4.4 MJ/kg$_{CO_2}$, CaL based capture is still less energy consuming than MEA capture (when standardized on the basis of CO_2 avoidance rates).

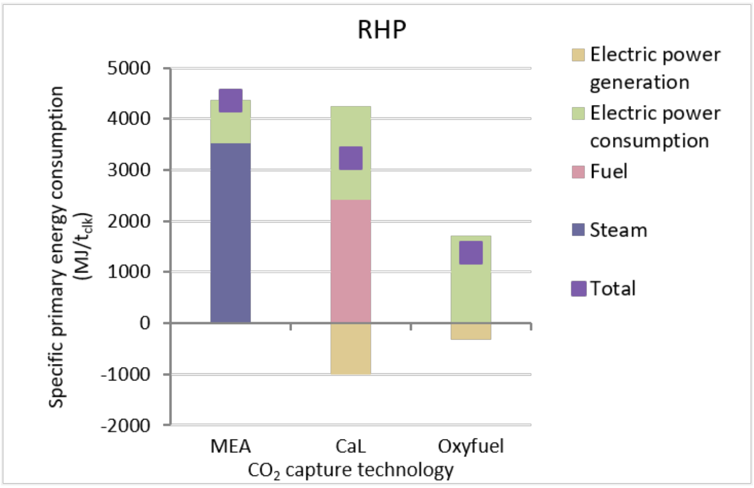


Figure 4.5: Specific primary energy consumption for the three CO_2 capture technologies retrofitted to a cement plant that uses 30% rice husk pellets

The system boundary defined for the technical assessment did not include the pre-treatment of biomass. It was considered that all the four biomass types are sourced for co-firing in a form suitable for co-firing with coal, after appropriate pre-treatment methods. Only the costs of this were included. Therefore, to observe the variation in SPECCA when the pre-treatment energy requirements are included, the thermal and energy consumption values stated in table 3.6 are included. The values of SPECCA on recalculation are indicated in the graph in figure 4.6. A significant increase in SPECCA for MEA capture technology was observed; about 19 to 48% increase in comparison to the initial values of SPECCA obtained without including the pre-treatment. With CaL technology, increase in SPECCA with respect to the initial values are in the range of 11 to 37%. There was a negligible variation in case of oxyfuel combustion capture, this is expected because there is low requirement of biomass. It can be inferred that, on inclusion of the energy requirements for the pre-treatment of biomass, there is a significant difference among biomass types for the same CO_2 capture technology. This pattern is visible particularly in MEA capture technology.

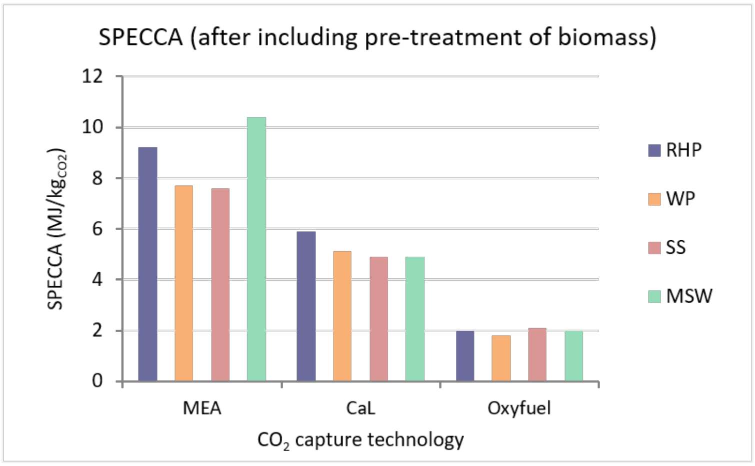


Figure 4.6: Specific primary energy consumption per CO_2 avoided (SPECCA) after including the energy requirements for pre-treatment of biomass

KPI 4 - Cement production costs:

Figure 4.7 illustrates the cement production costs for all the BECCS scenarios assessed.

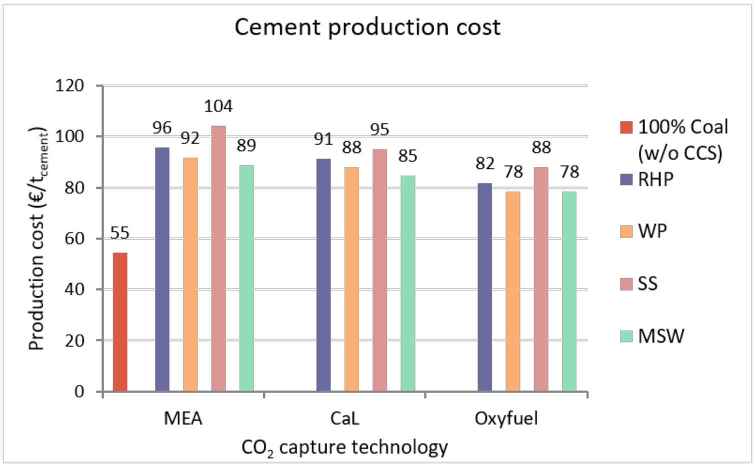


Figure 4.7: Cement production costs for the base cement plant and all the BECCS technologies

The production costs for the base case (100% coal, without CCS) have also been indicated on the graph. It can be inferred that the costs incurred due to MEA capture scenario are the highest, followed by CaL scenario. Oxyfuel combustion capture entails the least value. The production costs increase by 42% to 89% when the CO_2 capture technologies are retrofitted to the cement plant in which biomass is co-fired with coal. The pattern of variation in production costs for a specific CO_2 capture technology among different biomass types is similar in all the capture technologies. For instance, sewage sludge entails highest production costs and municipal waste entails the least, with MEA, CaL and oxyfuel capture.

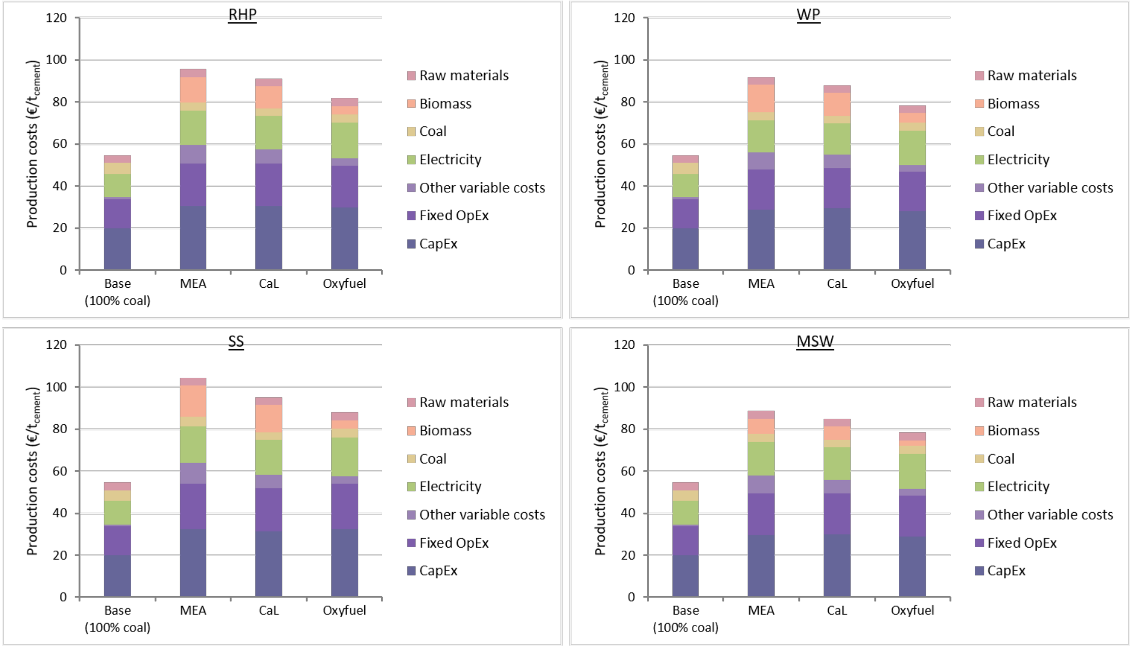


Figure 4.8: Breakdown of the cement production costs for the base cement plant and all the BECCS technologies

Figure 4.8 shows the breakdown of the cement production costs. It can be inferred from the breakdown that it is primarily the change in variable OpEx and the biomass costs that influence the production costs among the different CO_2 capture technologies. The 'other' variable operating expenses in MEA capture technology are 29 to 51% higher than the variable OpEx in CaL and 158 to 180% higher than variable OpEx in oxyfuel (other variable OpEx includes utilities and consumables other than fuel, electricty; even CO_2 transport and storage costs are included in this). The costs incurred for biomass in MEA capture technology are 12 to 16% higher than the biomass costs in CaL and 176 to 285% higher than the biomass costs in oxyfuel.

There is a variation in capital expenses, but to a very small extent. With respect to the capital expenditure in the base cement plant, 41 to 63% increase in capital requirement for the CO_2 capture technologies was observed. The costs incurred for electricity requirements for CaL process are 19 to 26% higher than the costs for MEA capture technology and about 2% higher than that of oxyfuel capture. However this high electricity requirement is not reflected in the final breakdown of the production costs for CaL technology. This is because the value of generated electricity is taken to consideration. After the value of generated electricity is accounted for in the cement production costs, the net electricity costs in CaL are 2 to 7% lower than MEA and 5 to 10% lower than the electricity costs for oxyfuel. As discussed earlier, this can be attributed to the multiple sources available for waste heat recovery in CaL process.

KPI 5 - Cost of CO_2 avoided:

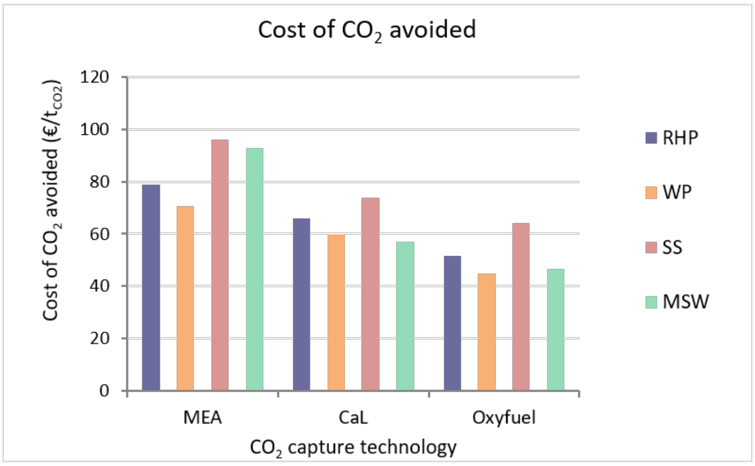


Figure 4.9: Cost of CO_2 avoided for all the BECCS technologies

Figure 4.9 illustrates the costs of CO_2 avoided for all the BECCS scenarios assessed. The costs of CO_2 avoided are estimated by dividing the difference in levelised clinker costs (for the BECCS scenario and base case) and the total CO_2 avoided. It is for this reason that the pattern of variation among the different BECCS cases is similar to the cement production costs. The costs are highest for MEA based capture, followed by calcium looping. And oxyfuel combustion capture entails least avoidance costs. With municipal solid waste used in MEA capture technology, there is a deviation observed as it does not adhere to the pattern of variation in cement production costs). The reason for this is the low CO_2 avoidance rates with MSW & MEA capture technology. And with all the CO_2 capture technologies, the costs when sewage sludge is used for co-firing are the highest among the four biomass types.

Change in CO_2 avoided after incorporating ash:

The primary reason to consider (partial) replacement of clinker with other additives (in this thesis) is to estimate the reduction in CO_2 emissions from cement production. The change in the amount of CO_2 avoided **per tonne of cement**, on incorporating ash into the BECCS (co-fire) scenarios assessed is illustrated in figure 4.10. The altered clinker-cement ratio values estimated based on the substitution rates mentioned in table 4.12 are used in this case. It can be observed that there is less than 1% increase in CO_2 avoidance rates, when standardized per tonne of cement. And particularly, with oxyfuel combustion capture, it shows less than 0.4% increase. Another

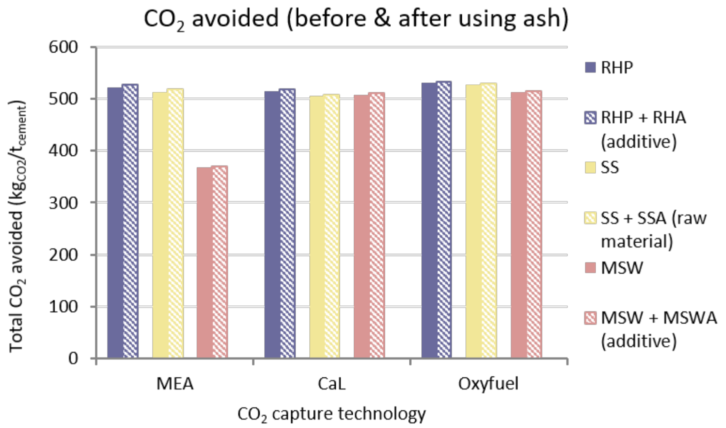


Figure 4.10: Change in total CO_2 avoided per tonne of cement on using bio-based ash

observation that can be made is that there can be no conclusion drawn as to whether using bio-based ash as a raw material is more advantageous or using the ash as an additive is more beneficial to increase the avoided CO_2.

4.4 CARBON ACCOUNTING

Gate-to-gate CO_2 accounting for the base case:

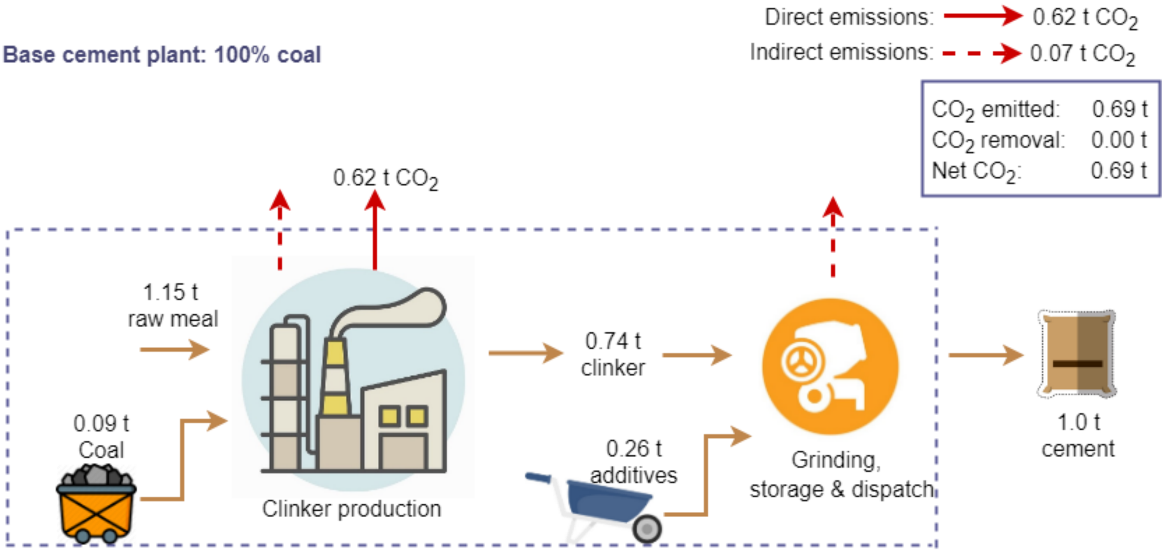


Figure 4.11: Gate-to-gate carbon accounting for the base case cement plant

The gate-to-gate boundary in case of the base cement plant (before retrofitting the CO_2 capture technologies) is illustrated in figure 4.11. In this section, the values are demonstrated for the production of 1 **tonne of cement**. The direct and indirect CO_2 emissions are accounted for; the amount of fuel (coal) consumed for producing 1 tonne of cement is presented in the figure for the base case. Direct CO_2 emissions in the base case were estimated to be 843 kg/t_{clk}. This amounts to 0.62 t_{CO_2}/t_{cement} of direct emissions. The indirect CO_2 emissions associated with the base cement plant are estimated to be 0.07 t_{CO_2}/t_{cement}. The net CO_2 emissions are positive in the base case without BECCS (it is 0.69 t_{CO_2}/t_{cement}). This estimated value of 0.69 tonnes of CO_2

per tonne of cement produced is in alignment with the value mentioned for a European BAT reference cement plant [7].

Gate-to-gate CO_2 accounting with C-neutrality of biomass in the BECCS cases:

For the BECCS cases, CO_2 emissions within the gate-to-gate boundary are accounted for, along with the CO_2 emitted by biomass considered to be removed from the atmosphere during the growth phases of the biomass feedstock. CO_2 emissions associated with the pre-treatment of biomass are also included. But other upstream and downstream CO_2 emissions like transport, storage of biomass feedstock, transport of pre-treated biomass, direct and indirect land-use are not included in this thesis. Hence this accounting cannot give a completer picture of whether negative emissions are actually achieved. But, for the boundary defined, when the CO_2 removed from the atmosphere is considered along with the gate-to-gate boundary defined for the cement plant retrofitted with CO_2 capture units, the net emissions are positive in 9 of the 12 BECCS cases. This can be attributed to partial substitution of fossil fuel with biomass. 70% of the heating fuel (on a mass-basis) in the cement plant was still coal.

An exception was observed in the case of Calcium looping (CaL), where the fuel supplied for the calciner in the CaL process was 100% biomass. In CaL scenario therefore, the calculated net CO_2 emissions result in a negative value when RHP, WP and SS are used as fuel. This is illustrated in figure 4.12. In this figure, an accounting of the CO_2 emissions are illustrated for a cement plant where 30% of the coal is substituted on a mass-basis with torrified wood pellets, and CaL technology is retrofitted. The diagram in the figure depicts a model of the calculation methodology used in this section to account for the net CO_2 emissions for all the BECCS scenarios studied in this thesis. Table 4.14 has the results of the CO_2 accounting for all the 12 BECCS cases – four biomass fuels and three CO_2 capture technologies.

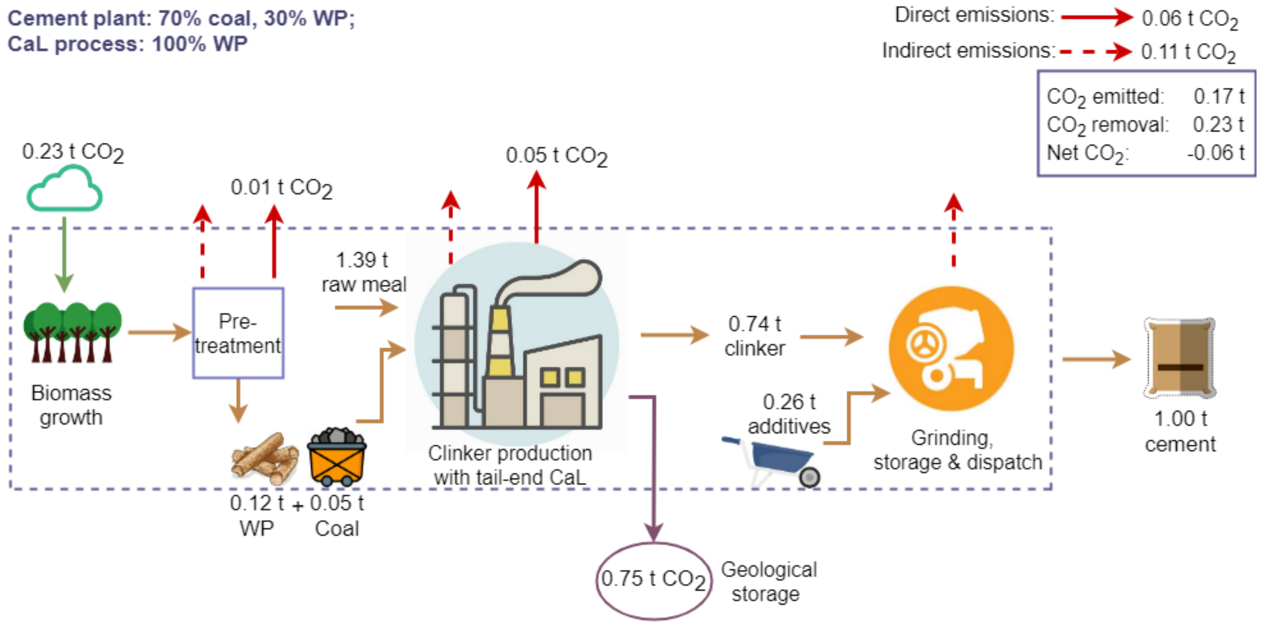
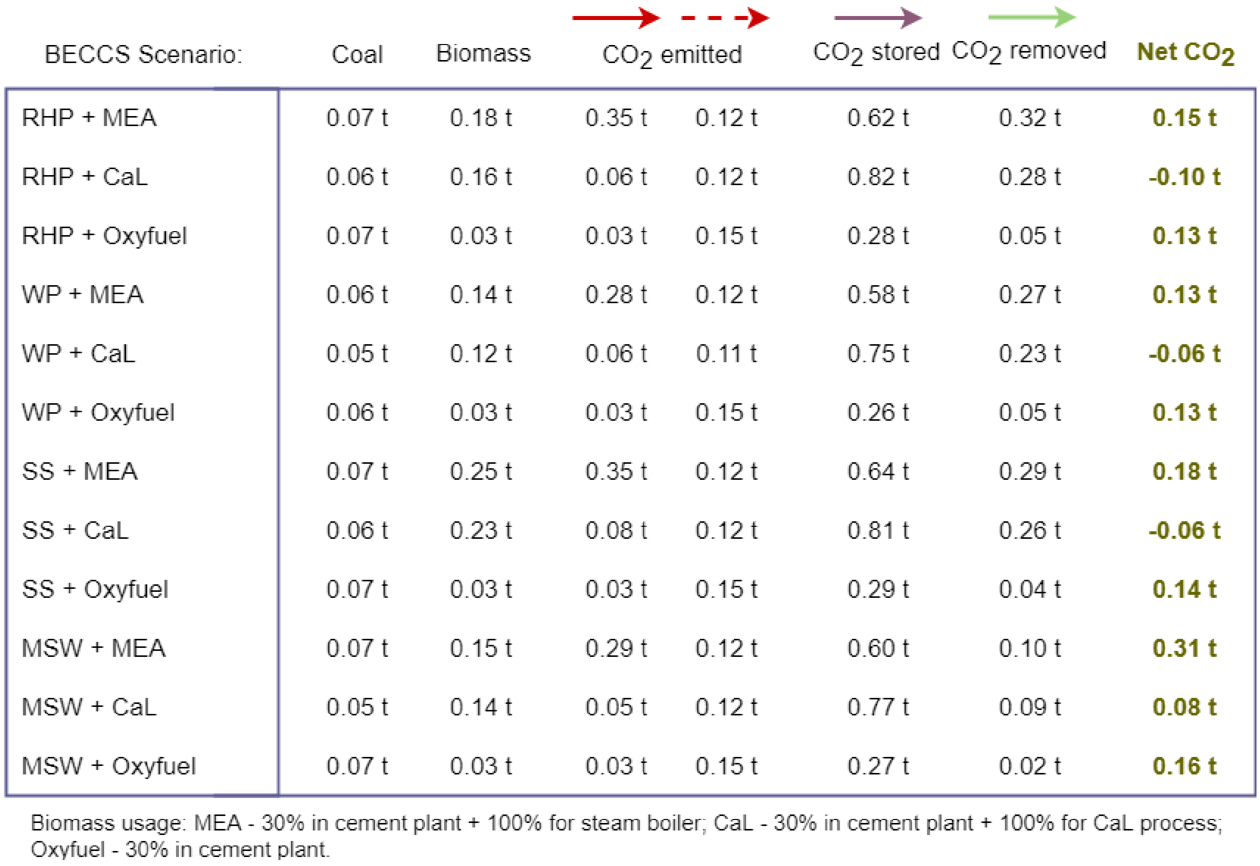


Figure 4.12: Gate-to-gate carbon accounting with C-neutral biomass illustrated for calcium looping (CaL) based CO_2 capture in a cement plant using wood pellets.

Table 4.14: Carbon accounting for all BECCS cases



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BECCS Scenario:	Coal	Biomass	CO_2 emitted		CO_2 stored	CO_2 removed	**Net CO_2**
RHP + MEA	0.07 t	0.18 t	0.35 t	0.12 t	0.62 t	0.32 t	**0.15 t**
RHP + CaL	0.06 t	0.16 t	0.06 t	0.12 t	0.82 t	0.28 t	**-0.10 t**
RHP + Oxyfuel	0.07 t	0.03 t	0.03 t	0.15 t	0.28 t	0.05 t	**0.13 t**
WP + MEA	0.06 t	0.14 t	0.28 t	0.12 t	0.58 t	0.27 t	**0.13 t**
WP + CaL	0.05 t	0.12 t	0.06 t	0.11 t	0.75 t	0.23 t	**-0.06 t**
WP + Oxyfuel	0.06 t	0.03 t	0.03 t	0.15 t	0.26 t	0.05 t	**0.13 t**
SS + MEA	0.07 t	0.25 t	0.35 t	0.12 t	0.64 t	0.29 t	**0.18 t**
SS + CaL	0.06 t	0.23 t	0.08 t	0.12 t	0.81 t	0.26 t	**-0.06 t**
SS + Oxyfuel	0.07 t	0.03 t	0.03 t	0.15 t	0.29 t	0.04 t	**0.14 t**
MSW + MEA	0.07 t	0.15 t	0.29 t	0.12 t	0.60 t	0.10 t	**0.31 t**
MSW + CaL	0.05 t	0.14 t	0.05 t	0.12 t	0.77 t	0.09 t	**0.08 t**
MSW + Oxyfuel	0.07 t	0.03 t	0.03 t	0.15 t	0.27 t	0.02 t	**0.16 t**

Biomass usage: MEA - 30% in cement plant + 100% for steam boiler; CaL - 30% in cement plant + 100% for CaL process; Oxyfuel - 30% in cement plant.

4.5 SENSITIVITY ANALYSIS

The sensitivity of the economic indicators (cement production cost and cost of CO_2 avoided) to the following parameters are investigated by performing a variation in the indicated ranges:

- Price of biomass: +/- 50% of the reference cost
- Coal price: +/- 50% of the reference cost
- Electricity price: +/- 50% of the reference cost
- Carbon tax: 0 to 100 €/t_{CO_2}
- Stage of operation when the CO_2 capture plant is retrofitted: 5th and 15th operating year of the cement plant

The effect of uncertainties in storage (costs) on the costs of CO_2 avoided are estimated using the range of 3 to 14[3] €/t_{CO_2} [118] for the case of 'offshore depleted oil and gas field'.

Also, the effect of the electricity mix on SPECCA and the cost of CO_2 avoided are investigated. Different cases of power generation (and hence different electric efficiency values and specific CO_2 emissions) are considered. Electric efficiency of 45% and specific CO_2 emissions of 295.8 kg_{CO_2}/MWh was considered in the earlier calculations (reference) [145]. The different cases of power generation considered for sensitivity analysis are listed in table 4.15.

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[3] The storage cost values for offshore DOGF for three cost scenarios in the stated reference document - low, medium and high are 3, 10 and 14 €/tonne of CO_2 stored.

Table 4.15: Different power generation scenarios used for sensitivity analysis [110]

Case of power generation	η_{el} (%)	Specific CO_2 emissions (kg/MWh)
EU – 2016 [a]	45	296
NW Europe Average – 2016 [b]	47.6	264
Pulverized coal	44.2	770
Natural gas combined cycle (NGCC)	52.5	385
Renewables	100	0

a – Reference value in this thesis, based on 2016 statistics for European Union taken from EEA

b – The average of values pertaining to North-Western Europe from the same source for 2016.

4.5.1 Parameter variation

In this section, the sensitivity of cement production costs and cost of CO_2 avoided to the parameters listed above are presented individually for all the biomass fuels. For every co-firing case, the variation for each of the CO_2 capture technologies are depicted in the graph.

Sensitivity to a change in biomass price:

The sensitivity of the economic parameters in this assessment to the variations in price of biomass is shown in figures 4.13 and 4.14. The cost of biomass has the largest impact on cement production costs and costs of CO_2 avoided for MEA and CaL based CO_2 capture, due to significant consumption of biomass fuel associated with these technologies. The calciner of the CaL process is fed with biomass, and the steam boiler in MEA is fed with biomass; therefore these capture technologies have the highest consumption of biomass in comparison to oxyfuel capture.

There is a +/- 4% to +/- 7% variation in the production costs of MEA and CaL technologies respectively with +/- 50% variation in the price of biomass, whereas with oxyfuel combustion capture, the variation in production costs is about +/- 2%. The CO_2 avoidance costs vary by about +/- 10% to +/- 17% with MEA and CaL technologies respectively; whereas with oxyfuel combustion capture, the variation in CO_2 avoidance costs is about +/- 5% to 10%. The highest variation in avoidance costs among the four biomass types was observed with torrified wood pellets and (+/- 17% in MEA capture technology) and the least variation was observed with municipal solid waste (+/- 5% in oxyfuel combustion capture). Another observation that can be made from the sensitivity graphs is that the slope of the CO_2 avoidance costs is higher in comparison to the slope of the cement production costs.

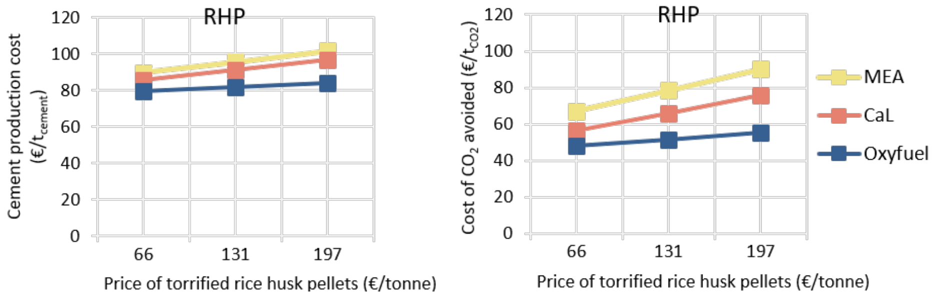

Figure 4.13: Sensitivity of cement production costs and cost of CO_2 avoided to uncertainty in price of biomass (RHP)

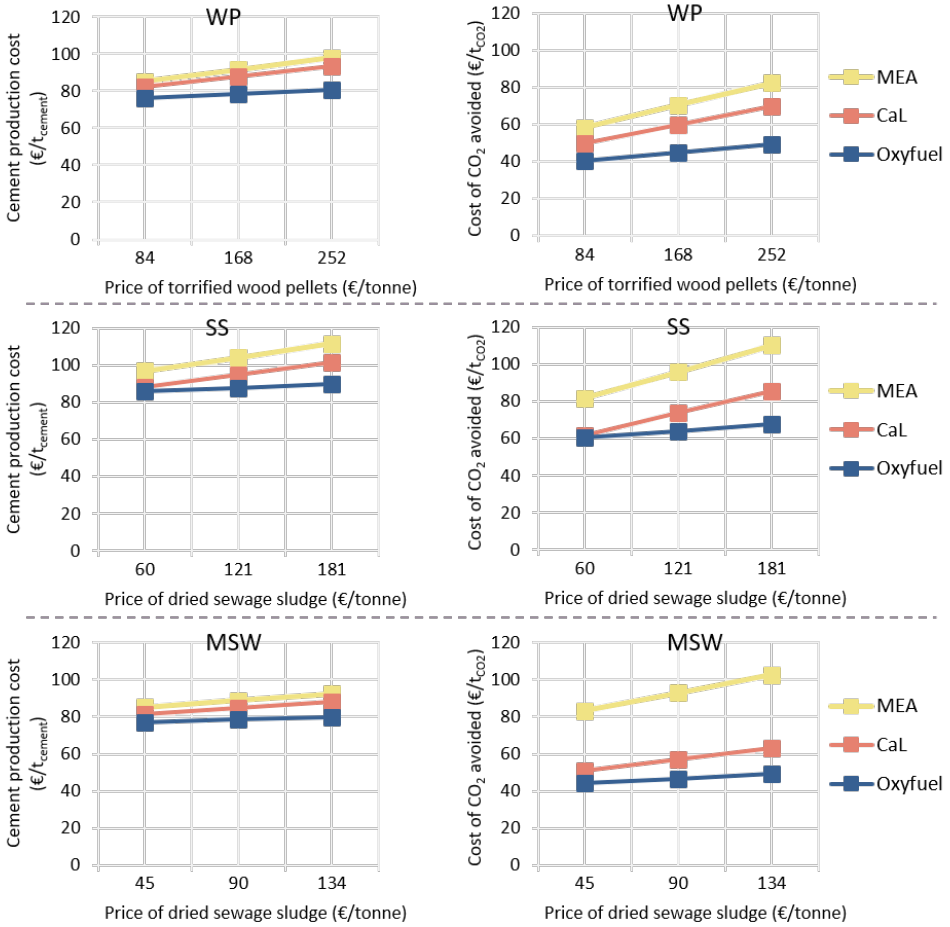

Figure 4.14: Sensitivity of economic parameters to uncertainty in price of biomass (WP, SS, MSW)

Sensitivity to a change in coal price:

Variations in the price of coal do not have a significant impact on the BECCS cases as can be seen from the graphs in figure 4.15. When compared with the effect of variations in the price of biomass, the increase in both the economic indicators (cement production costs and cost of CO_2 avoided) with increase in coal prices is a relatively smaller variation. There is only a +/- 3% variation in cement production costs for all the three CO_2 capture technologies.

However, the range of variation in CO_2 avoidance costs to uncertainty in coal price across the three CO_2 capture technologies was not similar. That is, with MEA and CaL technologies, the avoidance costs vary (on an average) by +/- 5% with +/- 50% variation in the coal price. But with oxyfuel combustion capture, the CO_2 avoidance costs vary by +/- 8% with +/- 50% variation in the coal price. The fraction of coal is the same in all the three capture technologies (70% in the cement plant), still this deviation was observed in oxyfuel combustion capture. Even though this may not be a significant variation, it is interesting to note the possible reason for this. With oxyfuel combustion, the biomass costs are not as significant as with the MEA and CaL. So there is higher contribution of costs incurred for coal to the total lifetime costs in oxyfuel combustion. In general, the slope of the CO_2 avoidance costs curve is observed to be higher than the slope of the cement production costs.

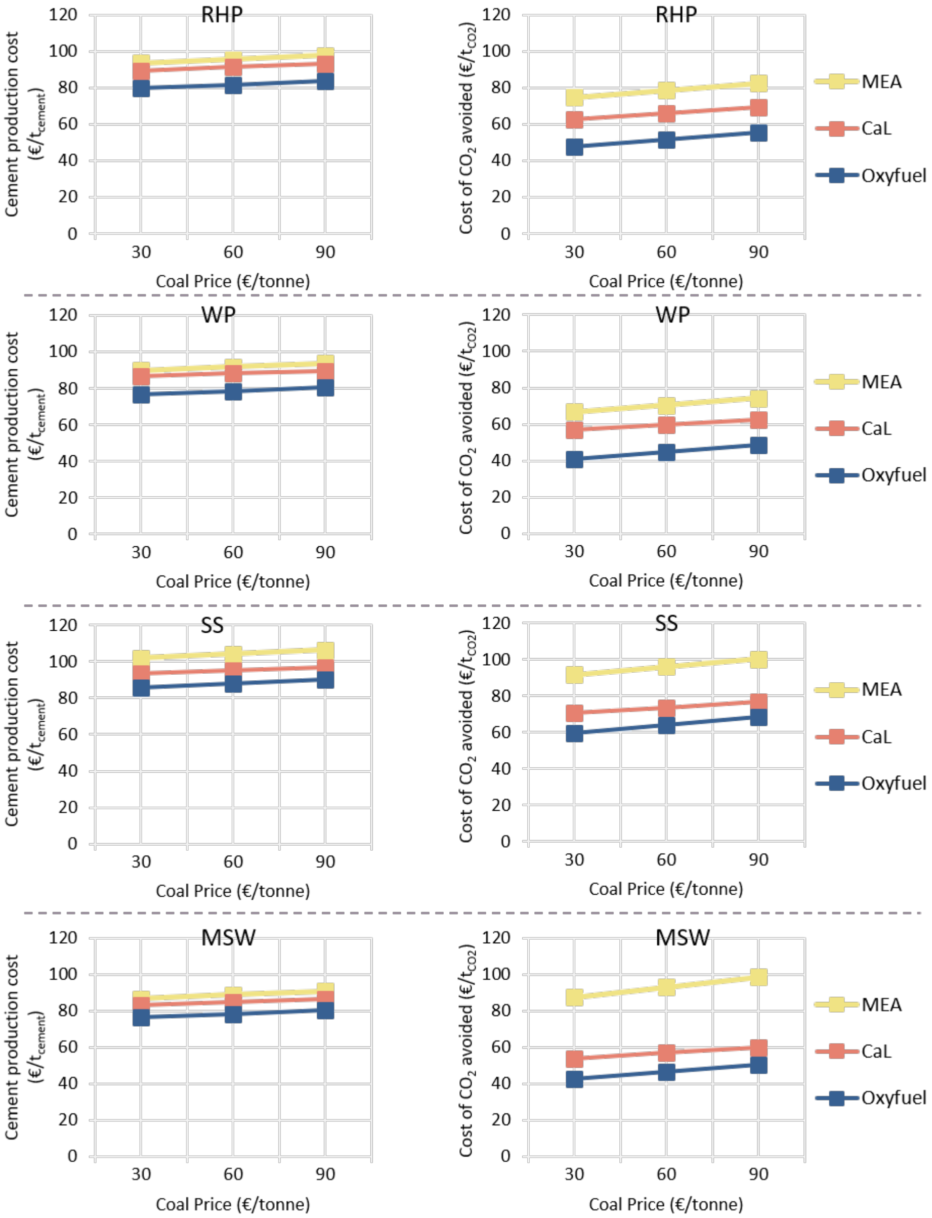

Figure 4.15: Sensitivity of cement production costs and cost of CO_2 avoided to uncertainty in coal price

Sensitivity to a change in electricity price:

The reference electricity prices were fixed at 114.2 Euro per MWh [167]. On estimating the cement production costs at +/- 50% of this reference electricity price, a variation in the range of -11% to +9% was observed. Both CaL and oxyfuel capture are electricity intensive technologies; yet the sensitivity of their costs to electricity price uncertainty is very similar to the pattern observed for MEA capture technology. In fact, it can be noted from the graphs in figure 4.16 that the line representing MEA capture technology has slightly higher slope than CaL and oxyfuel. The electricity generation in CaL and oxyfuel technologies is the reason for this. The CO_2 avoidance costs in oxyfuel combustion show the widest range of variation, -30% to -38% on the lower end to +25% to +32% on the higher end of the electricity price.

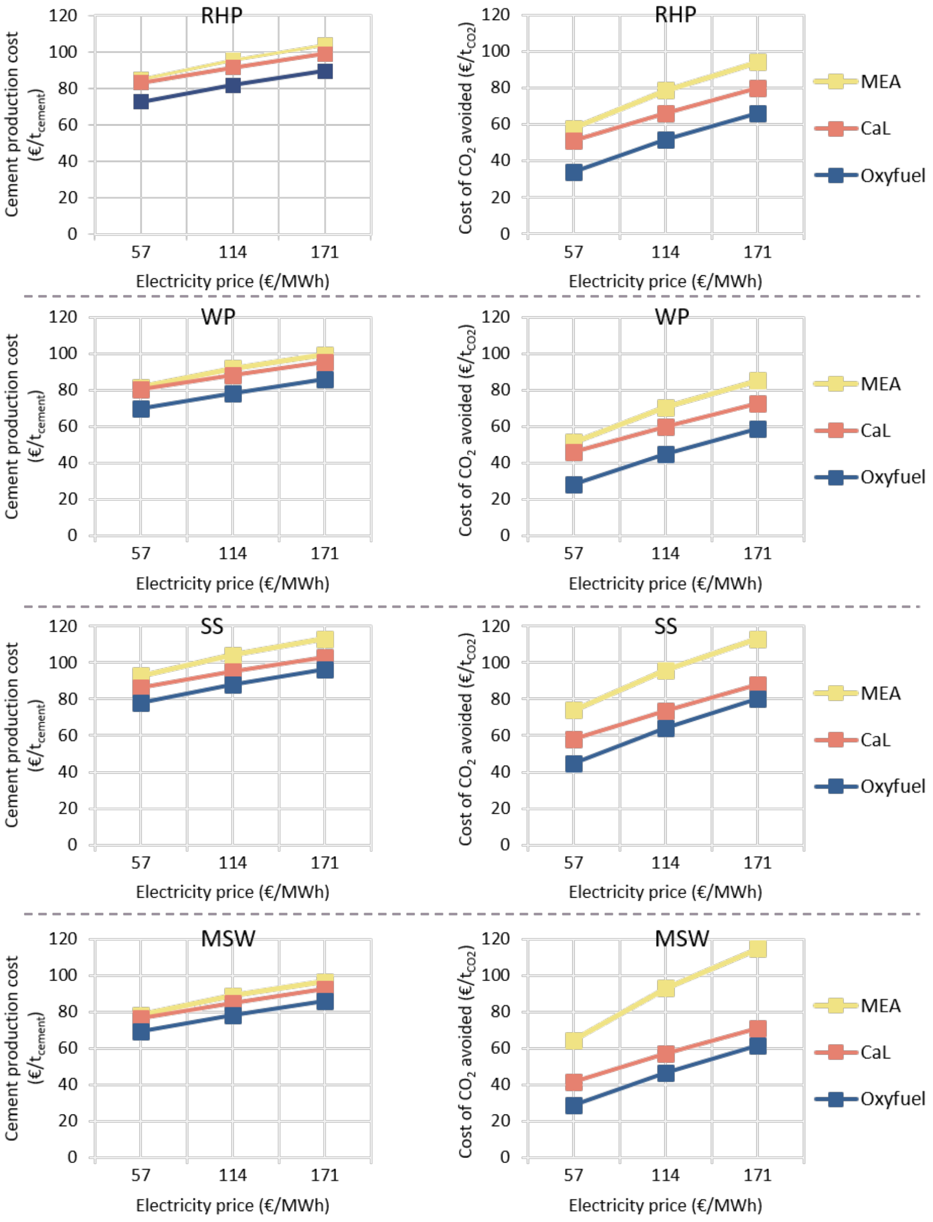

Figure 4.16: Sensitivity of cement production costs and cost of CO_2 avoided to uncertainty in electricity price

Effect of a carbon tax:

If a carbon tax were implemented, the cement production costs for the reference cement plant (without CO_2 capture) increases drastically. At a tax level of around 40 to 50 €/t_{CO_2}, the cement production costs in case of oxyfuel combustion capture becomes lower than in the reference (base) cement plant. At roughly 50 to 65 €/t_{CO_2} (for different biomass types), the cement production costs in case of CaL capture technology becomes lower than the base cement plant without CO_2 capture. Due to the additional direct CO_2 emissions on-site from the steam boiler associated with MEA based CO_2 capture, this technology is more sensitive to carbon taxation than the other CO_2 capture technologies.

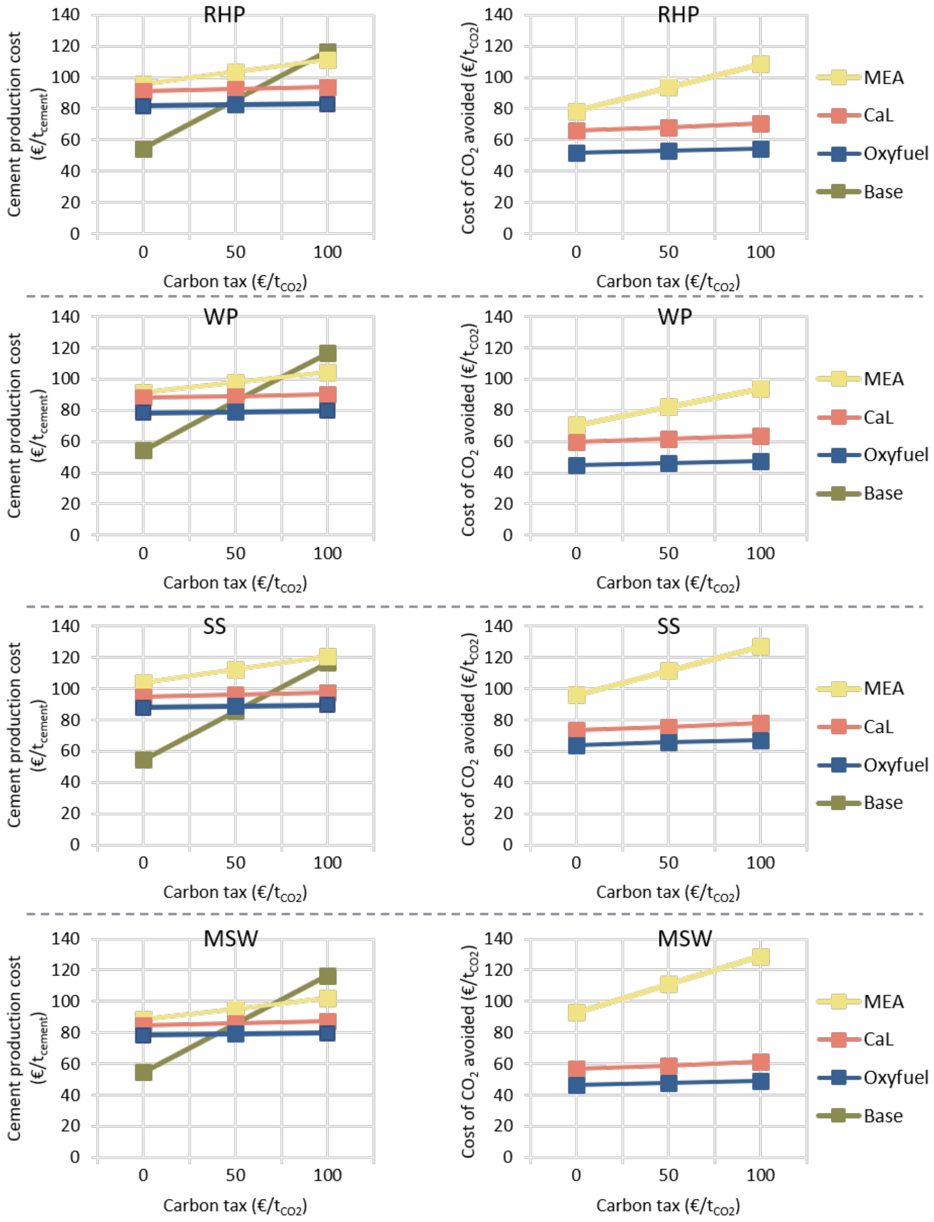

Figure 4.17: Effect of carbon taxation on the cement production costs and cost of CO_2 avoided

Variation in economic parameters to the stage of retrofitting:

In the economic assessment of the BECCS technologies, the CO_2 capture plants were assumed to be retrofitted during the 10th year of operation of the cement plant. The economic parameters were estimated to check for the cost variations when the CO_2 capture plants are retrofitted during the 5th and the 15th year of operation of the cement plant. On account of the depreciation factor in the levelised costs, the economic parameters are expected to be lower during the 15th year and higher when the retrofitting happens during the 5th year. It was observed that there is less difference among the three CO_2 capture technologies as the retrofitting happens during the later stages of operation of the cement plant.

The graphs in figure 4.18 indicate the variation in the production costs and avoidance costs when the CO_2 capture plants are retrofitted during the 5th, 10th, and 15th year of operation of the cement plant.

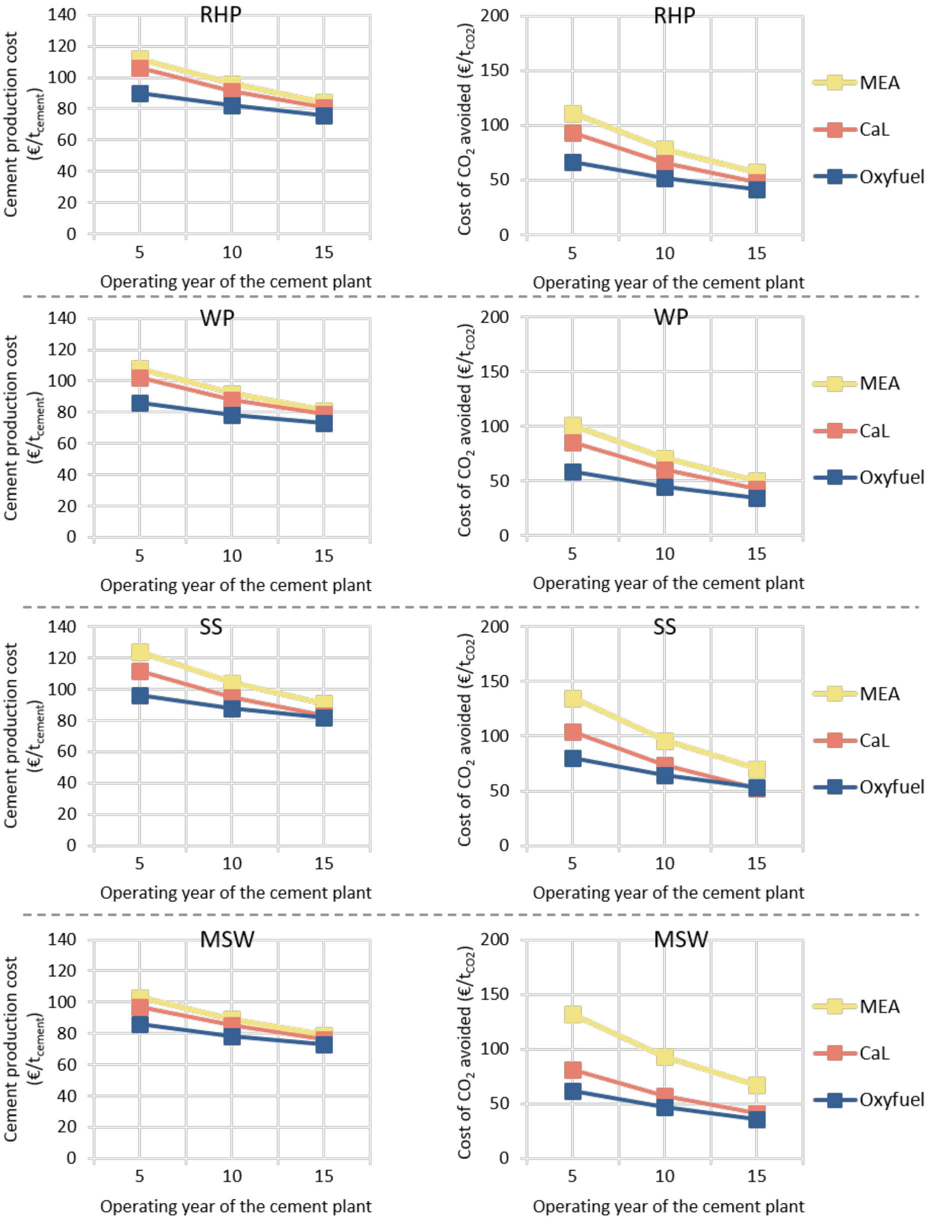

Figure 4.18: Variation in cement production costs and cost of CO_2 avoided to the stage of retrofitting of the CO_2 capture plant

Sensitivity to cost of CO_2 storage:

A significant variation in cost of CO_2 avoided was observed with changes in the costs of CO_2 storage, in case of calcium looping based CO_2 capture (as shown in figure 4.19). This can be attributed to the high CO_2 capture rates for CaL in comparison with MEA and oxyfuel capture. The amount of captured CO_2 in CaL is about 25 to 33% higher than the captured CO_2 in MEA and about 179 to 195% higher than the captured CO_2 in oxyfuel combustion. With CaL, a large amount of CO_2 is captured and sent for storage in offshore depleted oil and gas fields. Therefore CaL is most sensitive to the uncertainties in CO_2 storage costs. Between MEA and oxyfuel, oxyfuel combustion displays least sensitivity to uncertainties in CO_2 storage owing to a large fraction of the CO_2 stream being recycled to the cement plant; hence the CO_2 capture rates are lower in oxyfuel combustion.

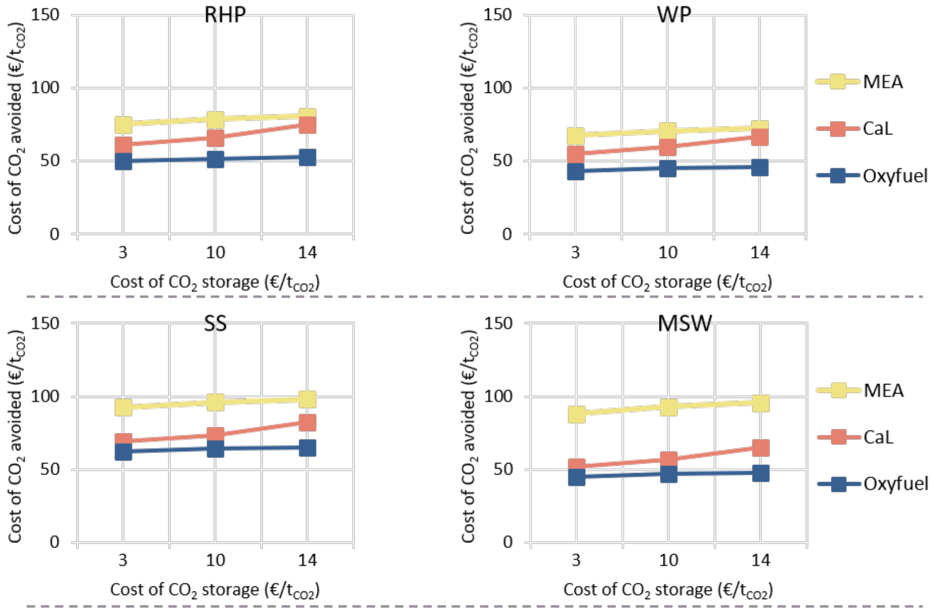

Figure 4.19: Sensitivity of cost of CO_2 avoided to uncertainty in CO_2 storage costs

4.5.2 Different power generation cases

The characteristics of the electricity generation case have an impact on SPECCA and the cost of CO_2 avoided. The electricity generation efficiency and the specific CO_2 emissions associated with every power generation case lead to a change in the indirect CO_2 emissions associated with the CO_2 capture technologies; hence the total CO_2 avoided (direct + indirect) is affected, thereby leading to a change in SPECCA. The change in total CO_2 emissions also implies a change in the cost of CO_2 avoided.

Effect of power generation cases on SPECCA:

Increased share of fossil fuels imply higher SPECCA, owing to the increased specific CO_2 emissions which reduce the total CO_2 avoided. This is observed from the graphs in figure 4.20, where the SPECCA is highest for pulverized coal, followed by NGCC. Similarly, low share of fossil fuels entail low SPECCA, as visible in the case of 'Renewables'. Another observation noted was with the CaL capture, the SPECCA for north-western Europe scenario is considerably higher than the reference power generation scenario, whereas for MEA and oxyfuel, this pattern is not visible.

It can be inferred from the graph that for CaL technology, the SPECCA is seen to increase with increase in electricity generation efficiency and with a decrease in the specific CO_2 emission factor. A possible reason for this pattern could be the high amount of electricity generated in CaL which substitutes part of the electricity that is sourced from the grid. In oxyfuel combustion, the SPECCA is reduced by about 75% from the reference case, when renewables are used for power generation. But the conclusion drawn is that SPECCA is significantly affected by different power generation scenarios in all the CO_2 capture technologies.

Effect of power generation cases on cost of CO_2 avoided:

Effect of power generation scenarios on the cost of CO_2 avoided followed a similar trend as observed in the case of the effect on SPECCA. This is shown in figure 4.21. The higher the share of fossil fuels, the higher the avoidance costs. With increased electricity generation efficiency and decreased specific CO_2 emissions, the cost of CO_2 avoided can be expected to decrease in the future (as can be witnessed from the low values for renewable power generation scenario).

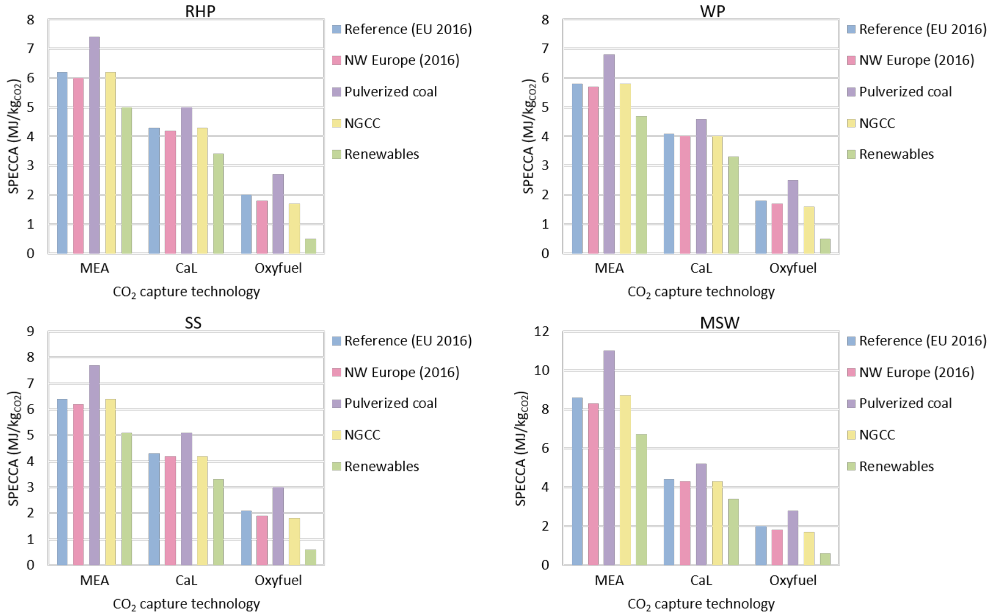

Figure 4.20: Effect of power generation scenarios on SPECCA

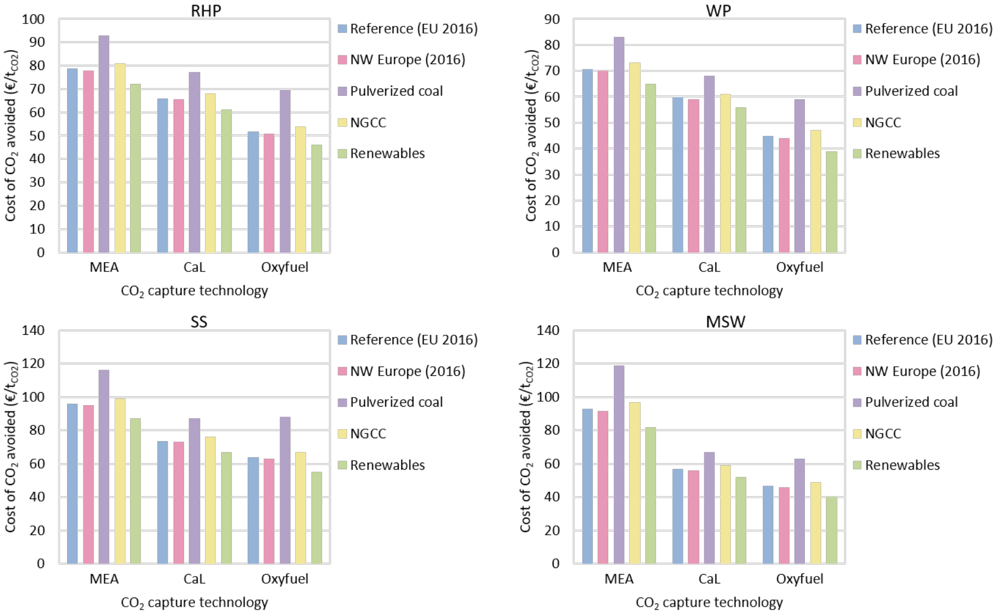

Figure 4.21: Effect of power generation scenarios on the cost of CO_2 avoided

5 CONCLUSIONS

In this thesis, the techno-economic performance of using biomass in conjunction with CO_2 capture technologies in the cement industry was assessed. To answer the research questions devised, a reference case (base cement plant without CCS) was set up. The base cement plant uses coal as a fuel. The key technical and economic parameters (rate of clinker produced, capital and operating expenses) were estimated for the base plant to enable a comparison with the BECCS technologies. To the base cement plant, retrofitting CO_2 capture technologies was considered, along with usage of biomass in existing boilers. The results of this assessment are outlined in this chapter, by answering the relevant research questions.

RQ 1 - What are the possible ways of using biomass as inputs in a cement plant?

It was observed from the literature review that biomass can be used primarily as a fuel in a cement plant, to provide the thermal energy required for the calcination process in a cement kiln. Calcination process leads to the formation of clinker, the major constituent of cement. Predominantly fossil fuels are employed in the cement industry. However it is possible to use biomass to meet the thermal energy requirements, partially or wholly. It is also possible to recover the ash generated during the combustion of the biomass fuel (or fuel mix which contains a share of biomass) and use it as a raw material. This is possible at two junctures in the chain of cement manufacture process - as a raw material for producing clinker and as an additive during the final grinding stage where clinker is ground with additives to produce cement. The bio-based ash serves as replacement of SiO_2, Al_2O_3, Fe_2O_3, MgO and CaO in the cement manufacturing process; these components are some of the commonly used additives in the industry. However, there are limitations with the usage of biomass as fuel and bio-based ash as a raw material or additive. This is in view of the environmental concerns associated with harmful emissions (such as chlorine, dust, heavy metals) among other possible negative impacts.

Four different types of biomass were chosen for this thesis - rice husk pellets, RHP (agricultural biomass), wood pellets, WP (forestry residues), sewage sludge, SS and municipal solid waste, MSW (bio-based waste material). A fuel substitution rate of 30% in the cement plant was decided upon from literature for all the four biomass types.

RQ 2 - What is the impact on the product yield (cement) and/or raw material consumption?

In this thesis, partial substitution of fuel (on a mass-basis) has been considered. For ease of retrofitting, the capacity of the furnace is held constant, this entails a reduction in the rate of clinker produced. Biomass has a lower calorific value than the fossil fuels commonly used in the cement plant. Hence in this thesis, the rate of clinker produced when biomass is used for co-firing is lower than in the base case when 100% coal is used. This results in a corresponding decrease in the annual cement production. The base cement plant produces clinker at the rate of 2901 tonnes per day; while the chosen biomass options produce clinker at rates ranging from 2385 to 2703 tonnes per day. The rate of clinker produced bear a direct relation to the heating value (LHV) of the biomass used; that is, the least production rates are observed in the case of sewage sludge (which has the least LHV among the four biomass types considered in this thesis).

RQ 3 - Among the selected biomass inputs and CO_2 capture technologies, which options are the least energy consuming and most economically viable?

Three CO_2 capture technologies were chosen:

- post combustion CO_2 capture using monoethanol amine (MEA),
- calcium looping (CaL) based CO_2 capture and
- oxyfuel combustion CO_2 capture.

The three CO_2 capture technologies were selected after a qualitative comparison of various CO_2 capture technologies on the basis of their ease of retrofitting. Mass balances have been performed for a base case scenario (100% coal without CO_2 capture) and the BECCS technologies using Microsoft Excel. The energy consumption for each of the processes in the CO_2 capture retrofits were estimated. Total CO_2 avoided in each of the BECCS cases have been calculated by including direct emissions (fuel consumption), indirect emissions (electric power consumption) and the CO_2 removed from the atmosphere through the growth of biomass. The incremental primary energy consumption as a result of the retrofitted CO_2 capture plant has been estimated and expressed as **SPECCA** (specific primary energy consumption per CO_2 avoided). This indicator was selected to identify the least energy consuming option among the assessed BECCS technologies. To identify the most economically viable technology, two economic indicators were selected - **cement production cost** and **cost of CO_2 avoided**.

Oxyfuel combustion was observed to be the least energy consuming; in case of wood pellets used with oxyfuel combustion capture, the least value of SPECCA was observed (1.8 MJ/kg_{CO2}). The most economical technology also happened to be oxyfuel combustion CO_2 capture with the least cement production costs of 78 $€/t_{cement}$ observed with wood pellets and municipal solid waste. The least CO_2 avoidance cost of 45 $€/t_{CO2}$ was observed in oxyfuel combustion when wood pellets were used for co-firing. The low costs can attributed to the process design requirements. Although in case of oxyfuel combustion, suitable modifications are required in the base cement plant which would entail shutting down the cement plant for a period of roughly six months. The other option which is in the moderate range of both technical and economical indicators is CaL-based CO_2 capture. MEA is the most energy consuming option and the least economical CO_2 capture technology as well.

RQ 4 - Are the net emissions for the assessed BECCS system in a cement plant actually carbon-negative?

A gate-to-gate system boundary was defined and the CO_2 emissions within this boundary were accounted for based on the results estimated in this thesis. To this, the CO_2 removed by the biomass from the atmosphere and the emissions associated with biomass pre-treatment were included to calculate the net CO_2 emissions. Upstream process emissions related to processing, harvesting, transportation of biomass and CO_2 emissions from direct, indirect land-use were not included in this thesis. So it is not possible to determine if the net CO_2 emissions are actually negative. Negative emissions may be obtained only when the emissions over the entire life cycle of the technology are accounted for. It can, however be concluded that further studies with wider system boundaries, taking into consideration the CO_2 emissions in other stages over the life cycle can take us closer to determining if negative emissions are possible to achieve. In this thesis, though, in the case of using RHP, WP, SS with CaL-based CO_2 capture, the net CO_2 happened to be a negative value. This was a result of increased share of biomass used within the system boundary defined for this thesis (the calciner of the CaL process was fed with biomass). However, this doesn't refer to any net removal of CO_2 from the atmosphere.

RQ 5 - How do the most significant economic parameters vary due to the effect of uncertainties?

It was established that oxyfuel combustion capture entails the least variations if the effect of uncertainties were taken into consideration. MEA capture technology is the least economical technology and also the most affected by uncertainties. Uncertainties in price of biomass and electricity significantly affect the economic parameters in MEA capture technology. Moreover, if carbon taxation were to be implemented in the future, MEA capture technology will be the most affected. CaL technology is more cost-effective than MEA capture technology. The economic parameters in CaL based CO_2 are highly sensitive to storage costs and the price of biomass. In spite of being more electricity intensive than MEA capture technology, CaL does not display a significant variation to changes in electricity prices. This can be attributed to the electricity generation in the CaL capture technology using recovered waste heat.

Broader conclusions:

At the end of this thesis project, it was observed that adoption of multiple decarbonization strategies is possible - efficiency improvements, using alternative fuels (biomass), using technologies like CCS, and using alternative materials (ash) for cement production. Using biomass for co-firing led to reduced clinker production rates, but substituting it with other additives can be an effective way to decarbonize the cement industry by reducing the clinker requirement. Furthermore, BECCS entails clubbing two decarbonization strategies: using low-carbon biomass fuel & using CO_2 capture and storage. Therefore, even if BECCS may or may not result in net negative CO_2 emissions, it has increased potential for CO_2 emission reduction. Adoption of multiple decarbonization strategies simultaneously for the cement industry is imperative for effective climate change mitigation.

5.1 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

This thesis accounted for the CO_2 emissions within a limited defined system boundary. When CO_2 emissions from raw material extraction & transport, biomass harvest, production & transport, other upstream & downstream emissions are included and a life-cycle assessment (LCA) is performed for the BECCS technologies, it may possibly give a better picture of the net CO_2 emissions. Therefore, extending the results of the techno-economic assessment by performing a life-cycle assessment would be one of the recommendations for future work. That way, other environmental impacts can also be accounted for. It was earlier stated that with oxyfuel combustion, there are added benefits of reduced NO_x and SO_2 emissions owing to combustion in an oxygen-rich environment. This information can be substantiated if an LCA study is carried out. It may be worth observing if, in addition to being the most energy-efficient and economically viable option (among the assessed CO_2 capture technologies in this thesis), oxyfuel combustion capture also presents the highest environmental benefits.

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