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Carbon Flows in Life Cycle Assessment of Carbon Capture

Assessing Environmental Impacts and Carbon Capture Potential in Industrial Processes

Master's thesis in Industrial Ecology

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Abstract

This thesis presents a detailed analysis of the environmental impacts and carbon capture potential associated with cement production and biomass combustion. Through the use of life cycle assessment and material flow analysis, this study also offers a comprehensive understanding of the carbon capture and purification process within the PYROCO2 system, specifically focusing on a post-combustion amino solvent-based approach. Additionally, the research explores opportunities for improving resource efficiency in the cement production process, aiming to the development of sustainable practices in these sectors.

The findings of this research provide valuable insights into the potential of carbon capture technologies in mitigating climate change. The life cycle assessment results reveal the environmental impacts associated with cement production and biomass combustion, highlighting the potential of carbon capture methods in reducing emissions.

By expanding the knowledge base on carbon capture and utilization technologies, this thesis contributes to the ongoing efforts to address climate change. The research outcomes aim to adopt sustainable practices and further advance carbon capture technologies to address the urgent challenge of climate change, which can contribute towards a more sustainable and carbon-neutral future.

Keywords: Life Cycle Assessment, Carbon Capture, Cement Production, Biomass Combustion, Carbon Flows, Environmental Impacts, Negative Emission Technology, openLCA.

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Jonathan Barclay & William Carlsson, Gothenburg, December 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Acidification.
ADP	Abiotic Depletion Potential.
BECCS	Bioenergy with Carbon Capture and Storage
CC	Climate Change.
CAC	Cement Association of Canada.
CCS	Carbon Capture and Storage.
CCU	Carbon Capture and Utilisation.
CCUS	Carbon Capture Utilisation and Storage.
DAC	Direct Air Capture
DOE	Department of Energy
EOL	End-of-Life.
ET	Ecotoxicity.
ET-FW	Freshwater Ecotoxicity.
EU	European Union.
F.U.	Functional Unit.
GHG	Greenhouse Gas.
GWP	Global Warming Potential.
HIP	Herøya Industrial Park.
HT	Human Toxicity.
IEA	International Energy Agency.
IPCC	Intergovernmental Panel on Climate Change.
ISO	International Organization for Standardization.

LCA	Life Cycle Assessment.
LCI	Life Cycle Inventory Analysis.
LCIA	Life Cycle Impact Assessment.
MFA	Material Flow Analysis
NETs	Negative Emission Technologys.
R.F.	Reference Flow.
UNFCCC	United Nations Framework Convention on Climate Change

Nomenclature

Below is the nomenclature of indices, sets, parameters, and variables that have been used throughout this thesis.

Chemicals

C	Carbon
CaO	Calcium Oxide
$CaCO_3$	Calcium Carbonate
C_8H_{18}	Petrol
CO_2	Carbon Dioxide
FeO_3	Iron (III) Oxide
Fe	Iron
H	Hydrogen
H_2	Hydrogen Gas
H_2O	Water
H_2CO_3	Carbonic Acid
HCO_3	MEA Bicarbonate
MEA	Monoethanolamine
MDEA	Methyldiethanolamine
N	Nitrogen
NO_x	Nitrogen Oxides
O	Oxygen
SO_x	Sulphur Oxides
SiO_2	Silica Dioxide
Si	Silica

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1
Introduction

Climate change is one of the most pressing issues facing our planet today. The Intergovernmental Panel on Climate Change (IPCC) states that the burning of fossil fuels is a major contributor to the rise in greenhouse gas (GHG) emissions, with carbon dioxide (CO_2) being the most significant contributor (IPCC, 2014). Climate change has already impacted the world in alarming ways, from more frequent and severe heat waves to rising sea levels, changing precipitation patterns, and an increase in the frequency and intensity of extreme weather events, as the global temperature has been rising at alarming rates in recent years. In order to mitigate the effects of these changes, a transition towards sustainability must be started as quickly as possible, and immediate actions taken to mitigate the harm they are causing to humans, agriculture, water resources, biodiversity, and ecosystems.

As part of the 2015 Paris Agreement, actions and investments needed for a sustainable low-carbon future were to be accelerated and intensified to combat climate change. The main goal of the Paris Agreement is to limit global warming to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. To achieve this goal, countries have pledged to reduce their GHG emissions and increase their use of renewable energy (UNFCCC, 2015).

One way that could effectively reduce CO_2 emissions in the atmosphere is through carbon capture and utilization (CCU) an innovative technology that aims to capture CO_2 emissions from industrial processes, power generation and utilize it in various ways. The captured CO_2 can be used to produce chemicals, fuels, and other products, or it can be stored underground in geologic formations, a process known as carbon sequestration (IEA, 2018). According to the International Energy Agency (IEA), CCU has the potential to significantly reduce CO_2 emissions while also creating new economic opportunities (IEA, 2018). The IEA estimates that by 2050, CCU could reduce CO_2 emissions by nearly 3 gigatons per year, which is equivalent to about 10 per cent of the emission reductions needed to meet the Paris Agreement's target of limiting global warming to well below 2°C above pre-industrial levels.

One of the most promising applications of captured carbon is the production of materials, chemicals and fuels. CO_2 can be used as a feedstock for the production of chemicals such as methanol, formic acid, and acetone (IEA, 2018). As building blocks for other chemical and material production, these chemicals are used in a variety of industrial processes. CO_2 can also be used as a feedstock for the production of biofuels, such as ethanol and biodiesel (IEA, 2018). These biofuels have the potential to reduce our dependence on fossil fuels, and they emit less CO_2 when they are burned compared to traditional fossil fuels.

However, there are also several challenges that need to be addressed, including the cost of carbon capture, the lack of infrastructure for transport and storage, and the need for further research to fully understand the long-term risks and benefits of carbon sequestration. There are already ongoing projects within the carbon capture field, progress is being made and the market is growing. $PYROCO_2$ is a recently started project within the carbon capture field which will be discussed further in this thesis.

1.1 PYROCO2-project

The $PYROCO_2$ project aims to demonstrate the scalability and economic viability of CCU in the production of climate-positive acetone (European Commission, 2022). In other words, produce acetone without having any impact on climate change and also the potential for a positive impact on the climate. The project is a part of the European Union (EU) research project that aims to find ways to reduce CO_2 emissions and increase the use of renewable energy. The project utilizes an energy-efficient thermophilic microbial bioprocess that converts industrial CO_2 and renewable electricity-derived hydrogen into acetone. The process is projected to reduce CO_2 emissions by 17 Mt CO_2eq by 2050, compared to the traditional production of acetone ($PYROCO_2$, 2022).

The $PYROCO_2$-pilot plant will be located at the industrial cluster of Herøya Industrial Park (HIP) in southern Norway, and will have the capacity to produce at least 4,000 tonnes of acetone annually from 9,100 tonnes of industrial CO_2 and green hydrogen. The location of the plant has been strategically chosen to have access to industrial CO_2 feedstock and green energy at a competitive price and also to facilitate industrial symbiosis between carbon-intensive industries and chemical production ($PYROCO_2$, 2022).

The acetone produced by the $PYROCO_2$ process can be used as a platform for the catalytic synthesis of a range of chemicals, synthetic fuels, and recyclable polymer materials, creating a portfolio of viable business cases for replication and commercialization. Thus, the $PYROCO_2$ project aims to not only reduce CO_2 emissions but also create value from industrial CO_2 emissions by converting them into useful products such as acetone ($PYROCO_2$, 2022).

The $PYROCO_2$ project also aims to explore the financial, regulatory, and environmental aspects of CCU and to study the factors that influence public acceptance and market exploitation. This will contribute to the emergence of CCU Hubs across Europe and further encourage the development of the CCU market (PYROCO$_2$, 2022).

1.2 Aim

The aim of this thesis is to investigate the carbon flows and environmental impacts of the carbon capture process within the PYROCO$_2$ system. The research focuses on understanding the differences between various CO_2 feedstocks and their impact on the overall CCU system from an ecological systems perspective. By analyzing the carbon flows of both fossil and biogenic carbon, and concurrently evaluating the environmental impacts linked to various CO_2 sources, this study aims to assess the carbon flows within the CCU system. The analysis extends from the origin of CO_2 emissions to the purified CO_2, providing an understanding of the carbon throughout the CCU process. This study aims to provide insights and sustainable solutions for CO_2 utilization in the European Union.

Research questions

- How does an industrial point source with a fossil or biogenic carbon source affect the carbon flows within a CCU system, and in which cases can the use of captured CO_2 be considered a negative emission?

- How does the implementation of carbon capture technology affect the environmental impacts of traditional production processes? Such as cement production and biomass combustion.

- How do regional variations in energy mixes, including the carbon intensity of the electricity grid and the share of renewable energy sources, influence the environmental impacts and climate benefits of carbon capture technologies?

2

Background

In this chapter, an overview of the Carbon Capture and Utilization technology will be discussed. Additionally, the methodology used to conduct an LCA and the relevant background information on the field of LCA will be explained and presented.

2.1 Carbon capture utilization and storage

Carbon Capture Utilization and Storage (CCUS) encompasses both the capture of concentrated CO_2 and its subsequent utilization for specific purposes (von der Assen, 2013). CO_2 can be obtained from various sources, including fossil-fueled power plants, and it is crucial to utilize it rather than solely storing it. This can be achieved by employing CO_2 as a solvent or converting it into other valuable products, thereby reducing carbon emissions. In contrast, processes solely focusing on CO_2 storage without additional utilization are known as carbon capture and storage (CCS).

A promising avenue within carbon capture is carbon sequestration, involving the injection of captured CO_2 into geological formations such as deep saline aquifers, depleted oil and gas reservoirs, and unmineable coal seams (IEA, 2018). This approach offers the potential to safely and permanently store substantial amounts of CO_2 underground, effectively decreasing atmospheric CO_2 levels. However, given that carbon sequestration is a relatively new technology, further research is required to comprehensively assess its long-term risks and benefits (DOE, 2019).

The integration of CCU techniques with carbon sequestration presents a comprehensive strategy for tackling carbon emissions. By capturing CO_2 from industrial and atmospheric sources and utilizing it for various purposes, such as solvent applications or conversion into valuable products, CCU helps mitigate emissions (von der Assen, 2013). Simultaneously, carbon sequestration provides a reliable and secure method to store captured CO_2 underground, ensuring its long-term removal from the atmosphere (IEA, 2018).

CCU is a technology that aims to convert GHG CO_2 into value-added products, reducing the use of fossil resources and emissions of GHG (Müller, 2020). This technology is considered a key enabler for a deep de-fossilisation effort in industries such as the chemical industry that currently rely on fossil feedstocks for energy and carbon. However, the utilization of CO_2 does not necessarily reduce climate change impacts. GHG emissions may even be higher compared to conventional technologies depending on the specific CCU technology, its supply chain, and the nature of the product.

Despite the potential benefits of CCU, are there also several challenges that need to be addressed. One of the major challenges is the cost of carbon capture. The technology is still relatively new, and the costs of capturing and utilizing CO_2 are currently high. However, as the technology matures, it is expected that the costs will decrease (IEA, 2018). Another challenge is the lack of infrastructure for the transport and storage of captured CO_2. The CO_2 captured at a power plant or industrial facility needs to be transported to the location where it will be utilized or stored, and this requires a significant investment in pipelines and other infrastructure (IEA, 2018).

According to Tanzer (2019), Negative Emission Technologies (NETs) such as CCU can be a promising solution to climate change as they have the potential to remove large amounts of carbon dioxide from the atmosphere. The most well-known NETs include afforestation, reforestation, soil carbon sequestration, bio-energy with carbon capture and storage (BECCS), direct air capture (DAC) and storage. However, despite their potential benefits, NETs also have their drawbacks. Some are too expensive, technical and unreliable in the long run.

Developing environmentally beneficial NETs, such as CCU technologies, requires a proper understanding of the underlying supply chains (Tanzer, 2019). The context in which the technology will be used, and at what scale the CCU technology will replace an existing service/technology in the market (Müller, 2020). A central part of all CCU supply chains is the capture and supply of CO_2 as carbon feedstock. CO_2 can be captured and supplied from various sources such as power or cement plants, bio-gas and wastewater treatment plants, and even directly from the air. Compared to the production plants, a lower concentration of in the ambient air of CO_2 requires more energy to capture the carbon (Kaiser et al, 2020). Thus, using DAC is more expensive than using CCU on a production site, both economically and environmentally.

2.1.1 Carbon Capture Technologies

Several different technologies are available for carbon capture, such as post-combustion, pre-combustion, and oxy-combustion (Wang, 2010; Finney et al, 2019). Post-combustion carbon capture involves capturing CO_2 after it has been released into the atmosphere, while pre-combustion carbon capture captures CO_2 before it is released. Oxy-combustion carbon capture involves burning fuel in an oxygen-rich environment, which makes it easier to separate CO_2 from the other gases (IEA, 2018). Each of these technologies has its benefits and disadvantages. Thus, it is important to determine the most appropriate technology according to the fuel type and the specific application.

For this thesis, the focus will be on post-combustion, due to post-combustion carbon capture technology offering the advantage of being compatible with existing combustion technologies without requiring significant modifications. This makes it easier to install on existing plants compared to other approaches. However, this advantage comes at the cost of reduced efficiency in the power generation process. (Wang, 2010; Finney et al, 2019). Post-combustion capture is a technology for CCU that involves the removal of CO_2 from the flue gas of combustion processes such as power plants and industrial processes. The process works by scrubbing the CO_2 from the flue gas after combustion, effectively separating the CO_2 from other gases (Koornneef, 2008).

Post-combustion capture technology is commonly favoured for implementation in the gas and oil industries, along with other industrial processes in addition to fossil-fueled power plants (Koornneef, 2008). Despite its potential, post-combustion capture has some limitations as well as challenges. Capture process costs are driven primarily by the price of the solvents used in scrubbing, which is one of the main challenges. There is also the issue of the process' energy demand, which can increase the power plant's or industrial process' overall energy consumption.

Dealing with the high volume of flue gas is also a challenge when attempting to implement post-combustion capture for carbon dioxide removal (Notz, 2007). Flue gas flow rates can be in the millions of cubic meters per hour range, each containing hundreds of tons of carbon dioxide. In contrast, currently, existing post-combustion CO_2 capture plants are considerably smaller, typically one to two orders of magnitude smaller.

2.1.2 Post-Combustion Technologies

In this section, the discussion by Finney et al (2009) revolves around two post-combustion CCU technologies: solvent-based and calcium looping. Of the two, the focus will be on the solvent-based approach. Solvent-based approaches have emerged due to more research and development of the technologies have been made.

2.1.2.1 Solvent-based technologies

In solvent-based CCU, a solvent is used to capture CO_2 from industrial processes, such as power generation or cement production. The solvent reacts with CO_2 to form a solution, which is then separated and the CO_2 is released for utilization. Solvent-based technologies are effective for post-combustion CO_2 capture, and several types of solvents are available, including amines, ammonia, and ionic liquids (Finney et al, 2019).

The Solvent-based technology involves the use of solvents, specifically amines, as the capture medium. A solvent is used to absorb CO_2 from flue gases generated by industrial processes, such as power plants (Koornneef, 2008). The CO_2-rich solvent is then passed through a regenerator where the CO_2 is stripped from the solvent. The purified solvent is recycled back to the absorber, while the CO_2 is compressed and sent to the utilization process.

Amines are commonly used as the capture media in solvent-based capture because they are highly effective in absorbing CO_2 and have low volatility (Finney et al, 2019). Generally, monoethanolamine (MEA) and methyldiethanolamine (MDEA) are used as solvents; their efficiency can vary based on the type of amine being used. This will be the method further researched for this thesis.

2.1.2.2 CO2 separation technologies

There are various separation technologies that can be used in solvent-based capture to remove CO_2 from flue gases. These include adsorption, physical absorption, chemical absorption, cryogenic separation, and membranes (Wang, 2010).

Adsorption involves using a solid material to selectively adsorb CO_2 from the gas stream. Physical absorption involves dissolving CO_2 in a solvent, while chemical absorption involves using a solvent that reacts chemically with CO_2 to form a new compound. Cryogenic separation involves cooling the gas stream to a very low temperature to condense CO_2, while membranes use a semipermeable membrane to separate CO_2 from other gases based on their molecular size (Wang, 2010).

Chemical absorption is a process in which carbon dioxide reacts with a chemical solvent to form a weakly bonded intermediate compound. This intermediate compound can be regenerated through the application of heat, which results in the production of the original solvent and a stream of CO_2. One of the advantages of chemical absorption is that it has a relatively high selectivity, which allows for the production of a relatively pure CO_2 stream. This makes it an ideal method for capturing CO_2 from industrial flue gases (Wang, 2010).

Liang (2016) supports the selection of post-combustion with chemical absorption as the preferred method for separating CO_2 from flue gas. Referencing the Electric Power Research Institute, it is noted that 60% of post-combustion carbon capture technologies utilize absorption. This suggests that absorption is the most developed and reliable option among the available post-combustion alternatives.

2.1.3 Negative Emission Technology

One of the main challenges in assessing the effectiveness of NETs is the inconsistent accounting of emissions according to Tanzer (2019). This is due in part to the influence of system boundary selection, which refers to the choice of boundaries for the system being studied. For example, when assessing the emissions of the BECCS system, one could choose to include the emissions associated with growing the feedstock, producing the bioenergy, capturing and transporting the CO_2, and storing it underground. In the Techno-Economic Assessment & Life Cycle Assessment Guidelines for CO_2 Utilization (Zimmermann, 2019) it is illustrated that CCU can be carbon neutral or contribute negative emissions. The latter when combining the uptake of CO_2, together with sequestration can be regarded as a negative emission.

NETs also face the challenge of long-term effectiveness. Despite the relatively well-established landscape-scale practices of reforestation, afforestation, soil carbon sequestration, and BECCS, little information is available on their long-term effectiveness, scalability, and environmental impact (Tanzer, 2019). On the other hand, DAC and storage is a newer technology and still in the early stages of development, making it difficult to assess its long-term effectiveness and scalability.

Despite these challenges, NETs are being increasingly considered as a potential solution to climate change (Tanzer, 2018). However, it is important to note that NETs alone will not be enough to mitigate the effects of climate change and should be considered as part of a broader strategy that includes reducing emissions, increasing energy efficiency, and investing in renewable energy sources. Additionally, research and development are needed to fully understand the potential of NETs and to ensure they can deliver the promised benefits. And it's important to ensure that the NETs are affordable and accessible to the communities that will be impacted by them.

2.2 PYROCO2 System Description

The following section will discuss and present the current background information on the PYROCO_2 system. The system includes the thermophilic gas fermentation and the microbial bioprocess, the feedstocks of industrial CO_2 and green hydrogen, the production of acetone, and the chemo-catalytic upgrading to products which can be seen in figure 2.1. CO_2 feedstock and green energy will be available at competitive prices in the industrial cluster of the HIP (Jiresten & Larsson, 2022).

In the process proposed by PYROCO_2, CO_2 goes through steps such as carbon capture and purification, hydrogen production, thermophilic fermentation, and lastly, acetone production before being transformed into acetone. The flowchart for the PYROCO_2 system of the CCU process can be broken down into the following steps:

Carbon Capture and Purification: The first step in the PYROCO_2 system is carbon capture where CO_2 is captured from the flue gas post-combustion process, with the amine solvent-based approach. The captured CO_2 needs to be purified to remove contaminated substances such as nitrogen oxides, sulfur dioxide, and water vapour. This step is crucial to ensure that the CO_2 feedstock is of high quality and suitable for further use.

Hydrogen Production: The PYROCO_2 project employs electrolysis to produce hydrogen for acetone production (PYROCO_2, 2022). Electrolysis, such as water electrolysis, involves the use of a membrane that separates positively charged anode and negatively charged cathode poles (Shiva Kumar, 2019). Renewable electricity powers the electrolysis process, enabling the generation of hydrogen as an energy source for the CCU system.

Thermophilic fermentation: Thermophilic fermentation involves three steps: substrate hydrolysis, acidogenesis, and acetogenesis. In substrate hydrolysis, complex organic compounds are broken down into simpler compounds through enzymatic hydrolysis. Acidogenesis converts these simpler compounds into organic acids, generating CO_2 and H_2 as by-products. Acetogenesis then transforms the organic acids into acetone while consuming H_2 and CO_2. Optimal pH, temperature, and nutrient conditions are required for the growth of thermophilic microorganisms and acetone production. Additionally, methane, ethanol, and lactic acid may be produced as by-products depending on the microorganisms, substrate, and process conditions (Pavlostathis, 2011; Redl, 2017).

Acetone Production: The purified CO_2 and hydrogen is used to produce acetone through the PYROCO_2 process. This process combines CO_2 and hydrogen in a reactor to produce acetone and water as byproducts. After the acetone product is separated from the water, the residual CO_2 can be re-injected back into the process or stored underground for permanent carbon dioxide removal.

By following these steps, the PYROCO_2 CCU process converts CO_2 from a waste product into a valuable product, making it possible to produce a more sustainable acetone product compared to traditional ways.

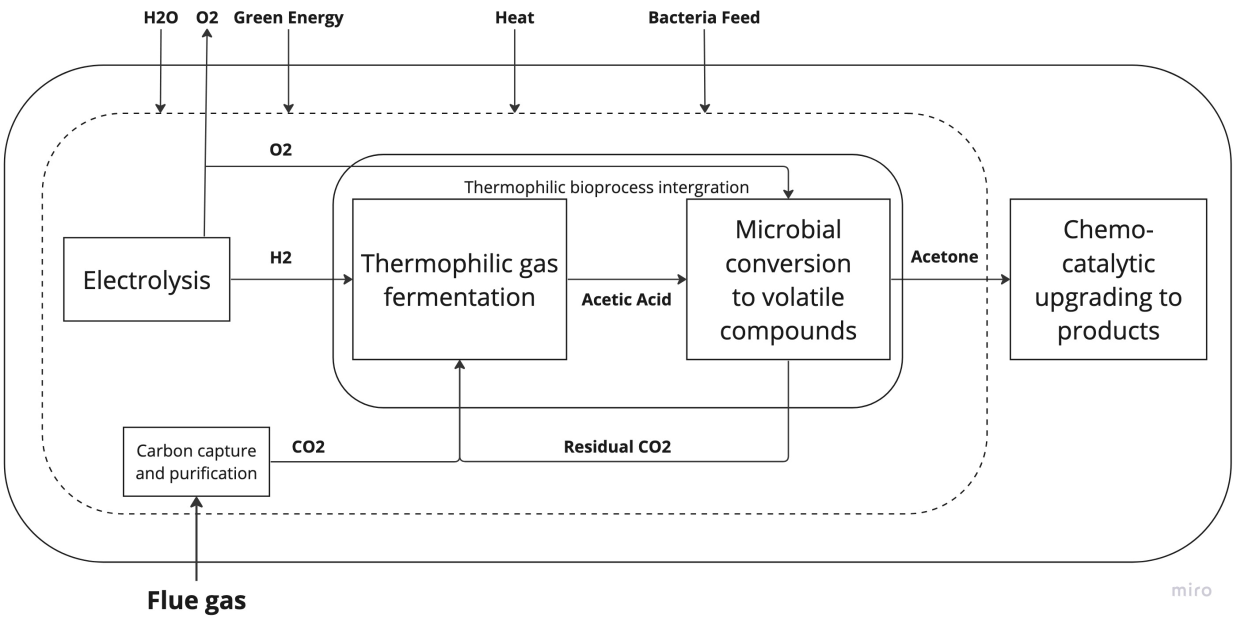


Figure 2.1: PYROCO_2's System Flowchart (Jiresten & Larsson, 2022).

2.3 Carbon Flows

The Carbon flows and environmental implications of different CO_2 sources in CCU systems is a critical topic in understanding the overall efficiency and sustainability of the process. However, not all CO_2 sources are equal in terms of their carbon flows and environmental implications.

CO_2 can be sourced from multiple industrial processes such as power generation, cement production, oil refining etc. The CO_2 captured from these sources is referred to as anthropogenic CO_2 (Koerner, 2002). Additionally, CO_2 can also be sourced from biogenic sources such as biomass incineration (Yoro, 2020). The CO_2 captured from these sources is referred to as biogenic CO_2.

The carbon flows within the CCU system also play a crucial role in the environmental implications of the process (Kaiser et al, 2020). The efficiency of the CCU process is directly related to the amount of CO_2 that is captured and utilized, as well as the energy inputs required for the process. The use of different CO_2 sources can have a significant influence on the environmental impact of the CCU process.

2.3.1 Cement Production

For this thesis, anthropogenic carbon is derived from the cement production process. Production of cement involves heating a specific mixture of limestone, clay or sand, and iron in a rotating kiln to extremely high temperatures of over 1400ºC, this is a common GHG emitting process in industries (CAC, 2021). The outcome of this process is a substance called cement clinker, an intermediate product. Once it emerges from the kiln, the clinker is cooled and ground into a fine powder, with the addition of small amounts of gypsum. With this mixture is cement produced, or Portland cement (Hossain, 2017; Li, 2014). Approximately 40% of emissions from cement production result from the fuels burned to heat the kiln, while the remaining 60% stem from what is known as "process emissions." These process emissions are intrinsic to the chemical reactions (Reaction 1) involved in cement production and are very difficult to reduce without using carbon-capture technologies.

Reaction 1

$$CaCO_3 \longrightarrow CaO + CO_2$$

2.3.2 Biomass combustion plant

Biomass combustion is the process of choice for the biogenic carbon source. Combustion of biomass can be a carbon-neutral process if the amount of carbon released during combustion is balanced by the amount of carbon absorbed by new biomass growth. This is known as the "carbon balance" of biomass combustion (Murphy, 2016). Unlike fossil fuels such as coal and oil, which release carbon stored underground for millions of years, the carbon in biomass is part of a natural carbon cycle. It is continuously recycled through photosynthesis and decomposition. The type of biomass source, and what type of biomass heating process is being used affects the overall performance in terms of efficiency of energy generated per tonne of biomass burned. Traditionally, the combustion of biomass is viewed as carbon neutral within LCA, assuming that the emitted carbon will be returned to new forests (Sokka, 2012).

2.4 Material flow analysis

Analyzing material flows and stocks within a defined system is known as material flow analysis (MFA) (Brunner and Rechberger, 2016). A key aspect of MFA is the establishment of a mass balance, which ensures a thorough comparison of all inputs, stocks, and outputs in a process. This enables stakeholders to identify the origins and impacts of waste and stocks using consistent and comprehensive information. MFA has the advantage of detecting early signs of stock depletion or accumulation, enabling timely interventions. Long-term MFA analyses reveal minor changes that may have long-term consequences, highlighting the need for continuous monitoring (Brunner and Rechberger, 2016).

Performing MFA before conducting an LCA offers several advantages. MFA provides a foundation for understanding material flows and identifying inefficiencies and waste generation points. It guides data collection efforts, focusing on relevant material flows and stocks. MFA helps identify hotspots and areas of concern, informing the selection of impact categories for the LCA. By conducting MFA prior to an LCA, the study benefits from a broad understanding of material flows, enhancing the reliability and relevance of the results for sustainable resource management.

2.5 Life Cycle Assessment

LCA is a methodology used to evaluate a product's or service's environmental impact throughout its entire life cycle (Baumann & Tillman, 2004). This includes the stages from raw material extraction to the final disposal (Zimmermann, 2018). LCA is a quantitative method that accounts for the natural resources consumed and pollutants emitted by the product at each stage of its life cycle. LCA is valuable in various fields, such as product and process design, decision-making in industry and policy, and marketing, because it takes a holistic approach and avoids problem-shifting between environmental impact categories and life cycle stages (Baumann & Tillman, 2004). The LCA methodology was standardized by the International Organization for Standardization (ISO) in ISO 14040 and 14044 and is regularly updated. LCA is viewed as an analytical pillar by the European Commission, and its strategy for reaching sustainable building initiatives, sustainability assessments, biomaterials, biofuels, etc. (Shaked, 2015). According to the ISO standard, an LCA study is divided into four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation, See figure 2.2 (Zimmermann, 2018; Shaked, 2015).

The European Commission has recognized the need to standardize LCA evaluations for CCU technologies (Zimmermann, 2018). It has been observed that LCA studies on CCU show a large variation in results, even for identical technologies. As a result, the primary goal of this document is to standardize LCA assessments, in order to improve transparency and comparability between LCA studies on CCU technologies. By following this framework, the LCA will be assured to keep in line with the recommended guidelines.

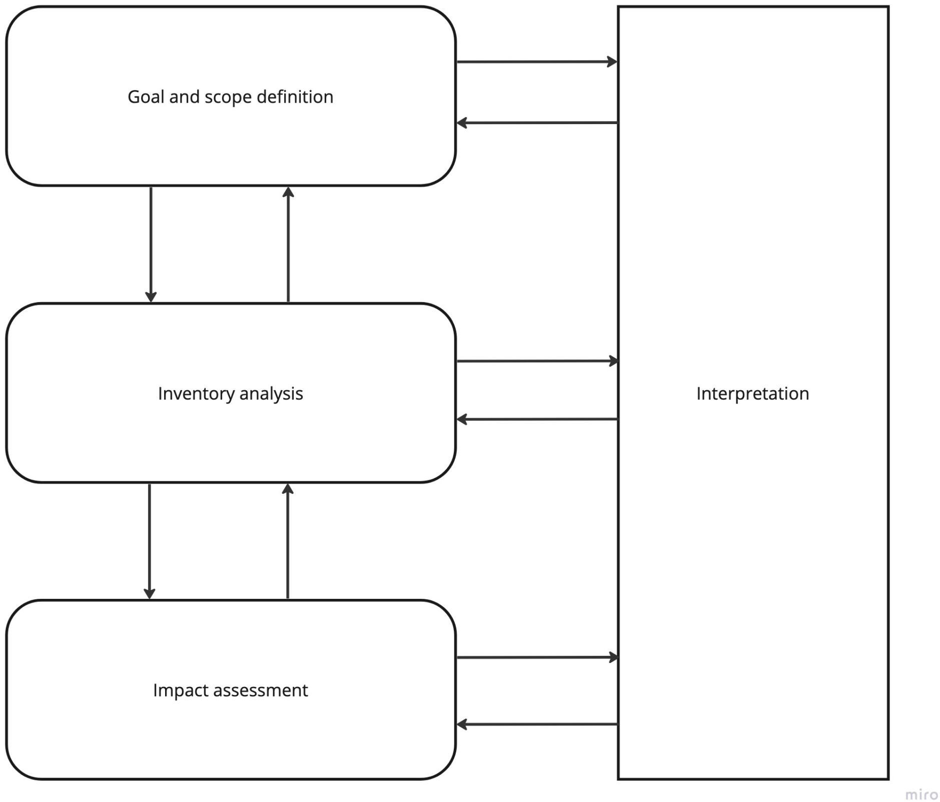


Figure 2.2: General LCA framework

2.5.1 Goal and Scope Definition

The goal definition is the starting point of every LCA study (Baumann & Tillman, 2004). According to the ISO 14040 standard, the goal definition should clearly describe the intended application of the study, the reasons for conducting it, the intended audience, moreover, whether the results will be used in comparative assertions made public (Shaked, 2015). All of these elements are linked to the overall goal of the study. Even though ISO provides a clear outline of the required elements of the goal definition, it is helpful to state the goal as a central research question, as this is more specific than a list of statements. A precisely defined goal is essential for the meaning and relevance of the LCA results (Zimmermann, 2018). However, LCA cannot determine whether a product is environmentally sustainable, as this would require an absolute threshold value for sustainability. LCA can only determine the environmental impacts of products and compare them to other products. Therefore, it is crucial to have a precise and reasonable definition of the initial research question, as it forms the basis for important methodological decisions in LCA, such as the definition of the system boundary and co-product allocation.

2.5.1.1 Functional Unit

In LCA, the functional unit is a quantifiable reference that defines the function or performance of a product, process, or service being studied (Baumann & Tillman, 2004). It serves as a basis for comparing different alternatives within an LCA. The functional unit provides a standardized measure that allows for meaningful comparisons between different scenarios or options. In a comparative study, the functional unit is particularly important as it ensures a fair and consistent basis for evaluating and comparing different products, processes, or services. By establishing a common reference point, such as the amount of product produced or the service delivered, the functional unit enables a meaningful comparison of the environmental impacts associated with different options.

2.5.2 Life Cycle Inventory Analysis

When doing the Life Cycle Inventory Analysis (LCI) of an LCA, the data collection and modelling of the product system occur according to the previously defined goals and scope (Zimmermann, 2018). The goal of this phase of an LCA is to quantify the pollution to the air, water and soil, together with the extraction of raw materials (Shaked, 2015). The LCI process begins by creating a flow chart that illustrates the product system and its boundaries, as established in the goal scope definition (Zimmermann, 2018). The flow chart should include all relevant unit processes and the associated elementary and technical flows (Baumann & Tillman, 2004). The next step is to gather and document insufficient mass and energy balances for each unit process. With this data, a linear, non-dynamic flow model is developed, and the elementary flows for the product system are calculated based on the functional unit.

2.5.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase of an LCA study is where the elementary flows calculated in the previous phase are translated into their potential environmental impacts (Baumann & Tillman, 2004; Zimmermann, 2018). This is done through a process called classification. LCIA improves the readability together with the comparability of results. Environmental impacts are caused by complex cause-and-effect chains in the natural environment and can be reported at different points within these chains (Zimmermann, 2018). Midpoint impacts and endpoint impacts are the two main distinctions in LCA. Midpoint indicators aggregate substances with the same primary effects (such as infrared absorption contributing to climate change). Aside from quantifying human health and natural resource impacts, endpoint indicators also regard the environment. A damage characterisation is used to translate the environmental impact categories into damage categories, such as ecosystem quality and damage to human health (Baumann & Tillman, 2004; Shaked, 2015).

2.5.4 Interpetation

The interpretation of LCA results involves evaluating the collected data from the LCI within the defined goal and scope as guiding parameters (Zimmermann, 2018). The LCA is finished once the questions in the goal and scope have been answered. The results should be presented with graphs or tables to show trends and patterns, furthermore, these trends and patterns can be used to find areas of improvement. It is also important to consider the limitations as well as uncertainties when interpreting the results.

Since there usually are several different types of parameters involved in the results it is, thus, usually necessary to polish them (Zimmermann, 2018). Moreover, make it understandable to the targeted audience. Examples of the results could be to present different types of inventory data that could be regarded as hot spots, and improvement options can be identified with the help of a sensitivity analysis (Shaked, 2015). The interpretation of the LCA is completed once the questions are answered from the goal and scope (Zimmermann, 2018).

2.5.5 Sensitivity Analysis

In LCA studies, a sensitivity analysis is done to identify input variables that have the greatest impact on model output uncertainty (Baumann & Tillman, 2004; Zimmermann, 2018). This is done by systematically varying input variables one at a time and observing the effect on the model results. Results are used to identify key variables, and if necessary, the study's goal and scope may be refined or data quality and modelling approach reviewed to ensure the significance of results. Scenario analysis or threshold value calculations for key variables may also be done to further understand the range of possible outcomes.

3
Methods

The primary method of analysis in this research will be a Cradle-to-Gate Life Cycle Assessment of the CCU process. The LCA is carried out using the ISO 14040 series and the ISO 14044 series standards and focuses on evaluating the environmental impact of different CO_2 sources and tracking the carbon flows within the system from the source of emitted CO_2 to the production of the final product.

Before performing the LCA, a literature review is conducted to gather information on needed data, methodological choices in LCA and relevant background information including CCU, carbon flows, MFA etc. This involves reviewing relevant studies, articles, and reports to understand the current state of knowledge on the topic. The literature review provides a basis for the LCA and helps identify gaps in the current knowledge.

The LCA procedure for this thesis is as follows:

- **Goal and scope definition**: Defining the research objectives, system boundaries, and functional unit to ensure the LCA is focused on the most relevant aspects of the CCU process.
- **Life cycle inventory analysis**: Collecting data on all inputs and outputs associated with the CCU process, including the source of emitted CO_2, production, and transportation of the final product, will enable the calculation of carbon flows throughout the system. The gathered information from the literature review is utilized in multiple MFAs for cement production, combustion of biomass, and the carbon capture process. Incorporating this information into the LCA is expected to enhance the accuracy and precision of the results.
- **Life cycle impact assessment**: Translating the LCI data into calculating the environmental impacts associated with the CCU process, including the impacts of the different CO_2 sources on the environment.
- **Interpretation**: Interpreting the results of the LCA to provide a comprehensive understanding of the environmental implications of different CO_2 sources in the CCU process and the carbon flows throughout the system.
- **Sensitivity analysis**: A sensitivity analysis is a part of the interpretation and is used to pinpoint the hotspots of the LCA, in other words, what parameters have the most impact, allowing for improvements of the LCA by focusing on these key areas.

3.1 System Description

This project's system description focuses on the CCU system proposed by the PYROCO$_2$ project. See figure 3.1 for an overview of the PYROCO$_2$ system.

The thesis specifically delves into the "Carbon capture and purification" process, which is shown in figure 3.1 and highlighted within the red boundary in the figure. The research in this thesis delves deeper into carbon capture technology, specifically employing the post-combustion amino solvent-based method. The investigation encompasses two distinct scenarios or processes, namely Scenario (a) Cement production and Scenario (b) Combustion of biomass, as illustrated in figure 3.2. This thesis aims to shed light on the environmental impacts and potential carbon capture benefits associated with these processes, contributing to the knowledge and understanding of sustainable practices in the respective industries.

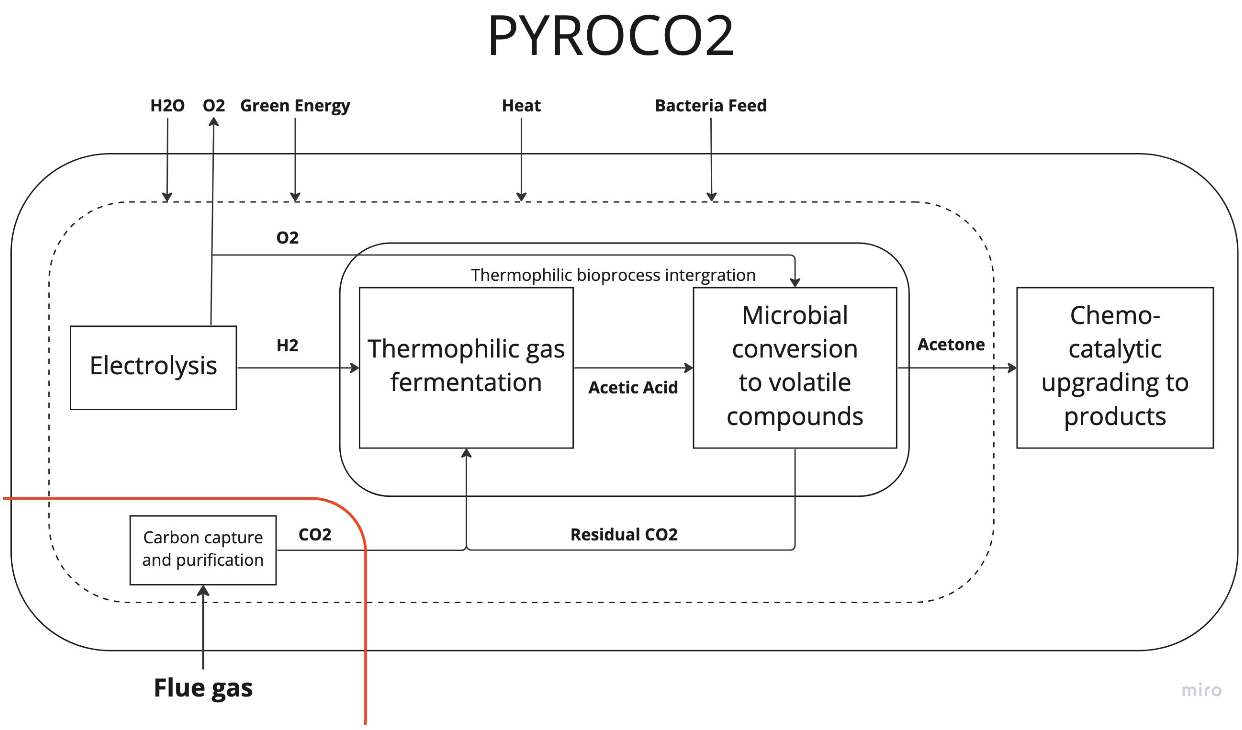
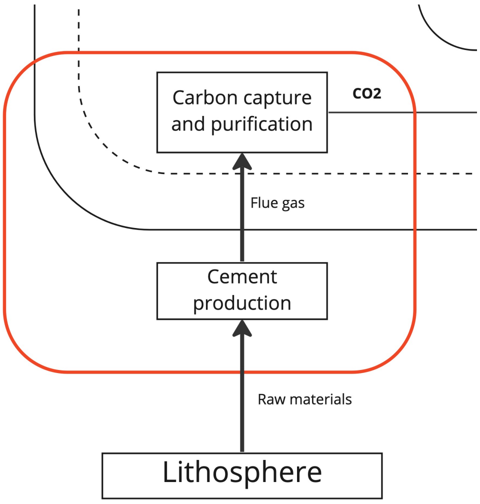
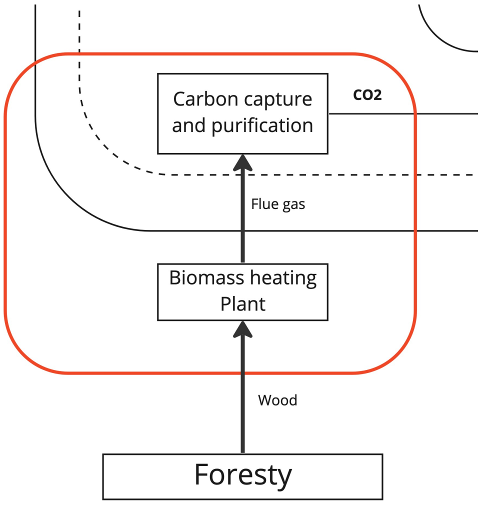


Figure 3.1: The PYROCO$_2$'s System Flowchart (Jiresten & Larsson, 2022). In the diagram, the red boundary highlights the specific objective and target of this thesis. This boundary is dedicated to examining the carbon capture process and its related flows.



(a) Cement production



(b) Combustion of biomass

Figure 3.2: Provides a visual representation of the flowchart of the two distinct scenarios investigated in this thesis for carbon capture and utilization and purification. The figure illustrates the application of carbon capture technology in two different processes: (a) Cement production and (b) Combustion of biomass.

3.1.1 Material Flow Analysis

As stated in section 2.4 MFA is preferably used as a basis for conducting an LCA. Therefore, conducting an MFA before performing an LCA can provide valuable insights and help ensure that the LCA is accurate and comprehensive. The procedure of the MFA for this thesis is as follows according to Brunner and Rechberger, (2017).

- **Problem Definition**: The first step in conducting an MFA is to define the problem that needs to be addressed. In the case of cement production, the problem is the high carbon dioxide emissions associated with the process. The goal of the MFA is to evaluate the effectiveness of post-combustion capture technologies in reducing emissions and identify opportunities for improving resource efficiency.

- **System Definition**: The second step is to define the system boundaries, which include the processes and activities to be included in the analysis, and the temporal and spatial boundaries of the analysis. For this process, the system boundaries would start from the raw material and end when the carbon dioxide has been through various processes and is ready for utilization. The inputs required for the system are raw materials, fuel, electricity, and water, while the output of the system includes captured CO_2. Data on the efficiency of the processes must be collected to define the system.

- **Determination of Flows and Stocks**: The third step is to determine the flows and stocks of the system, which involves developing a material flow model that accounts for the inputs, outputs, and stocks of carbon-containing materials in the system. The model calculates the carbon content of the input and output materials and tracks the flow of carbon dioxide emissions throughout the production process. The post-combustion capture technology is incorporated into the material flow model, and the flow of captured carbon dioxide is tracked. This step is crucial to understanding the sources and magnitude of carbon dioxide emissions, and how they can be reduced.

- **Interpretation**: The last step is to interpret the results of the MFA. This involves analyzing the results of the MFA to identify areas of inefficiency and opportunities for improvement. The carbon footprint of the process is estimated both with and without the post-combustion capture technology, to evaluate the effectiveness of the technology in reducing emissions. Ways to optimize the use of raw materials and energy in the production process are identified to reduce emissions and increase resource efficiency.

3.1.2 Cement production

To track the carbon and environmental impacts of cement production it is necessary to analyze the whole process from mining to the final product (CAC, 2021). The system includes six key processes: mining, crushing, pre-heating, rotating kiln, cooling, and grinding as shown in figure 3.3.

- **Mining and Crushing** Mining involves extracting raw materials such as limestone, shale, and clay from the lithosphere. Once the raw materials are extracted, they are crushed into smaller pieces using a crusher.

- **Pre-heating** The crushed materials are then preheated in a preheater to prepare them for the rotating kiln. The preheater is a series of cyclones that heat the material and reduce its moisture content.

- **Rotating-kiln** In the rotating kiln, the materials are exposed to high temperatures of up to 1450°C, which causes chemical reactions that transform the raw materials into cement clinker. This process releases large amounts of CO_2 and other emissions, making it a major contributor to climate change.

- **Cooling** After leaving the rotating kiln, the cement clinker is cooled using a cooler. The cooler reduces the temperature of the clinker to around 100°C and captures the heat, which can be used for other processes in the cement plant.

- **Grinding** The final process is grinding, where the cooled clinker is ground into a fine powder with a small amount of iron and gypsum to produce cement. This process requires a significant amount of energy and produces more emissions.

Inputs to the system include raw materials such as limestone and clay, water, fuel, and electricity (EAD, 2001). The clinker used in Portland cement contains 80% limestone 18% clay/sand and 2% iron. The final Portland cement product contains 95% clinker and 5% gypsum (Hossain, 2017; Habert, 2014). Portland cement will be the focus of investigation for this thesis. Outputs include cement and various emissions generated during the production process, such as carbon dioxide, sulfur dioxide, and nitrogen oxides. In addition, 40% of the emissions from cement manufacturing comes from the fuel used to heat the kiln. Approximately 60% of the remaining emissions are from the chemical process. (EAD, 2001; CAC, 2021).

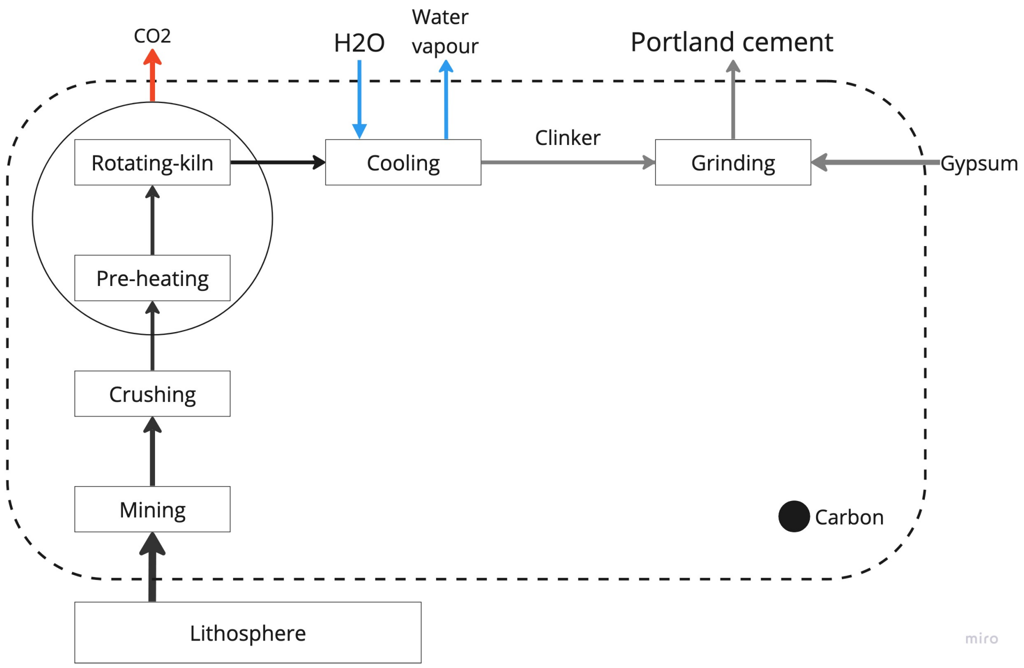


Figure 3.3: Cement Flowchart, Black arrows indicate carbon trajectory. Materials heated in the kiln release carbon as CO_2. Grey arrows represent carbon-free flow beyond the kiln.

3.1.3 Biomass Combustion

This section will discuss the process of producing energy from forestry using biomass combustion. It will cover the harvesting and processing of wood, the combustion process, electricity production, and the byproducts of this process as shown in figure 3.4.

- **Forestry** The process begins with the planting of seeds, and then forest harvesting, which involves cutting down trees in a forest (Paletto, 2019).

- **Chipping** Roundwood, which is harvested from trees, is used to produce lumber and other wood products in sawmills. The process of producing wood chips and other wood products involves chipping the roundwood into smaller pieces, which will also be used as fuel in biomass power plants (Paletto, 2019).

- **Power plant** The wood chips are then transported to the biomass power plant, where it is burned in a combustion chamber. The heat generated by the combustion process is used to boil water, which creates steam. The steam is then used to turn a turbine, which generates electricity.(Paletto, 2019).

The heat generated by the combustion process can also be referred to as thermal energy. This thermal energy can be used for various purposes, such as heating buildings or generating steam for industrial processes (Paletto, 2019).

The process of producing energy from forestry using biomass power plants produces some waste, including ash and emissions. The ash produced by burning the wood chips must be disposed of properly to prevent environmental contamination. The emissions produced by the combustion process can have negative environmental impacts if not properly managed (Paletto, 2019).

According to Caserini (2010), a biomass powerplant using chip together with industrial and forest residues have an efficiency rate of 52% corresponding to the useful energy generated. Furthermore, the carbon content of wood chips and sawdust are 46.7% and 53.07 % respectively (Velusamy, 2022).

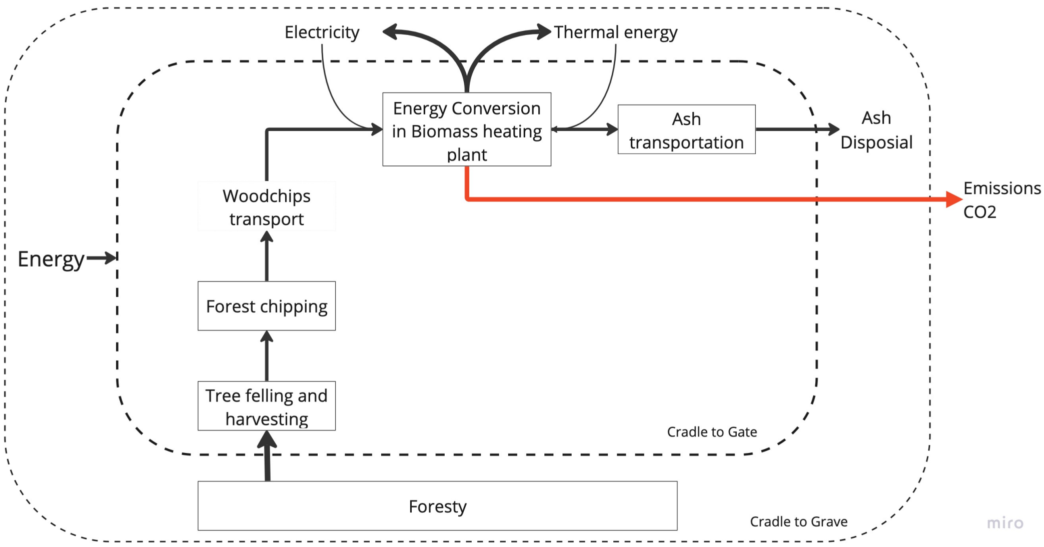


Figure 3.4: Initial Biomass Flowchart

3.1.4 Carbon Capture

Wang (2011) has reviewed different types of carbon capture facilities. One of which goes by the name CASTOR. This facility is similar to PYROC02, commission-funded by the EU and several industrial firms, such as Vattenfall and Statoil. This facility has the ability to capture 24 tons of CO_2 per day. On that note, insights from the flows and measurements from the facility are used for this research. This paper along with the literature review has gathered the information and data for the figure 3.5 to be conducted.

Post-combustion carbon capture is a process used to remove CO_2 from the flue gas emitted by power plants, industrial processes, and other sources. The process involves absorbing the CO_2 from the flue gas using a solvent, such as MEA, which is then regenerated to release the CO_2 for storage or utilization (Wang, 2011).

Regarding the type of reactions that occur in the different processes, the absorption of CO_2 by the MEA solvent in the absorber stage is a chemical reaction that involves the formation of a carbamate (Yin, 2019). In the stripper stage, heating the CO_2-rich solution breaks down the carbamate and releases the CO_2 gas.

Step 1: CO_2 dissolution in water

$$\mathrm{CO_2(g) + H_2O(l) \xrightarrow{\hspace{2em}} H_2CO_3(aq)}$$

In the first step, CO_2 dissolves in water to form carbonic acid (H_2CO_3).

Step 2: Reaction between MEA and carbonic acid

$$\mathrm{H_2CO_3(aq) + 2MEA(aq) \xrightarrow{\hspace{2em}} H_2O(l) + MEA - HCO_3(aq)}$$

In this step, carbonic acid reacts with MEA to form water and MEA bicarbonate (MEA-HCO3).

Step 3: Formation of carbamate

$$\mathrm{MEA - HCO_3(aq) \xrightarrow{\hspace{2em}} H_2O(l) + MEA - CO_2(aq)}$$

The MEA bicarbonate further decomposes into water and MEA-CO_2, also known as carbamate.

Step 4: MEA regeneration

$$\mathrm{MEA - CO_2(aq) + heat \xrightarrow{\hspace{2em}} CO_2(g) + MEA(aq)}$$

The MEA-CO_2 compound can be regenerated by applying heat, resulting in the release of CO_2 gas and the regeneration of MEA, allowing MEA to be reused in the absorption process.

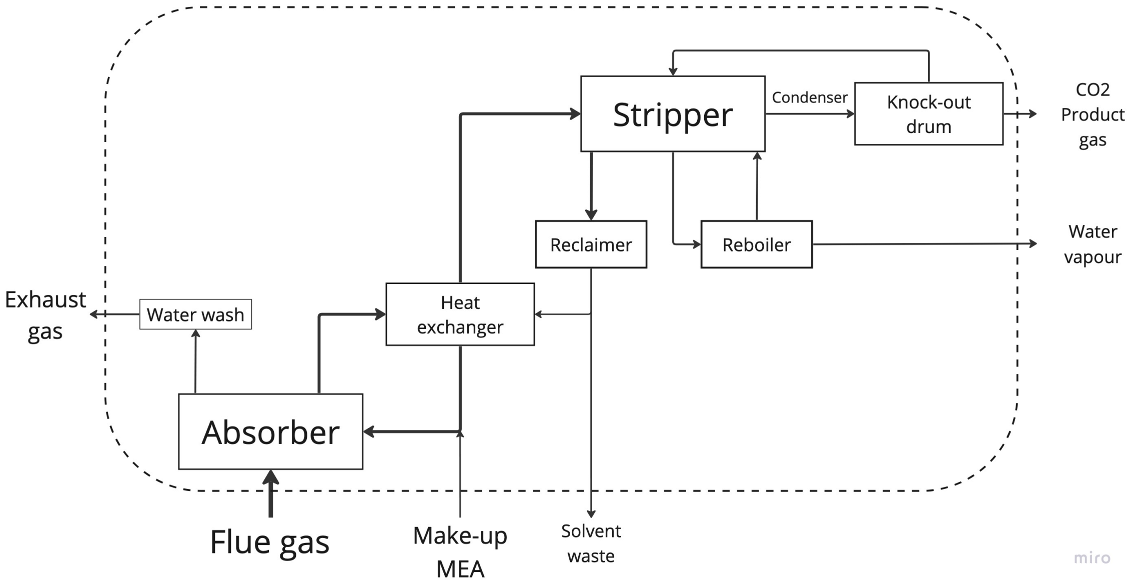


Figure 3.5: Flowchart over the carbon capture process

3.1.4.1 Absorber

In the carbon capture process, the absorber is responsible for removing CO_2 from a gas stream using a solvent. The solvent used in this process is the lean solvent, which is initially fed into the absorber.

During the absorber process, the lean solvent with typically around 0.10-0.25 mol CO_2/mol MEA is contacted with the CO_2-rich gas stream, which results in the absorption of CO_2 by the solvent. The solvent is then collected at the bottom of the absorber and then sent as a rich solvent to the heat exchanger unit for regeneration to release the CO_2. At the same time, the lean solvent is recirculated back to the absorber to repeat the absorption process. (Wang, 2011; IPCC, 2005).

The CO_2 capture process is a crucial step in mitigating GHG emissions from industrial processes. The use of the absorber unit enables the separation of CO_2 from the flue gas stream, resulting in cleaner exhaust gas emissions. The lean solvent, which is recirculated in the process, plays a crucial role in absorbing the CO_2 and converting it into a rich solvent. The process of absorption results in a temperature rise and an increase in the solvent's viscosity, leading to the need for regeneration in the heat exchanger (DEA, 2021).

To maintain the efficiency of the solvent and ensure the success of the CO_2 capture process, a water wash process is utilized in the absorber unit. The water wash process involves washing the flue gas stream to remove impurities that were not absorbed by the solvent. This helps to ensure that the exhaust gas released into the atmosphere is cleaner and less toxic, contributing to reducing the harmful effects of industrial processes on the environment (DEA, 2021).

The rich solvent leaving the absorber usually has around 0.40-0.50 mol CO_2/mol MEA. As the solvent absorbs CO_2, it gradually heats up, and the temperature inside the absorber is maintained between $40\circ$C and $60\circ$C (Wang, 2011; Davis, 2009).

3.1.4.2 Heat exchanger

The Heat exchanger process starts with the rich solvent from the absorber, which is a mixture of water, amines and CO_2 that has been captured from the flue gas. The rich solvent is then heated in a cross-heat exchanger using heated regenerated lean solvent from the stripper. In the heat exchanger, the lean solvent is cooled by the rich solvent, which is then heated up, thereby improving the overall efficiency of the carbon capture system. Resulting in a lean and cooled solvent that is then recycled back to the absorber for reuse (Yin, 2019; Wang, 2011).

3.1.4.3 Stripper

One of the key components of the carbon capture system is the stripper, which plays a critical role in separating CO_2 from the solvent used to capture it.

The stripper process in the carbon capture system occurs at slightly higher than atmospheric pressure (around 1.75 atm) and elevated temperatures (around 110°C). During this process, the rich solvent has been heated, causing the absorbed CO_2 to be released from the solvent. The released CO_2 is then sent to a compression unit for further processing, while the stripped solvent is cooled down and returned to the absorber for reuse (Wang 2011).

The stripper process is essential to maintain the efficiency of the carbon capture system, as it allows for the separation of CO_2 from the solvent used to capture it. By using a combination of heating and cooling, the stripper process can regenerate the solvent and recover the captured CO_2 for storage or use. The heat exchanger, which transfers heat from the lean solvent to the rich solvent, is an important component of the stripper process that improves the efficiency of the carbon capture system (IPCC, 2005).

3.1.4.4 Knock-out drum

The knock-out drum is a vessel used to remove liquid and solid particles from gas streams in various applications, including carbon capture processes. In post-combustion carbon capture, the knock-out drum separates CO_2 gas from any remaining water or solvent droplets that may have carried over from the stripper unit, while the remaining water and solvent can be recycled back into the process. The knock-out drum's design and operation parameters are critical for the carbon capture process's efficiency and effectiveness, making it an essential component to consider during system design and optimization (Coker, 2007).

The composition of the liquid or particles removed from the gas stream varies depending on the specific capture technology and flue gas characteristics. The difference between the input and output of the knock-out drum process is typically insignificant in terms of the total gas volume. The knock-out drum primarily removes liquid droplets, solid particles, and condensable vapours that may include solvent vapours, water vapour, and other impurities. However, the gas volume lost during this process is usually manageable through appropriate system design and operation (Coker, 2007).

3.1.4.5 HYSYS Model

The effective implementation of CCU processes relies on precise modelling and simulation to ensure feasibility and effectiveness. This study utilizes the HYSYS simulation program, a widely adopted software in the chemical engineering industry, capable of simulating all flow rates in the CCU process.

The simulation aims to model the CCU process and calculate expected mass and energy flows. HYSYS facilitates the creation of detailed process flow diagrams, specifying critical process conditions such as temperature, pressure, and flow rates (refer to Appendix A). The process flow diagram in HYSYS includes components like the absorber, stripper, heat exchanger, and other relevant units, with specified conditions for inlet and outlet streams, along with the chemical properties of the solvent and other compounds used in the process.

Utilizing HYSYS enables the calculation of expected mass and energy flows in the CCU process. The simulation models absorption of CO_2 by the lean solvent in the absorber, heating and separation of the rich solvent in the stripper, and cooling of the solvent in the heat exchanger. It also computes the energy requirements for heating and cooling the solvent, as well as compressing and transporting the captured CO_2.

HYSYS serves as a valuable tool, allowing for the creation of a detailed process simulation that accurately represents the CCU process. The simulation results are then leveraged to conduct an LCA in subsequent chapters, providing insights into the feasibility and environmental impact of the CCU process. Through the use of HYSYS, this study identifies areas for improvement and optimization within the CCU process.

3.1.4.6 System losses

In terms of losses in the system, gas may escape during the flue gas input stage due to leaks or insufficient capture mechanisms, which can include the CO_2 gas that is needed as the final output. Additionally, not all of the CO_2 in the flue gas is absorbed by the solvent in the absorber stage. The unabsorbed CO_2, along with other gases in the flue gas, will exit the absorber as the exhaust gas output. Some CO_2 may not be fully released during the stripper stage due to incomplete heating or insufficient stripping. Circular processes in the system, such as the lean and rich solvent, may also result in some losses of gas (Wang, 2011).

3.2 Functional Unit

The functional unit for the systems is one metric tonne of CO_2 as the outflow from the carbon capture facility, needed to produce acetone. This choice is made because CO_2 is a critical factor in the systems, both as an input to the carbon capture and needed to produce the acetone. Tracking the carbon flows of CO_2 allows for a clear and consistent measurement of the environmental impact of the systems. By focusing on one metric tonne of CO_2, the system can provide a standardized and comparable basis for a clear and consistent comparison of the environmental impacts of the different processes across different CO_2 feedstocks and methodological choices in LCA.

3.3 System Boundaries

To perform the LCA for this study, a foreground and a background system must be separated. Where the foreground accounts for the CCU process and everything that happens within the frames of the CCU. The background refers to the activity surrounding the CCU plant, such as the electricity grid that supplies the energy that powers the CCU (Jeswani, 2011).

The boundaries for the biomass- and cement systems are considered to be cradle-to-gate. Where the boundaries start where the material is extracted. Moreover, the end of the boundaries is when the products that the respective facility has produced are made. However, since this project aims to track the carbon flow, it is, thus, important to look at the emissions, especially the CO_2. When the carbon (CO_2) has been tracked accordingly, it can then be used for the CCU process.

For the carbon capture system, the boundary starts at the inflow of the flue gas and ends where the now pure CO_2 is ready for storage or utilization. Since the focus of the thesis is the carbon capture process and the carbon flow, the system boundaries are cradle to gate, since the end goal is to have a CO_2 product stream ready to be utilized. The use of the CO_2 product stream is not included.

3.3.1 Foreground

The foreground system will encompass all the activities and inputs that are directly associated with the carbon capture process. Moreover, the carbon flow is present in the foreground. In other words, both scenarios (a) and (b) are included, as seen previously in figure 3.2. As the figure demonstrates, the boundary starts with the extraction of raw material, until it has been captured by the post-combustion carbon capture technology at the end.

3.3.2 Background

The background system includes the activities and inputs that are indirectly related to the carbon flow processes, such as the acquisition of industrial CO_2 and electricity, and the disposal or reuse of waste products (Jeswani, 2011). For this thesis, a comparison between Swedish and German electricity will be performed, in order to quantify the differences the different types of electricity mix have on the environmental impacts.

3.4 Life cycle impacts assessment

Environmental impacts are a crucial aspect to consider in all industrial processes, and the carbon capture system is no different. The carbon capture system entails various impacts, including acidification (AC), climate change (CC), freshwater aquatic ecotoxicity (ET-FW), human toxicity (HT), and abiotic depletion potential (ADP). These impacts bear significance in relation to GHG emissions and carbon capture, as they are closely tied to the system's potential for reducing emissions.

The LCA conducted for this master's thesis used the CML method (v4.8 2016) as the impact assessment method. Developed by Leiden University in the Netherlands, the CML method is widely recognized for containing commonly used impact categories and characterization factors based on scientific consensus (Acero et al, 2016). This assessment encompassed the process and various fossil fuel CO_2 feedstocks, with results presented for each impact category per functional unit and reference flow. The utilization of the CML method facilitated a comprehensive and scientifically grounded analysis of the environmental impact associated with the carbon capture process.

Table 3.1: Environmental impact categories used for the study

Impact category	**Abbreviation**	**Description**	**Unit**
Acidification	AC	Acidification (incl. fate, average Europe total, A&B)	kg SO_2-eq
Climate Change	CC	Global warming potential (GWP100)	kg CO_2-eq
Freshwater Aquatic Ecotoxicity	ET-FW	Ecotoxicity: freshwater - freshwater aquatic ecotoxicity (FAETP inf)	kg 1,4-DCB
Human Toxicity	HT	Human toxicity (HTP inf)	kg 1,4-DCB
Abiotic Depletion Potential	ADP	Energy resources: non-renewable - ADP: fossil fuels	PER MJ

Acidification is a significant environmental impact associated with the carbon capture system. The release of acid gases such as CO_2, SO_2, and NO_X can cause acidification of soils, water bodies, and other natural environments. Carbon capture can help reduce the acidification potential by capturing these gases before they are released into the atmosphere (Baumann & Tillman, 2004; Acero et al, 2016).

Climate change is another significant environmental impact that is relevant to carbon capture. The primary objective of carbon capture is to reduce GHG emissions, which contribute to climate change. By capturing CO_2 from industrial processes, the carbon capture system can help reduce the amount of CO_2 released into the atmosphere and mitigate the impacts of climate change (Baumann & Tillman, 2004).

Freshwater aquatic ecotoxicity is a concern associated with the chemicals used in the carbon capture system. Some of these chemicals can be harmful to aquatic life, and their discharge into water bodies can have severe consequences. However, proper design and operation of the carbon capture system can help minimize the potential for freshwater aquatic ecotoxicity (Baumann & Tillman, 2004).

Human toxicity is another important consideration when evaluating the environmental impacts of the carbon capture system. Some of the chemicals used in the process, such as solvents and amines, can be toxic to humans. However, appropriate safety measures and regulatory compliance can minimize the potential for human toxicity (Baumann & Tillman, 2004).

Abiotic depletion potential is a method used in life cycle assessment (LCA) to evaluate the impact of a product or process on non-renewable resources. ADP measures the potential for depletion of resources such as minerals, metals, and fossil fuels based on the energy required to extract and process them. The unit of measurement for ADP is "person-equivalent resource" (PER), which represents the amount of a resource needed to support one person for one year. ADP helps to compare the impact of different products or processes on non-renewable resources and determine their sustainability (Baumann & Tillman, 2004).

3.5 Data & openLCA

The method used for the LCA of this research will detail the use of openLCA, an open-source software tool, to conduct an LCA of the PYROCO_2 project and environmental impacts of different CO_2 feedstocks. The LCA will be conducted in accordance with the ISO standard as mentioned previously. openLCA allows navigation of the database, data selection, and LCA calculations for desired impact categories (Wernet, 2016).

The ecoinvent database is a widely used comprehensive source of life cycle inventory data, encompassing over 17,000 materials, processes, and services. It offers input/output and impact factor information for various environmental impacts. Using ecoinvent in openLCA enables environmental impact assessment in categories like climate change and human toxicity, with regionalized LCIA facilitating local-level evaluations (Wernet, 2016).

3.6 Limitations & Assumptions

In this research, the aim is to investigate the carbon flows and the environmental implications of different CO_2 sources in a CCU system. While the study provides valuable insights into the topic, it is important to keep in mind certain limitations that may affect the results. The following limitations should be considered when interpreting the results and drawing conclusions from the research:

- **Scope of the study**: The study is limited to a post-combustion with chemical absorption CCU process and a specific geographic region (EU), and the results may not be generalizable to other types of CCU processes or regions.

- **Timeframe**: This thesis is focused on a 6-month period of time, which may result in not all aspects and information of the project being analysed which may give a one-sided view and the result may not be applicable to other timeframes.

- **Impact categories**: The study is limited to the impact categories chosen for the LCIA, and it does not include other potential impact categories that may be relevant.

- **Carbon flows**: The study focuses on the carbon flows within the CCU system, but it does not take into account the potential carbon flows that may occur outside the system.

- **Transportation**: The transportation of the limestone from the mining sight to the cement factory will not be calculated, where the assumption will be that they are next to each other.

4

Life Cycle Inventory Analysis

In this chapter, an inventory analysis of the collected data along with the assumptions and limitations used in the study is presented, together with energy and mass balances. The inputs, processes, and corresponding impacts were sourced from the ecoinvent 3.8 database unless otherwise specified. A comprehensive inventory of all flows is available in Appendix A, all calculations used for the flows and assumptions made are presented in Appendix B.

4.1 Overall Flowchart

The process will start from two different scenarios as previously presented in figure 3.2. These scenarios are based on two different sources of carbon, where the first carbon flow source is from cement production, named (a) Cement production and the second is from the combustion of biomass, named (b) Combustion of biomass.

Table 4.1: This table summarizes the key raw material sources for Portland cement production, specifying the processes, product types, and associated cutoff systems. The materials include iron ore concentrate, limestone (unprocessed), silica sand, and niobium (from pyrochlore ore), with cutoff systems denoted as "U - RoW" in OpenLCA.

Process	**Product type**	**Cutoff System/Region**
iron ore beneficiation	*iron ore concentrate*	*Cutoff, U - RoW*
limestone quarry operation	*limestone, unprocessed*	*Cutoff, U - RoW*
silica sand production	*silica sand*	*Cutoff, U - RoW*
limestone quarry operatio	*limestone unprocessed*	*Cutoff, U - RoW*
silica sand production	*silica sand*	*Cutoff, U - RoW*
niobium mine operation and beneficiation, from pyrochlore ore	*iron ore concentration*	*Cutoff, U - RoW*

(a) Cement production: The process starts with raw materials such as limestone, sand, and iron ore are extracted and processed using electricity-powered crushers. The heating processes, involving pre-heating and kiln operations, rely on coal/lignite, resulting in the release of CO_2 and SO_2. The hot clinker produced from the heated and mixed materials is cooled with water, assuming complete water evaporation. All carbon released during the kiln process is considered as CO_2 emissions. The final production stage involves grinding the clinker with gypsum to produce Portland cement, necessitating electricity. Additionally, the CCU process captures flue gas emissions from both pre-heating and kiln operations.

Table 4.2: This table outlines the biomass combustion process in the German scenario, starting with sustainable hardwood forestry (birch). Key steps include harvesting, chipping logs, and combustion in a heating plant. Petrol (unleaded) is used in the chipping operation, sourced from the market under the cutoff system "U - GLO" in OpenLCA. The energy content of logs is assumed to be 72 MJ per m3, and the heating plant, operating at 25% efficiency, produces 2280 MJ of energy with CO2 emissions.

Process	Product type	Cutoff System/Region
hardwood forestry, birch, sustainable forest management	*bundle, energy wood, measured as dry mass*	*Cutoff, U - RoW*
market for petrol, unleaded, burned in machinery	*petrol, unleaded, burned in machinery*	*Cutoff, U - GLO*

Table 4.3: This table details the biomass combustion process in the Swedish scenario, beginning with sustainable hardwood forestry (birch) and covering activities such as logging, wood chip production, and combustion in a heating plant. The chipping operation uses 1.678 litres of petrol (unleaded) from the market under the cutoff system "U - GLO" in OpenLCA. The assumed energy content of logs is 72 MJ per m3, and the heating plant, with 25% efficiency, generates 2280 MJ of energy, accompanied by CO2 emissions.

Process	Product type	Cutoff System/Region
s hardwood forestry, birch, sustainable forest management	*bundle, energy wood, measured as dry mass*	*Cutoff, U - SE*
market for petrol, unleaded, burned in machinery	*petrol, unleaded, burned in machinery*	*Cutoff, U - GLO*

(b) Combustion of biomass: The process starts with tree harvesting from forests, executed with heavy machinery, contingent on tree size and density. Post-harvest, trees are transported to processing facilities for sorting, debarking, and chipping into small fuel-appropriate pieces. This chipped wood is conveyed to a biomass power plant for combustion in a chamber, generating heat. The heat is harnessed to boil water, producing steam used to turn a turbine, ultimately generating electricity. Byproducts from the combustion process include carbon dioxide, greenhouse gases, ash, and particulate matter, collectively referred to as flue gas emissions.

Relevant data from the carbon capture process will be presented in the following section. For the general carbon capture process see section 3.1.4. 90% of the flue gas released in the scenarios is targeted for absorption in the carbon capture process, as illustrated in Figure 3.5. The objective of this process, detailed in Section 3.2, is to produce 1 ton of CO_2 gas. The required mass flow of flue gas, factoring in the 90% capture rate, is calculated based on the assumption of standard pressure and temperature, where the flue gas comprises 14% CO_2. The total flow rate of flue gas needed to yield 1 ton of CO_2 gas is estimated using equations (B.1) and (B.2). The functional unit is set at 1 ton of CO_2, necessitating the absorption of at least 7,936.51 kg of flue gas, as detailed in Appendix B.

In the carbon capture process, the flue gas enters the absorber unit, where it comes into contact with a lean solvent composed of water, MEA, and CO_2. The solvent's role is to absorb CO_2 from the flue gas, resulting in a "rich solvent." Following a water wash, the remaining flue gas is released into the atmosphere. The rich solvent undergoes temperature increase in a heat exchanger, reaching around 110 °C for the subsequent stage. In the stripper, the elevated temperature causes the separation of CO_2 and solvent. The released CO_2 is available for utilization, while the solvent is cooled in the heat exchanger and recycled in the process.

4.2 Background system

Table 4.4: Scenario a), the selected energy source for the carbon capture process is identified as *market for heat, future / heat, future / Cutoff, U - GLO.* This choice reflects a reliance on industrial heat from a global market perspective.

Process	Product type	Cutoff System/Region
market for heat, future	*heat, future*	*Cutoff, U - GLO*
market for electricity, high voltage	*electricity, high voltage*	*Cutoff, U - DE*
market for electricity, high voltage Potential	*electricity, high voltage*	*Cutoff, U - SE*
ethanolamine production	*monoethanolamine*	*Cutoff, U - RER*

Table 4.5: Scenario b), the carbon capture process is powered by the heat source *wood pellets, burned in stirling heat and power co-generation unit, 3kW electrical, future | heat, future | Cutoff, U - CH.* This scenario specifically employs industrial heat generated through the burning of wood pellets in a stirling heat and power co-generation unit.

Process	Product type	Cutoff System/Region
wood pellets, burned in stirling heat and power co-generation unit, 3kW electrical, future	*heat, future*	*Cutoff, U - CH*
market for electricity, high voltage	*electricity, high voltage*	*Cutoff, U - DE*
market for electricity, high voltage Potential	*electricity, high voltage*	Cutoff, *U - SE*
ethanolamine production	*monoethanolamine*	*Cutoff, U - RER*

Electricity mix

The German electricity mix consists of mostly coal and nuclear, while the Swedish mix has more renewables such as hydro, and nuclear. Overall, the Swedish electricity mix can be viewed as having less climate impact. When the different mixes are referred to it is important to know that the locations have been taken into consideration.

Ash Disposial

The combustion of wood chips does produce ash. 1% of the total mass of the combusted wood chips is assumed to become ash. Moreover, it is considered waste that is emitted to the environment.

Production of MEA

The utilization of MEA on a global scale has the potential to significantly impact the production landscape and associated costs of this chemical compound. However, it is imperative to acknowledge the consequential environmental implications stemming from increased production and the consequent release of CO_2 emissions during the manufacturing process. To discern the key focal points of concern, it is necessary to provide a concise overview of the fundamental MEA production process, which involves the amalgamation of ammonia (NH_3) and ethylene oxide (EO). To attain a comprehensive perspective, the overall framework needs to be analysed from the start of NH3 production to EO production, and ultimately, the synthesis of MEA. Both ammonia and EO exert notable environmental impacts individually. These chemicals rank among the top 50 globally produced compounds. Ammonia production is associated with CO_2 emissions ranging from approximately 1.15-1.4 kg or 2-2.6 kg per kg of ammonia produced, contingent upon the utilized fuel sources.

On the other hand, EO poses hazards due to its reactivity and toxicity. (Luis, 2016).

4.3 Cement production

The CO_2 content of the flue gas exiting the cement power plant as emissions are 14% (Knudsen, 2014).

Before starting the calculations, the content of the cement product needs to be defined. The type of cement used for the calculations for this thesis will be based on Portland cement (80% limestone, 18% sand and 2% iron). The flows for the calculations will be presented in table 4.1.

According to CAC (2021), the amount of CO_2 that is being released from the production of cement can be divided into two parts, the chemical and the manufacturing, where the chemical stands for 60% of the emissions, while the manufacturing process stands for the last 40%. On the other hand, Hossain (2017) states that on average 0.79 tons of CO_2 is emitted per one ton of cement being produced (depending on what type of fuels are used). Moreover, what types of fuel and electricity are being used for the assessment is important. According to Taylor et al (2006), the most commonly used fuel for cement production is coal or lignite. The actual carbon content of lignite is around 78% (Huaijun, 2020). Furthermore, approximately 150kg of lignite per ton of clinker produced is the average within the EU. The fuels are used for heating up the materials, hence the other processes such as grinding and crushing all require electricity to be performed.

The materials do not change their composition until they are heated inside the rotating kiln that is heated to approximately 1450 degrees Celsius. The main reaction in the kiln is between the calcium from the limestone and the silica from the sand. This creates the well-known clinker powder. It is during this step of the process where essentially all of the carbon dioxide emissions together with some other emissions occur and where the carbon goes from being solid, into carbon dioxide gas, it is assumed that all of the carbon will react and form carbon dioxide.

Due to the high temperatures, the clinker needs to be cooled. According to Stajanča (2012), the water needed for cooling the clinker ranges from 100-600 kgs per ton clinker. For this thesis, 500kg of water will be the value used for calculations, also assuming that everything will vaporise.

With the chemical reactions occurring in the rotating kiln, the material composition changes. This means that among others, the molecular weight also changes, see Table (C.1). The most important reaction is the reaction from limestone into lime and CO_2 (because the other reactions do not emit any carbon from their reactions) see Reaction 1. To phrase it differently, it is the limestone, that has stored the carbon in the lithosphere, that is then released into the atmosphere or captured.

To calculate the carbon emissions from the chemical reactions happening within the rotating kiln, a chemical and molar balance is conducted. Reaction 1 shows that the mole ratio is 1:1. Thus, the reaction creates the same amounts of mole CO_2 as CaO. Also, 80% of the total weight of the clinker is limestone. With the mass of limestone and the amounts of moles, the weight of CO_2 and CaO is calculated with the use of equation (4.1) The full inventory data and calculations can be found in Appendix B.

Reaction 1

$$\mathrm{CaCO_3} \longrightarrow \mathrm{CaO} + \mathrm{CO_2}$$

Equation 4.1. Mole-mass relationship

$$M = \frac{m}{n} \tag{4.1}$$

With the composition, equations, and molar masses it was possible to make calculations on the amount of raw materials needed to emit one ton of carbon dioxide from a cement production, see Appendix C. The calculations indicate that the statement from Hossain (2017) is accurate.

4.4 Combustion of biomass

The composition of the flue gas exiting the biomass heating plant as emissions are 14% CO_2 (Lasek, 2017).

The combustion biomass starts with the seeding of the tees, then harvesting, and then logging of the trees. The total mass of logs converted into wood chips amounts to approximately 634 kg, as determined through a comprehensive calculation based on the required CO_2 content in the flue gas. For inventory data used for calculations, please refer to Appendix D. Following the logging process, the chipping operation ensues, necessitating the use of 1.678 litres of petrol (Paletto, 2019). The energy content of the logs is assumed to be 72 MJ per m3. Lastly, the combustion heating plant, operating with an efficiency of 25%, generates 2280 MJ of energy alongside CO_2 emissions. All of the carbon released from the use of gasoline as well as the combustion of biomass is assumed to turn into CO_2.

4.5 Carbon Capture

No specific data is allocated to carbon capture processes independently. The exclusive method employed involves the utilization of MEA in conjunction with industrial heat, as elucidated earlier in this report.

4.6 Sensitivity Analysis

Sensitivity analysis is a valuable technique in LCA to evaluate the influence of input parameters on study results. One common approach is the one-way sensitivity analysis, which examines the impact of varying individual parameters while keeping others constant. By systematically adjusting parameter values within a defined range, practitioners can assess the resulting changes in environmental indicators. This analysis helps identify critical parameters that significantly affect LCA results, enabling informed decision-making and the prioritization of actions for sustainability (Baumann & Tillman, 2004).

In the case of this thesis, the heat sources, comparison between baseline scenarios: (a) and (b) with the different electricity mixes, to the removal of the carbon capture technology, a total 50% decrease in the heat required, and change in efficiency for the biomass heating plant will be analyzed.

4.6.1 Heat Source

Scenario a) and b) uses different heat sources for the carbon capture as stated in table 4.4 & 4.5

The baseline scenario is set to require 6GJ for the carbon capture process, nevertheless a low case scenario was analysed as well. The low case scenario required 3GJ of heat energy, a reduction of 50%. The impact category climate change was examined for this analysis, and it shows that overall the impact decreases, but with less than 10% for both scenarios, and in both countries.

4.6.2 Cement Production & Biomass Combustion Without Carbon Capture

Without the addition of carbon capture technology to the process, the impact categories differentiates. In short, only climate change and acidification have a decrease, while ET-FW, HT, and ADP all increase. However, the change of the climate change impact is a lot larger than for the other categories.

4.6.3 Efficency

Initially, the efficiency of the biomass heating plant was set at 25%. However, when the efficiency was increased to 50%, it became evident that the energy output doubled. Additionally, if the energy output remains constant for both efficiency rates, it would result in a reduction of the required amount of wood chips by half. Thus, reducing the CO_2 emissions by 50%.

5

Result & Discussion

In this chapter, the results of the environmental impact will be presented. Together with discussions about the environmental impacts causes.

5.1 Anthropogenic & Biogenic Carbon

In this section, the result from the first research question in section 1.2 will be presented. This question addresses the comparison of an analysis of the carbon flows within the different systems.

The results obtained from the analysis provide insights into the carbon flows and their contributions to climate change in Scenario (a) and Scenario (b) which was presented in figure 3.1. Biogenic carbon is carbon released from biogenic sources such as the combustion of wood chips and hydro-powered electricity, to phrase it differently, renewable sources. While anthropogenic carbon originates from oil, natural gas, and other non-renewables. See figures 5.1 and 5.2 for an overview of the carbon distribution. The "other" category is a bunch small of stand-alone processes that contribute to less than 1% of the total climate impact on their own.

In Scenario (a) with the German electricity mix,5.1 it is evident that the majority of the carbon causing climate impact (47%) comes from anthropogenic carbon in the background processes. This indicates the significance of considering the carbon emissions associated with these background processes, which may have a substantial influence on the overall environmental impact. Additionally, only 3% of background biogenic carbon from background processes is present, while 33% originates from fossil foreground processes.

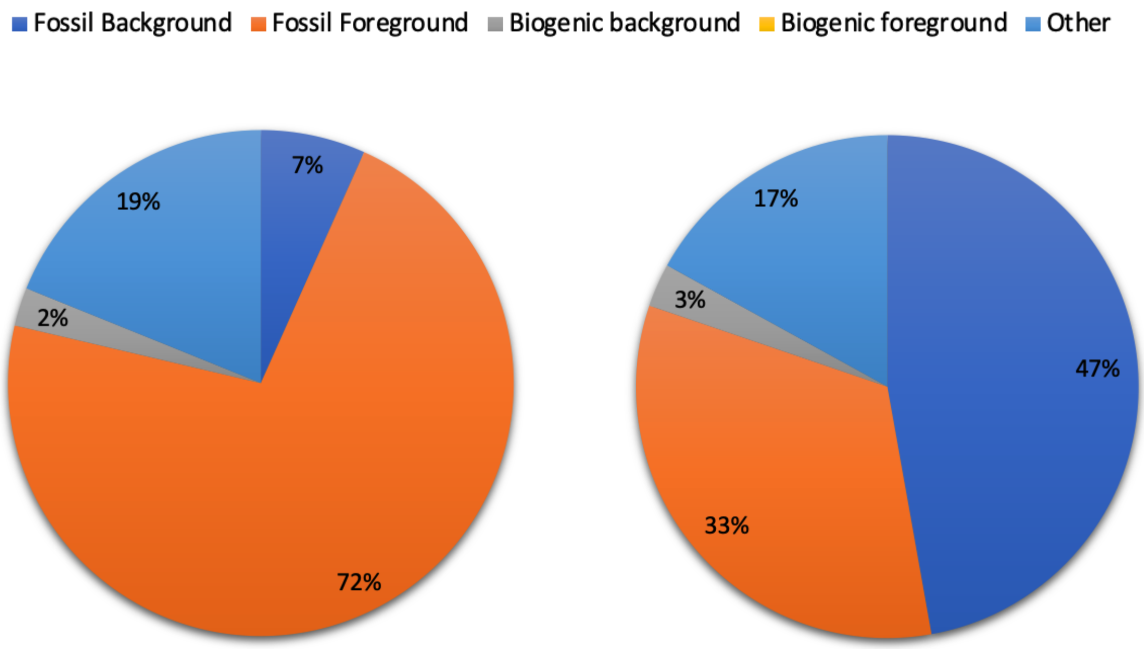
In contrast, in Scenario (a), 5.2 the distribution of carbon contributions is different. Here, anthropogenic carbon from background processes accounts for only 7% of the total carbon contributing to climate change. The percentage of anthropogenic carbon from foreground processes increases to 72%, indicating the importance of considering the direct emissions from these foreground activities. Interestingly, biogenic carbon from background processes is accounting for 2% of the total carbon emissions.

Moving on to Scenario (b), 5.1 which involves the German electricity mix, the results demonstrate that anthropogenic carbon from background processes is the dominant contributor, representing 78% of the total carbon emissions. It is noteworthy that a significant proportion of carbon (6%) comes from biogenic sources in the foreground processes. This indicates the relevance of accounting for the emissions associated with these biogenic activities. Additionally, a small percentage (2%) of carbon stems from biogenic background processes.

Finally, in Scenario (b) Germany 5.2, the carbon flows show a different pattern. Biogenic foreground processes contribute the most to carbon emissions (67%), emphasizing the significance of considering the impact of these biogenic activities. anthropogenic carbon from background processes represents 2% of the total carbon emissions, while just 1% from biogenic background processes and 8% from fossil foreground processes.

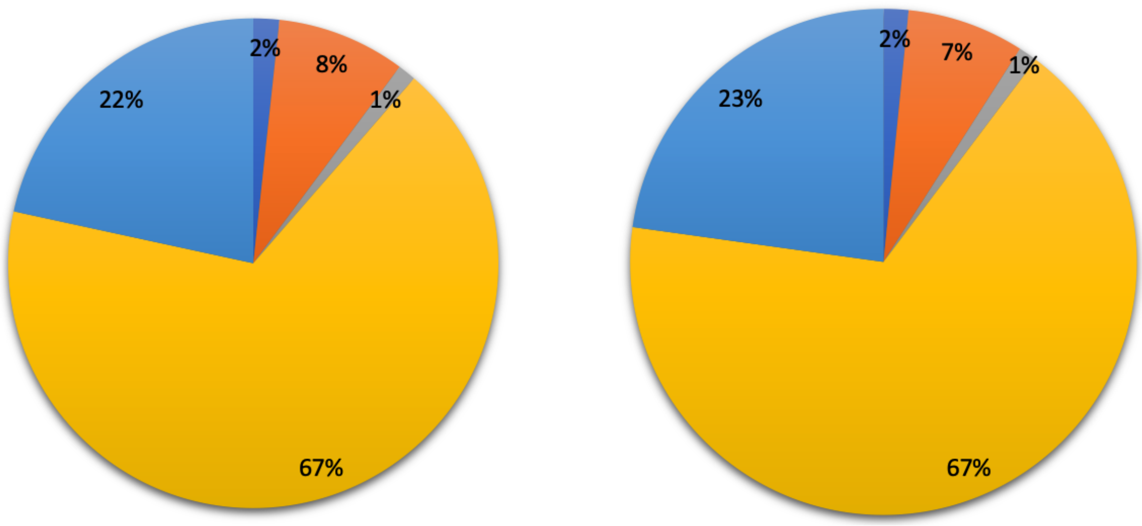
For the Swedish case, the results in scenario b) are almost completely identical. The only visible difference is the fossil foreground going from 8-7% together with the other category going from 22% to 23%. Thus, shows that combustion of biomass does not have a significant impact when it comes to the carbon flows when comparing different locations in Europe.

Our findings highlight the critical role of background processes, particularly anthropogenic carbon emissions, in contributing to climate impact, emphasizing the need for a holistic environmental assessment. The choice of electricity mix significantly influences carbon flows, with a notable shift observed in scenarios. Biogenic processes, especially in foreground activities, play a key role in carbon emissions. Interestingly, the Swedish case shows consistency, suggesting biomass combustion has a limited impact across European locations. Overall, transitioning to sustainable energy sources is crucial for mitigating environmental consequences associated with carbon emissions.



(a) Cement production Sweden **(b)** Cement production German

Figure 5.1: Foreground And Background Carbon Cement, Carbon Capture



(a) Combustion of biomass Sweden **(b)** Combustion of biomass Germany

Figure 5.2: Foreground And Background Carbon Biomass, Carbon Capture

5.2 Environmental impacts

In this section, the results from research questions two and three from section 1.2 will be presented. These questions address the comparison of the environmental impact of two different processes with two different electricity sources. Firstly, the impacts of the cement production process without and with CCU will be discussed and analyzed, including the impact categories from the Environmental impacts assessment choices in section 3.4 of Acidification, Climate Change, Freshwater Ecotoxicity, Human Toxicity, and Abiotic Depletion Potential. This set of impacts will also be examined for biomass combustion, both without and with CCU, and will be presented and analyzed. For a detailed breakdown of the total impacts in their respective SI units, please refer to Appendix E. The comparison will provide insights into the contribution of each process to the overall environmental impact by using the presented tables in the following section and also with the use of Appendix E.

5.2.1 Environmental Impact with Carbon Capture

In this section, a discussion on the results of the environmental impact of climate change resulting from the implementation of CCU technologies in cement production and biomass combustion processes is presented. Additionally, the discourse will address how various electricity choices influence these impacts.

Comparing the impacts of these processes with and without CCU, it is evident that CCU leads to an increase in most impact categories. However, a notable exception is the impact on climate change, where the application of CCU significantly reduces carbon dioxide emissions which can be seen in figure 5.3 & 5.4. This highlights the potential of CCU technologies in contributing to climate change mitigation efforts.

The analysis of the environmental impacts associated with cement production and carbon capture also emphasizes the importance of the electricity mix in influencing overall environmental performance. The German electricity mix, with its higher carbon intensity and resource depletion, tends to result in higher impacts across various categories. In contrast, the Swedish electricity mix, relying more on renewable energy sources, demonstrates relatively lower impacts. However, in the case of biomass combustion, the impacts are not affected by the choice of energy mix since the energy consumed is primarily driven by petrol.

Therefore, it is crucial to carefully assess and consider the trade-offs associated with CCU implementation. While CCU offers the potential to reduce carbon dioxide emissions and combat climate change, the overall environmental impacts should be taken into account. The increased impacts observed in other categories should be evaluated comprehensively to ensure a balanced understanding of the net environmental benefits and drawbacks.

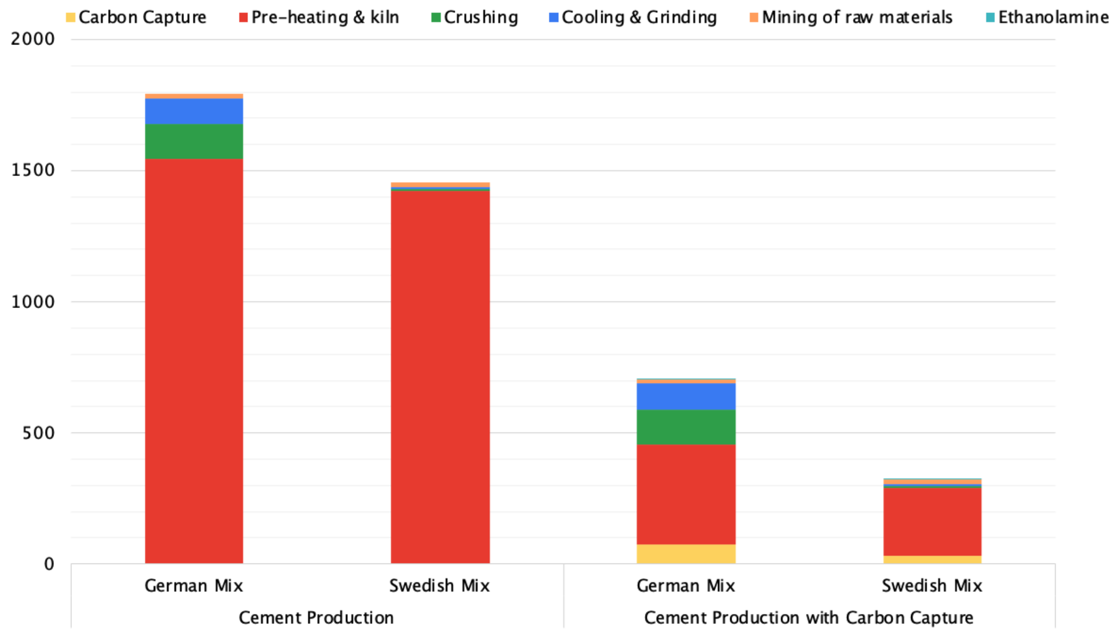


Figure 5.3: Illustrates the total impact on climate change [kg CO_2-eq] resulting from cement production. It provides a clear visual representation of the CO_2 emissions associated with the different processes during cement prodcution, both with and without the implementation of CCU technologies.

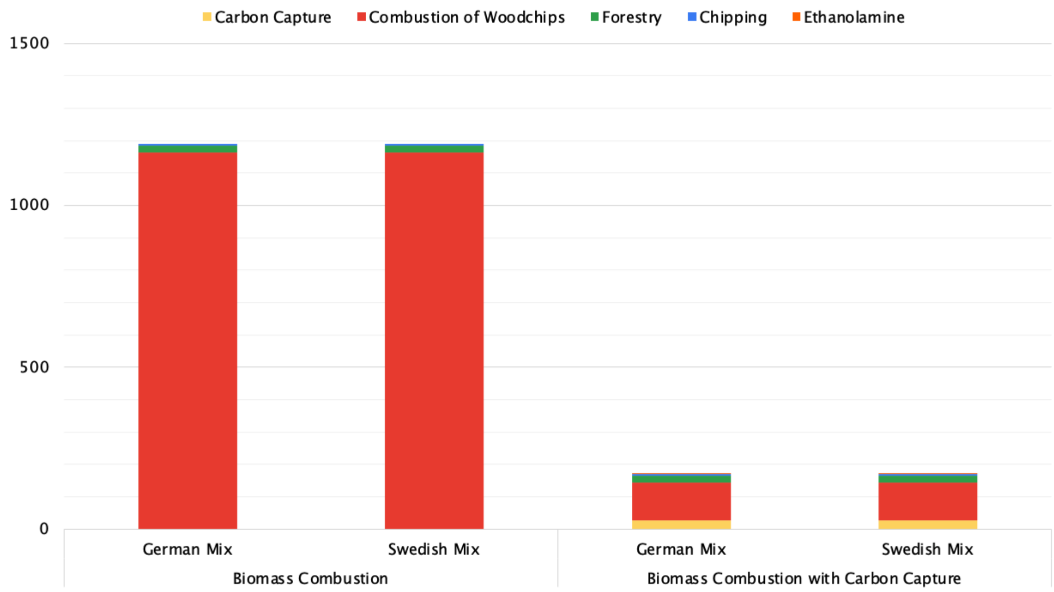


Figure 5.4: Illustrates the total impact on climate change [kg CO_2-eq] resulting from biomass combustion processes both with and without the implementation of CCU technologies.

The findings show a noteworthy impact on climate change arising from key processes in both cement production and biomass combustion. Within cement production, the pre-heating and kiln phases play a significant role, releasing substantial carbon dioxide and other compounds like sulfur dioxide. This heightened emission profile can be mainly attributed to the energy-intensive nature of these stages, utilizing coal/lignite as the primary energy source. Simultaneously, in biomass combustion, the combustion process of woodchips emerges as a crucial factor influencing the environmental impact of climate change. This is due to the release of carbon dioxide and other byproducts during the biomass combustion process.

It is important to note that the specific electricity mix used in each scenario can influence the environmental impacts. The Swedish electricity mix consistently demonstrates better environmental performance, exhibiting lower values in most impact categories. This is attributed to the lower carbon intensity and overall environmental footprint associated with the Swedish electricity mix. These differences highlight the significance of considering regional electricity sources when evaluating the environmental performance of cement production.

In conclusion, the analysis of the environmental impacts of cement production and biomass combustion processes, along with the integration of carbon capture technologies, provides valuable insights. It emphasizes the trade-offs and potential benefits associated with CCU implementation. While CCU effectively reduces carbon dioxide emissions and mitigates climate change, it introduces increased impacts in other categories. Optimizing the electricity mix, reducing emissions, and improving process efficiency are crucial steps in minimizing the environmental footprint of these processes. Further research and analysis are necessary to fully assess the overall sustainability and long-term benefits of biomass combustion and its associated processes.

5.2.2 Analysis of Cement Production

Figure 5.5 presents data for the relative environmental impacts associated with the cement production process. The impacts are analyzed for both Swedish and German electricity mixes, considering the impact categories presented in section 3.4.

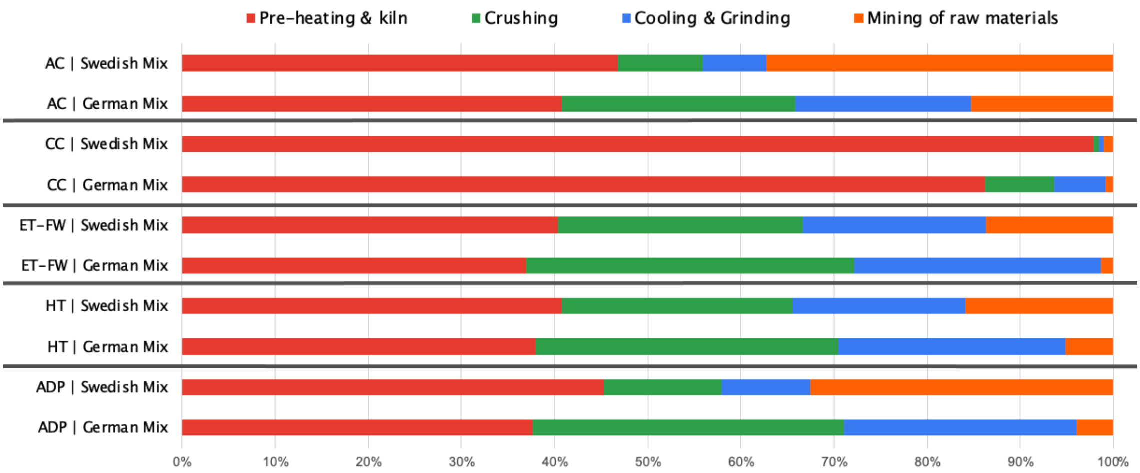


Figure 5.5: Illustrates the environmental impacts associated with the cement production process across the following impacts, Acidification (AC), Climate Change (CC), Freshwater Ecotoxicity (ET-FW), Human Toxicity (HT), and Abiotic Depletion Potential (ADP), considering two different electricity mixtures.

Figure 5.5 provides a visual representation of the magnitudes of each impact category for different stages of the processes. Each impact category is represented by a bar, and the length of the bar indicates the impact. The individual stages of the processes, namely Pre-heating & kiln, Crushing, Cooling & Grinding, and Mining of raw materials, are shown separately to analyze their respective contributions to the overall impacts. Comparing the impacts attributed to the Swedish and German electricity mixes enables an evaluation of how the choice of electricity source influences environmental performance.

5.2.3 Analysis Cement Production with Carbon Capture in Scenario (a)

Figure 5.6 presents the environmental impacts related to the cement production process, specifically focusing on its connection to the carbon capture process depicted in scenario (a) of figure 3.2. The results examine the same five environmental impacts and employ the same processes as figure 5.5, but with the inclusion of two additional processes associated with the carbon capture process. These supplementary processess encompass the energy consumption required for operating the carbon capture process, as well as the utilization of MEA as a solvent in the carbon capture process.

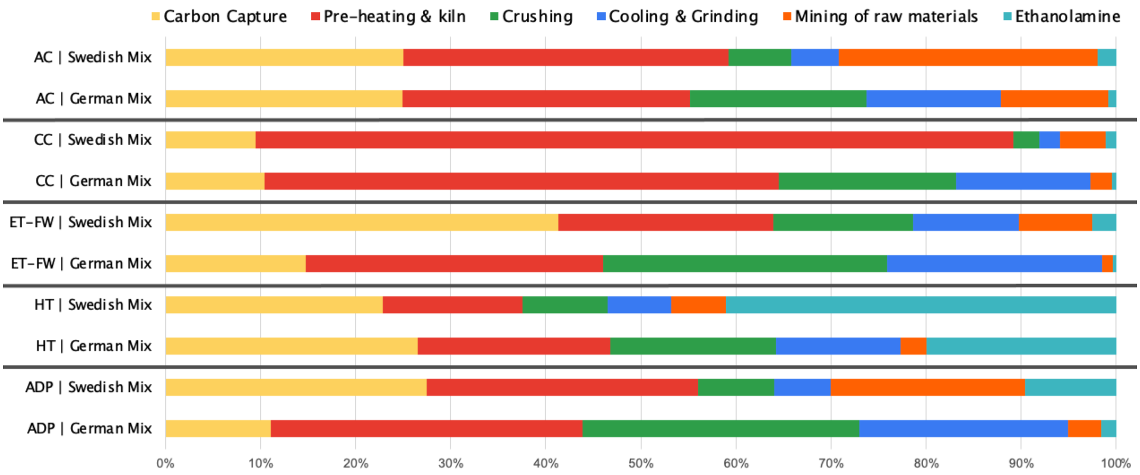


Figure 5.6: Illustrates the environmental impacts associated with the cement production process with the use of carbon capture across the following impacts, Acidification (AC), Climate Change (CC), Freshwater Ecotoxicity (ET-FW), Human Toxicity (HT), and Abiotic Depletion Potential (ADP), considering two different electricity mixtures.

5.2.4 Comparison of Conventional Cement Production vs. Carbon Capture Technology Integration

The results of the environmental impacts for both the ordinary cement process and the cement process with CCU have been presented. In previous sections 5.2.2 & 5.2.3, a comparison between these two sets of results will be made to assess the differences and implications of incorporating carbon capture technology. Subsequently, an analysis, discussion, and conclusions will be drawn based on the comparison of these findings. As stated earlier for a better understanding and interpretation of the environmental impacts and result, please refer to Appendix E.

Regarding acidification, the impacts remain relatively low for both processes. However, the ordinary cement process shows slightly higher acidification values compared to the process with carbon capture, primarily driven by the stages of pre-heating & kiln and crushing.

In terms of CC, the inclusion of carbon capture and the associated energy requirements contribute to increased CO_2-equivalent emissions. However, the implementation of carbon capture led to a reduction in the environmental impact of the pre-heating & kiln stages, resulting in the carbon captured process exhibiting lower impacts compared to the conventional cement process.

The assessment of ET-FW reveals that the application of CCU leads to an increase in the environmental impacts for both German Mix and Swedish Mix. This suggests that while CCU offers the potential to reduce carbon emissions, it may introduce additional environmental burdens in terms of resource consumption and emissions within the system. These results emphasize the importance of carefully assessing the trade-offs and considering the overall environmental implications when implementing CCU technologies in the cement industry.

Regarding HT, the ordinary cement process exhibits lower impacts compared to the process with carbon capture. This reduction is due to the incorporation of ethanolamine in the latter, which introduces potential risks to human health. It is important to note that the combustion stage contributes significantly to HT impacts in both processes.

In terms of ADP, the ordinary cement process shows lower values for both the German and Swedish mixes compared to the process connected to carbon capture. This difference can be attributed to the additional energy and resources required for carbon capture, which contributes to increasing the overall ADP effect.

The introduction of CCU amplifies environmental impacts, including increased energy use, freshwater consumption, and resource depletion. While effectively mitigating CO_2 emissions and addressing climate change concerns, CCU introduces trade-offs by escalating burdens in other environmental areas.

5.2.5 Analysis of Biomass Combustion

Figure 5.7 presents data for the relative environmental impacts associated with the biomass combustion process. The impacts are analyzed for both Swedish and German electricity mixes, considering the same impact categories as for the cement production process.

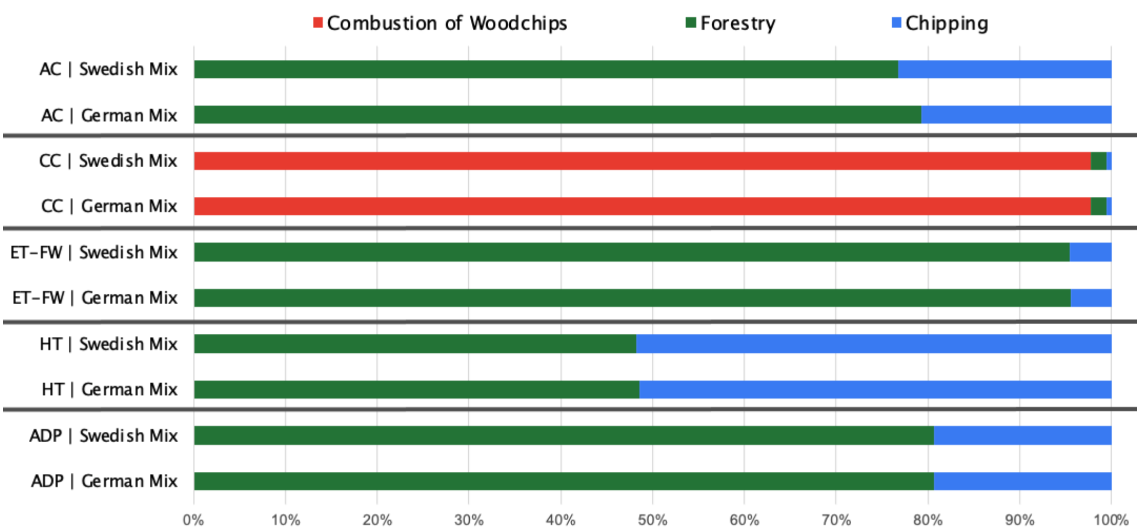


Figure 5.7: Illustrates the environmental impacts associated with the biomass combustion process across the following impacts, Acidification (AC), Climate Change (CC), Freshwater Ecotoxicity (ET-FW), Human Toxicity (HT), and Abiotic Depletion Potential (ADP), considering two different electricity mixtures.

To analyze the contributions of individual stages within the process, namely, combustion of woodchips, forestry, and chipping these stages are shown separately. This allows for a detailed examination of their respective impacts on the overall environmental performance of the biomass combustion and carbon capture system.

5.2.6 Analysis of Conventional Biomass Combustion vs. Carbon Capture Technology Integration

Figure 5.8 presents the environmental impacts related to the biomass combustion process, specifically focusing on its connection to the carbon capture process depicted in scenario (b) of figure 3.2. The results examine the same five environmental impacts and employ the same categories as figure 5.7. In addition, the study will encompass the examination of supplementary categories related to the carbon capture process, namely the energy consumption necessary for its operation and the use of MEA as a solvent in the carbon capture process.

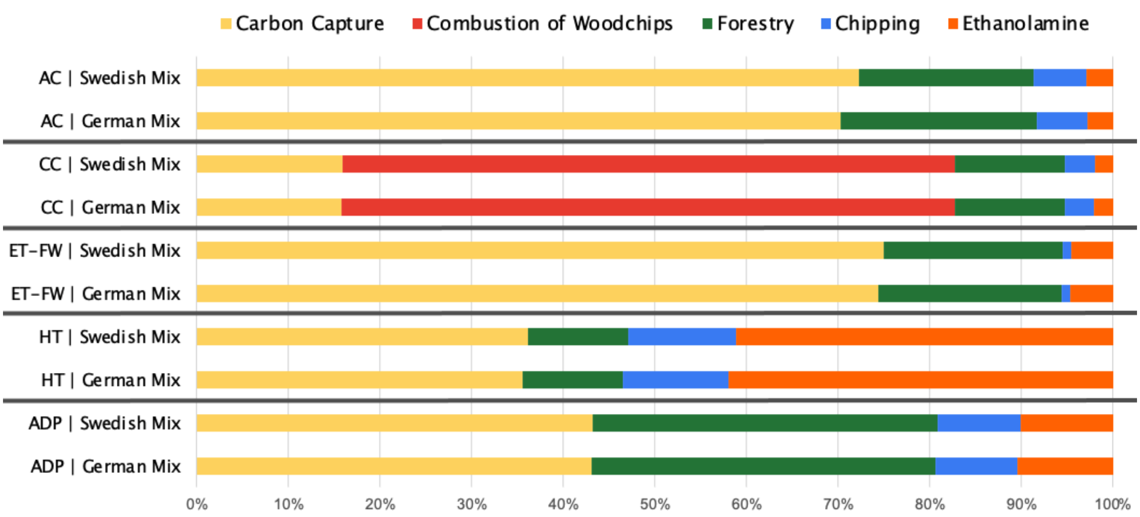


Figure 5.8: Illustrates the environmental impacts associated with the biomass combustion process with the use of carbon capture across the following impacts, Acidification (AC), Climate Change (CC), Freshwater Ecotoxicity (ET-FW), Human Toxicity (HT), and Abiotic Depletion Potential (ADP), considering two different electricity mixtures.

5.2.7 Comparison of Conventional Biomass Combustion vs. Carbon Capture Technology Integration

The environmental impact results for both the biomass combustion process and the biomass combustion process with CCU have been presented in the two previous section, 5.2.5 & 5.2.6. In the following section, a comparison will be conducted to evaluate the differences and implications of integrating carbon capture technology in the biomass combustion process. Similar to the cement production analysis, the comparison will assess the environmental performance of the two processes, with and without CCU. Following the comparison, an analysis, discussion, and conclusions will be drawn based on the findings to provide insights into the potential benefits and drawbacks of incorporating carbon capture in biomass combustion. As stated earlier for a better understanding and interpretation of the environmental impacts and result, please refer to Appendix E.

In the category of acidification, the impacts are minimal for both scenarios, with negligible contributions from the biomass combustion stages and minor contributions from the forestry and chipping stages.

In terms of CC, the biomass combustion process alone contributes to significant CO_2-equivalent emissions for both the German and Swedish mixes. However, incorporating carbon capture technology in the biomass plant reduces the CC impacts, as seen in the lower total emissions. The carbon capture stage plays a crucial role in mitigating climate change impacts by capturing or storing CO_2 emissions.

The assessment of ET-FW demonstrates minimal impacts from the biomass combustion stages, with the German and Swedish mixes showing similar results. The contribution from forestry and chipping stages is relatively small, resulting in low overall ET-FW impacts.

Regarding HT, the impacts are primarily driven by the forestry and chipping stages in both the German and Swedish mixes. However, the overall HT impacts remain relatively low for both scenarios, suggesting a relatively low risk to human health associated with biomass combustion.

For ADP, both the German and Swedish mixes show negligible impacts from the combustion of woodchips, forestry, and chipping stages. The total emissions are relatively low for both scenarios, indicating that the biomass combustion process has limited resource depletion effects.

Analyzing biomass combustion, initial impacts on acidification, freshwater ecotoxicity, human toxicity, and abiotic depletion potential are relatively low. However, integrating carbon capture technology heightens these impacts, except for climate change, where there is a substantial reduction. This underscores the effectiveness of carbon capture in mitigating CO_2 emissions and suggests its potential to enhance the overall environmental performance of biomass combustion processes.

5.3 Further Discussion

It is important to note that further research and analysis are necessary to confirm these observations and explore additional factors that may influence the outcomes, such as the specific carbon capture techniques employed and the associated energy requirements. Additionally, investigating potential synergies between renewable energy expansion and carbon capture technologies could yield insights into optimizing climate change mitigation strategies.

5.3.1 Limitations, Assumptions & Uncertenties

The capture rate of the post-combustion carbon capture, the standardised pressure and temperature, the exclusion of transportations, as well as all of the carbon available within the materials that are being combusted is reacting and becomes CO_2, was made to simplify the analysis and calculations. This may not accurately represent real-world operating conditions, potentially affecting the efficiency and performance of the process. Furthermore, several aspects and complexities associated with carbon capture processes may not be accounted for, affecting the results. Additionally, it is important to note that the analysis was conducted within a limited timeframe of 6 months. This temporal restriction resulted in the exclusion of the circulating MEA within the carbon capture system from our calculations. Specifically, the calculations considered the requirement of 1.3 kilograms of MEA per 1 ton of CO_2 produced as a continuous flow but neglected to account for the 5 tons of MEA that are present in the system and circulated throughout the process.

During calculations in OpenLCA, some processes had to be combined, especially in the case of carbon capture. Due to the software limitations, it was not possible to make a recirculating product system. Therefore, the energy and all other input/output data required for each process had to be combined into one single process. This made it not possible to identify the hotspots for the carbon capture technology itself.

Lastly, the use of different literature sources to gather inventory data introduces uncertainties associated with data quality, reliability, and representativeness. Variations in methodologies, data collection techniques, and system boundaries among the literature sources may impact the overall accuracy of the analysis.

6
Conclusion

This thesis has provided valuable insights into the carbon flows within the PYROCO2 system, focusing on the environmental impacts and carbon capture potential associated with cement production and biomass combustion. By employing an LCA approach and integrating MFA, this study has enhanced our understanding of the carbon capture and purification process, particularly emphasising the post-combustion amino solvent-based approach.

In Scenario (a), dominated by the German electricity mix, the prevalence of fossil carbon in background processes underscores the need to account for emissions from often overlooked contributors. Scenario (b), also with the German mix, highlights the complexity of carbon flows, emphasizing the significant role of biogenic carbon from foreground processes.

Surprisingly, the Swedish case in Scenario (b) mirrors the German results, emphasizing that biomass combustion, a major biogenic source, does not significantly impact carbon flows across different European locations.

In summary, a nuanced approach considering regional factors, background processes, and distinct contributions of fossil and biogenic carbon is vital for comprehensive assessments. These findings emphasize the need for tailored strategies and policies to address the intricacies of carbon emissions within CCU systems.

The study also reveals that integrating carbon capture technology in traditional processes, such as cement production and biomass combustion, leads to a substantial reduction in carbon dioxide emissions, particularly beneficial for climate change mitigation. However, this positive outcome is accompanied by increased impacts in other environmental categories, emphasizing the need for a balanced evaluation.

Regional variations in energy mixes play a crucial role, in influencing environmental performance. The German electricity mix, with higher carbon intensity, results in elevated impacts compared to the Swedish mix, highlighting the significance of tailoring strategies based on local conditions.

6.1 Further Research Suggestions

This thesis serves as a foundation for future studies and initiatives aimed at reducing the environmental impacts of cement production and biomass combustion through carbon capture and utilization. Based on the findings and limitations presented, there are several avenues for further research and development in the field of sustainable carbon capture and utilization:

Data Improvement: Address the limitations of data availability by conducting additional data collection efforts, ensuring higher quality and reliability. This would enhance the accuracy and robustness of future analyses.

Expanded Scope: Explore other types of carbon capture and utilization processes beyond post-combustion amino solvent-based approaches. Investigate alternative capture technologies, such as pre-combustion or oxy-fuel combustion, and their applicability in different industrial contexts.

Regional Variation: Expand the geographic scope of the study to encompass a wider range of regions and industrial settings. This would enable a better understanding of the variations in carbon flows and environmental implications, considering different regulatory frameworks and energy mixes.

Technological Advancements: Investigate emerging technologies and innovations in carbon capture and utilization, such as novel solvents or catalysts, to enhance the efficiency, cost-effectiveness, and scalability of the processes. This could involve experimental studies and pilot projects to assess their feasibility and potential integration with existing industrial systems.

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A

Appendix 1

In this Appendix, all flows and input data from the Aspen HYSYS model simulations are presented. All flows are calculated from the F.U. of 1 metric ton of CO_2 emitted from the system.

A.1 Processes and Flows in the Carbon Capture Process

In this section, an overview of the mass flows, thermodynamic properties, and composition of various streams within the carbon capture process is presented. The tables provide information on mass flows, temperatures, pressures, and molar flows, allowing for a thorough understanding of the system's behaviour and dynamics. Additionally, the composition of each flow is outlined, highlighting the presence of specific compounds and their concentrations. These tables serve as a valuable resource for further analysis and calculation of the environmental impacts associated with the carbon capture process.

Table A.1: Flue gas Stream entering the Absorber

Captured Flue gas Stream entering Absorber	
Conditions	**Value**
Mass Flow [kg/h]	7 479
Temperature [C]	37
Pressure [kPa]	108
Molar Flows [kgmole/h]	270
Components	
Compositions	**Mass fraction**
Carbon dioxide (CO_2)	14%
Water (H_2O)	13%
Oxygen (O)	8%
Nitrogen (N)	65%

Table A.2: Clean exhaust-gas leaving the system

Clean exhaust-gas leaving the system	
Conditions	**Value**
Mass Flow [kg/h]	5725
Temperature [C]	41.59
Pressure [kPa]	101
Molar Flows [kgmole/h]	206.9
Components	
Compositions	**Mass fraction**
Water (H_2O)	4.62%
Oxygen (O)	10.45%
Nitrogen (N)	84.91%

Table A.3: Rich Amine solvent leaving the Absorber

Rich Amine solvent leaving the Absorber	
Conditions	**Value**
Mass Flow [kg/h]	19 300
Temperature [C]	66.64
Pressure [kPa]	108
Molar Flows [kgmole/h]	833.1
Components	
Compositions	**Mass fraction**
Carbon dioxide (CO_2)	7.26%
Water (H_2O)	67.28%
Monoethonolamine (MEA)	25.45%

Table A.4: Rich Amine solvent entering the Stripper

Rich Amine solvent entering the Stripper	
Conditions	**Value**
Mass Flow [kg/h]	19 300
Temperature [C]	110
Pressure [kPa]	330
Molar Flows [kgmole/h]	833.1
Components	
Compositions	**Mass fraction**
Carbon dioxide (CO_2)	7.26%
Water (H_2O)	67.28%
Monoethonolamine (MEA)	25.45%

Table A.5: Lean Amine solvent leaving the Stripper

Lean Amine solvent leaving the Stripper	
Conditions	**Value**
Mass Flow [kg/h]	17 980
Temperature [C]	122.8
Pressure [kPa]	198
Molar Flows [kgmole/h]	794
Components	
Compositions	**Mass fraction**
Carbon dioxide (CO_2)	1.97%
Water (H_2O)	70.70%
Monoethonolamine (MEA)	27.32%

Table A.6: Lean Amine solvent entering the Absorber

Lean Amine solvent entering the Absorber	
Conditions	**Value**
Mass Flow [kg/h]	17 550
Temperature [C]	37.01
Pressure [kPa]	130
Molar Flows [kgmole/h]	770
Components	
Compositions	**Mass fraction**
Carbon dioxide (CO_2)	2.02%
Water (H_2O)	69.98%
Monoethonolamine (MEA)	28.00%

A.2 Heat Flows in the Carbon Capture Process

In the following section, The table below illustrates the heat flows associated with the carbon capture process, specifically for cooling and heating the flows within the process. These heat flows are essential components of the overall energy demand within the process and have significant implications for its efficiency and environmental impact. The presented values serve as inputs for calculating the environmental impacts using openLCA.

Table A.7: Heat Flows and Energy Demand for Cooling and Heating of the Flows in the Carbon Capture Process

Heat Flow	
Process	**Value [GJ/h]**
Flue gas cooler duty	3.139
Cooler	2.887
Stripper reboiler	6.020
Stripper Condenser	2.324

B

Appendix 2

In this appendix, all data and calculations are presented.

B.1 Carbon capture calculations

Since the total outflow of CO_2 is 1 000kg, and the flue gas contains 14% CO_2. The total amount of flue gas capture is estimated to be:

$$\frac{1\ 000 \text{ kg } CO_2}{0.14} = 7\ 142.86 \text{ kg of flue gas} \tag{B.1}$$

Since only 90% of the input is captured, the actual flow rate of flue gas needed would be:

$$\frac{7\ 142.86 \text{ kg of flue gas}}{0.9} = 7\ 936.51 \text{ kg of flue gas} \tag{B.2}$$

C

Appendix 3

In this appendix, physical and chemical constants together with parameters used in the modelling will be presented.

Table C.1: Molar mass

Molar masses		
Substance	**Molar mass [g/mol]**	**Source**
Elements		
Hydrogon (H)	1.0079	(Atkins, 2016)
Carbon (C)	12.010	(Atkins, 2016)
Nitrogen (N)	14.007	(Atkins, 2016)
Oxygen (O)	15.999	(Atkins, 2016)
Silicon (Si)	28.085	(Atkins, 2016)
Iron (Fe)	55.845	(Atkins, 2016)
Component		
Carbon dioxide (CO_2)	44.088	(Atkins, 2016)
Calcium oxide (CaO)	56.077	(Atkins, 2016)
Silicon dioxide (SiO_2)	60.083	(Atkins, 2016)
Monoethanolamine (MEA)	61.080	(Literature)
Calcium carbonate ($CaCO_3$)	100.086	(Atkins, 2016)
Iron (III) oxide (FeO_3)	103.842	(Atkins, 2016)

D

Appendix 4

In this Appendix, detailed inventory data is used in the LCA calculations for both cement production and biomass combustion. These tables present an overview of the inputs and outputs associated with each process. The inventory data serves as a foundation for the environmental impact assessments conducted in this study. By providing this detailed information, the appendix aims to enhance the understanding of the inventory data utilized in the LCA and contribute to the overall understanding of the research.

D.1 Cement Production

In this Section, the table presents the inventory data specifically related to cement production. It includes detailed information on the material inputs, energy consumption, and emissions associated with each stage of the production process. The inventory data for cement production encompasses raw material used to calculate the CO_2 released from the chemical process, and the CO_2, clinker production, and the subsequent grinding and packaging stages.

Table D.1: Cement Inventory

Cement Inventory		
Raw materials	**Mass [kg]**	**Moles**
Limestone ($CaCO_3$)	1485.23	14839.53
Silica sand (SiO_2)	334.18	5561.914
Iron ore (FeO_3)	37.13	357.5694
After Reaction in kiln		
Compositions	**Mass [kg]**	**Moles**
Carbon dioxide (CO_2)	654.25	14839.53
Calcium oxide (CaO)	832.16	14839.53
Silica (Si)	156.21	5561.91
Iron (Fe)	19.97	357.57

D.1.1 Emissions from fuel

Table D.2: Cement Inventory

Emissions from lignite		
Fuel	**Carbon mass fraction [%]**	**Mass [kg]**
Lignite	78	177.89
After combustion		
Compound	**Mass [kg]**	**Moles**
Carbon (C)	509.33	11552.48
Carbon dioxide (CO_2)	654.25	11552.48

D.2 Biomass Combustion

In this section, the inventory data related to biomass combustion is presented, encompassing the inputs and outputs associated with the combustion process. The table includes information on biomass feedstock, energy inputs, emissions, and ash residues generated during the combustion process. The presented inventory data allows for a detailed analysis of the resource requirements, energy consumption, and environmental impacts associated with biomass combustion. By examining the compound compositions and quantities of various emissions, this data contributes to the assessment of the environmental performance and the potential for carbon capture and utilization in biomass combustion processes.

Table D.3: Biomass Inventory

Biomass Inventory		
Raw materials	**Mass [kg]**	**Moles**
Energy wood (50% C)	633.90	26388.13
Fuel		
Compositions	**Mass [kg]**	**Moles**
Petrol (C_8H_{18})	1.24	10.87
Carbon dioxide (CO_2)	0.48	10.87

E

Appendix 5

In this Appendix, all calculated environmental impacts with openLCA are presented in their respective SI-unit.

Table E.1: The total impact for the cement process from each of the chosen impact categories for both Sweden and German electricity mixes.

Environmental impact for the cement process			
Impact category	**Swedish Mix Value**	**German Mix Value**	**Unit**
Acidification	0,35947	0,87783	kg SO2-eq
Climate Change	1453,95353	1792,86599	kg CO2-eq
Freshwater Aquatic Ecotoxicity	29,88222	301,082527	kg 1,4-DCB
Human Toxicity	76,74962	235,52651	kg 1,4-DCB
Abiotic Depletion Potential	513,06836	4249,87581	PER MJ

Table E.2: The total impact for the cement process with carbon capture from each of the chosen impact categories for both Sweden and German electricity mixes.

Environmental impact for the cement process with carbon capture			
Impact category	**Swedish Mix Value**	**German Mix Value**	**Unit**
Acidification	0,49258	1,18425	kg SO2-eq
Climate Change	324,76445	707,41419	kg CO2-eq
Freshwater Aquatic Ecotoxicity	53,27307	355,79378	kg 1,4-DCB
Human Toxicity	214,00562	441,13613	kg 1,4-DCB
Abiotic Depletion Potential	819,95295	4877,97238	PER MJ

Table E.3: The total impact for the Biomass combustion from each of the chosen impact categories for both Sweden and German electricity mixes.

Environmental impact for the cement process with carbon capture			
Impact category	**Swedish Mix Value**	**German Mix Value**	**Unit**
Acidification	0,0841	0,09421	kg SO2-eq
Climate Change	1190,16571	1190,11196	kg CO2-eq
Freshwater Aquatic Ecotoxicity	5,8735	6,04904	kg 1,4-DCB
Human Toxicity	46,69711	46,98071	kg 1,4-DCB
Abiotic Depletion Potential	351,06113	351,6913	PER MJ

Table E.4: The total impact for the cement process with carbon capture from each of the chosen impact categories for both Sweden and German electricity mixes.

Environmental impact for the cement process with carbon capture			
Impact category	**Swedish Mix Value**	**German Mix Value**	**Unit**
Acidification	0,33955	0,34921	kg SO2-eq
Climate Change	173,91147	173,98747	kg CO2-eq
Freshwater Aquatic Ecotoxicity	28,67304	28,89438	kg 1,4-DCB
Human Toxicity	205,99481	209,53091	kg 1,4-DCB
Abiotic Depletion Potential	752,99643	756,5566	PER MJ

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