A Comparative Cradle-to-Gate Life Cycle Assessment of Sweden Cement Industry

Master's Thesis in Sustainable Energy Systems

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Abstract

This master thesis conducts a comparative cradle-to-gate Life Cycle Assessment (LCA) of cement production at the Slite plant, located in Gotland, Sweden. Cement production is recognized as one of the most carbon-intensive industrial processes, contributing approximately 8% of global CO_2 emissions. The study focuses on evaluating the environmental impacts of the traditional cement production process, with particular emphasis on the emissions from clinker production, and compares it with the potential reductions achieved through the integration of Carbon Capture and Storage (CCS) technology.

The research identifies clinker production as the most energy-intensive stage, responsible for the highest CO_2 emissions. The implementation of MEA-based CCS technology at the Slite plant, expected to capture up to 1.8 million tons of CO_2 annually by 2030, is analyzed for its potential to reduce the overall carbon footprint.

The results demonstrate that while CCS significantly lowers CO_2 emissions, the process introduces new challenges, including increased energy consumption and emissions associated with the transport and storage of captured carbon. This LCA provides insights into the feasibility of CCS as a decarbonization strategy and underscores the importance of innovative approaches to reducing emissions in the cement industry, contributing to Sweden's ambition to achieve carbon neutrality in cement production by 2030.

Introduction

For every ton of cement produced, approximately 900 to 1000 kg of CO_2 is emitted, primarily during the heating of limestone and clay to 1450°C—a crucial step in cement production (Andrew 2018). This energy-intensive process makes cement production the second-largest industrial source of carbon emissions, contributing approximately 5–10% of global anthropogenic CO_2 emissions and 3% of total greenhouse gas (GHG) emissions. Additionally, the cement industry is responsible for about 12–15% of total global industrial energy usage. The industry also generates significant air pollutants, including nitrogen oxides (NO_X) and sulfur dioxide (SO_2), which contribute to air quality degradation(Aranda-Usón et al. 2012). CO_2 emissions from cement production are both direct and indirect, where direct emissions mainly result from the calcination of calcium carbonate ($CaCO_3$) to calcium oxide (CaO) during clinker production, while indirect emissions arise from burning fossil fuels for calcination, material processing and transportation (Ige and Oludolapo 2023). Globally, cement factories are among the largest industrial emitters of CO_2, responsible for around 8% of global CO_2 emissions, roughly 40% of these emissions come from fossil fuels combustion, while the remaining 60% result from the process of converting limestone into clinker(Ruiz Sánchez et al. 2021). Achieving carbon neutrality in cement production requires innovative approaches such as Carbon Capture and Storage (CCS) technologies (J. et al. 2017).

Sweden's cement industry is at the forefront of efforts to decarbonize one of the most carbon-intensive sectors globally. With cement production contributing around 8% of global CO_2 emissions, largely due to the high energy demands of clinker production and calcination (Lehne and Preston 2018), the need for sustainable solutions is paramount. In response, Sweden has set ambitious targets to reduce emissions, aiming for a climate-neutral cement industry by 2030 (Fossilfritt Sverige 2019). Leading this effort is the Slite cement plant, operated by Heidelberg Materials, on the island of Gotland. As the largest cement production facility in Sweden, Slite plays a significant role in meeting national demand. In recent years, Swedish cement production has shifted toward lower-carbon alternatives with reduced clinker content, designed to meet growing demand for sustainable construction materials. Additionally, Sweden is pioneering the integration of carbon capture and storage (CCS) technologies, this proactive approach has positioned Sweden as a leader in the transition to fossil-free cement production, contributing to the country's broader climate goals of reducing carbon emissions to making all concrete climate-neutral by 2045 (Fossilfritt Sverige 2019). Despite these advances, significant challenges remain in scaling up low-carbon technologies across the industry, making further research into the environmental impacts and potential solutions essential.

This master's thesis focuses on the cement production process at the Slite cement plant. During 2023, the most produced cement type at Slite was BAS cement, officially known as "Bascement", a Portland-limestone cement (CEM II/A-LL 42.5R) designed to lower its CO_2 footprint (Cementa Heidelberg 2021). By reducing the proportion of clinker in its composition, this cement minimizes limestone consumption and energy use, making it a more environmentally friendly option. It is widely used in Sweden and can be combined with additives like fly ash and ground granulated blast furnace slag to enhance its properties(Cementa Heidelberg 2021).

To further mitigate its environmental impact, the Slite cement plant is planning to implement CCS as part of a larger decarbonization strategy. In 2023, Heidelberg Materials finalized a feasibility study for the Slite CCS project, which outlined a capacity to capture up to 1.8 million tons of CO_2 annually—equivalent to 4% of Sweden's total CO_2 emissions (Heidelberg Materials 2024a). The CCS plant will be situated near a limestone quarry, allowing for efficient energy recovery and logistical operations to transport the captured carbon to the North Sea for storage. Given these developments, this thesis will conduct a Life Cycle Assessment (LCA) cradle-to-gate to evaluate two scenarios: the traditional cement production process and the environmental impact of CCS implementation. The LCA will quantify the total CO_2 emissions and energy consumption during the entire life cycle of producing one ton of BAS cement, offering critical insights into the effectiveness of CCS in reducing the cement industry's carbon footprint.

Accurately representing carbon emissions requires robust data collection across all stages of cement production in Sweden, from raw material extraction and clinker production to grinding and distribution. Emission factors specific to Swedish cement production technologies will offer a detailed measurement for each stage. A foundation for this approach is provided by the study "Evaluation of Carbon Emission Factors in the Cement Industry: An Emerging Economy Context"(Khaiyum et al. 2023) that identifies ten CO_2 emission factors from the literature and ranks them by applying the Bayesian best–worst method (BWM),which is a new benchmarking and multicriteria decision-making (MCDM) method based on various performance indicators(M. and Rezaei 2020). In this context, the results of this comparative life cycle assessment will offer a detailed understanding of the emissions at every stage of production, while the analysis of CCS technology aims to provide practical insights into its potential for reducing the cement industry's carbon footprint. The following sections will outline the specific goals of this research, the methodology employed, and the significance of this work in the context of Sweden's climate objectives. Ultimately, the results of this comparative LCA will support Slite and the broader Swedish cement industry in pursuing effective decarbonization strategies for this heavy industrial sector.

1.1 Aim of the Thesis

The aim of this research is to accurately quantify the emission factors associated with each stage of the traditional cement production process in Slite, Gotland, using life cycle assessment (LCA) methodology. By comparing these emissions with the implementation of carbon capture technology, the study seeks to evaluate the potential reduction in CO_2 emissions and assess the environmental impact of integrating carbon capture and storage (CCS) into Sweden's cement industry. Additionally, the research will explore both the environmental and economic implications of CCS integration and propose effective decarbonization strategies to address the challenges faced in reducing emissions in this sector.

Literature Review

2.1 Definition and purpose of LCA

Life Cycle Assessment (LCA) is a widely adopted, systematic method used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle. This assessment encompasses every stage of the product's life—from raw material extraction, production, and use, to its final storage, a comprehensive view of its ecological footprint. The main objective of LCA is to facilitate informed decision-making regarding sustainability by offering a holistic understanding of the environmental impacts associated with a specific product or system (Guinée 2002).

The methodological framework for conducting an LCA as outlined by ISO 14040 and 14044 standards is shown in Figure 2.1 and consists of four interconnected phases: Goal and scope definition, the life cycle inventory (LCI) compilation, the evaluation of life cycle impacts associated in the whole process (LCIA), and the result interpretation.

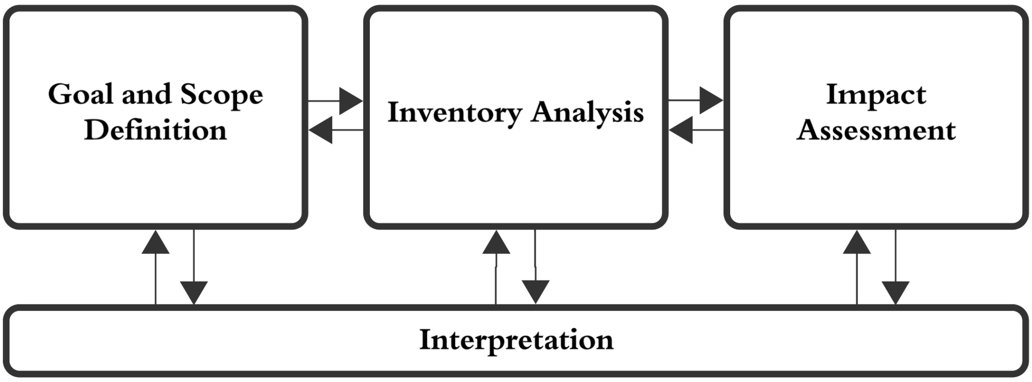

Figure 2.1: LCA Framework

The first phase involves clearly defining the goal of the LCA, which serves as the foundation for the entire study. The goal explains the purpose of the assessment, such as whether it aims to inform internal decision-making, support public disclosure, or comply with regulatory requirements. It also identifies the target audience, which may include internal stakeholders, regulators, or the general public (Guinée 2002). The second phase focuses on collecting data on all inputs and outputs throughout the product's life cycle. This includes raw material extraction, energy usage, emissions, waste generation, and transportation. The LCI phase requires a thorough data-gathering process to build a comprehensive inventory that accurately represents the product or process under study (Carbon Bright 2024)

In the third phase, the environmental impacts of the life cycle inventory data are evaluated. The LCI data is categorized into various environmental impact categories, such as global warming potential, acidification, and resource depletion. Each category quantifies the potential impacts that the process has on the environment, enabling a detailed assessment of its ecological footprint. The impact assessment provides insights into which stages of the life cycle are the most environmentally significant

(Carbon Bright 2024) The final phase involves analyzing the results of the LCA and making informed conclusions. The interpretation phase looks at the data holistically to understand the most significant environmental impacts and identify opportunities for improvement, it also ensures that the study's goals have been achieved, providing clarity for decision-makers (Carbon Bright 2024).

2.1.1 Scope of the LCA

The scope of the LCA defines the depth and detail of the study, ensuring that the goal can be achieved within its limitations. It covers the entire product system, which includes all relevant processes from raw material extraction to disposal or recycling. The scope also outlines key parameters like system boundaries, assumptions, and allocation procedures, ensuring that the study's limits and methodology are clearly defined and understood. Defining the scope ensures the study's feasibility and clarifies its depth and limitations, laying the groundwork for the subsequent phases (Carbon Bright 2024).

2.1.2 Functional Unit

The functional unit is a quantifiable measure of the service provided by the product or system under study. It acts as a reference point for comparisons between different products or processes. In an LCA, it must be clearly specified to ensure consistency and allow for accurate comparison of alternatives (Guinée 2002).

2.1.3 System boundaries and assumptions

System boundaries define which processes are included in the analysis. This can range from raw material extraction to end-of-life stages like recycling or disposal. Assumptions regarding data quality, limitations, and allocation methods must be documented, ensuring transparency and reproducibility. At the same time, the boundaries should align with the goals and limitations of the study(Carbon Bright 2024).

2.1.4 Data Sources and Impact categories

Impact categories refer to the environmental effects being assessed, such as global warming potential, resource depletion, or acidification. The selection of impact categories depends on the study's focus and lays the groundwork for the Life Cycle Impact Assessment phase. These categories quantify the environmental consequences of different life cycle stages and help highlight key areas for improvement (Carbon Bright 2024). While, data sources play a critical role in the LCA, as the accuracy and reliability of results depend heavily on the quality of input data. Databases such as Ecoinvent provide comprehensive, scientifically datasets that cover a wide range of environmental impacts across various industries, ensuring consistency and comparability in LCA studies. The choice of the right data source is crucial for accurately representing the processes and materials in a specific industry, as using incorrect or outdated data can lead to misleading conclusions.

2.1.5 Life Cycle Inventory (LCI)

As previously mentioned the Life Cycle Inventory phase involves collecting detailed data on the inputs (e.g., raw materials and energy) and outputs (e.g., emissions and waste) throughout the system's life cycle. A flow model is created to represent the technical system, and data is gathered for each process within the system boundaries. This data is then validated and aggregated to provide a comprehensive inventory of material and energy flows (Carbon Bright 2024)

2.2 Cement Production Process

Cement production is a key industrial activity in Sweden, serving the needs of the construction sector. However, it is also one of the most energy-intensive industries, contributing significantly to CO_2 emissions. In Sweden, the cement industry primarily relies on domestic sources for its raw materials, such as limestone, clay, and iron ore, which are critical for clinker production. Swedish cement plants are implementing advanced technologies to improve energy efficiency and reduce emissions. Nevertheless, the cement manufacturing process remains a substantial source of greenhouse gases, particularly from the high-temperature clinker production stage. As a result, cement companies in Sweden are increasingly exploring Carbon Capture and Storage (CCS) technologies as part of their decarbonization strategies to mitigate climate impacts (Millar 2017)

2.2.1 Raw Material Extraction and Preparation

The production of cement begins with the extraction and preparation of raw materials, the most important of which is limestone, accounting for around 60-70% of the raw mix. In Sweden, limestone is primarily sourced from quarries located near cement plants to reduce transportation costs, other essential raw materials include clay, marlstone, sand, and iron ore, which are added to adjust the chemical composition of the clinker (Worrell 2014). After extraction, these raw materials are crushed and blended in the correct proportions to form a raw meal, which is then finely ground to achieve uniform particle size. This mixture is stored in silos to ensure homogeneity before being fed into the kiln. The pre-treatment of raw materials consumes a significant amount of energy, particularly during the grinding process, which typically requires 25-30 kWh per ton of material processed, moreover, the dust control and water usage are critical at this stage to minimize environmental impacts (Worrell 2014).

2.2.2 Clinker Production

Clinker production is the most energy-intensive and environmentally critical stage of the cement manufacturing process. The raw meal prepared in the previous step is heated in rotary kilns to temperatures as high as 1450°C, resulting in a series of chemical reactions known as calcination. During calcination, limestone ($CaCO_3$) breaks down into calcium oxide (CaO) and CO_2 (Worrell 2014). Clinker production accounts for approximately 90% of the energy consumed in cement production, mainly due to the high thermal energy required to reach the necessary reaction temperatures. Typically between 3.2-3.5 GJ of energy is needed to produce one ton of clinker, and the amount of clinker required to produce cement depends on the type and quality of cement (Worrell 2014). Moreover, the combustion of fossil fuels such as coal, petcoke, or natural gas in the kiln contributes significantly to CO_2 emissions, alongside the CO_2 released directly from the calcination of limestone. The produced clinker is then cooled rapidly to preserve its reactive properties before being stored for the final stages of cement production.

2.2.3 Cement Production

After the clinker has cooled, it is mixed with small amounts of gypsum and other additives to control the setting time of the cement. The amount and type of additive used depend on the specific type of cement being manufactured, for example, cement types such as CEM II/A may contain significant amounts of fly ash or slag, which helps to reduce the clinker content, thus lowering the CO_2 emissions per ton of cement (Worrell 2014). The mixture is then finely ground in mills to produce the final cement powder. This grinding process can use ball mills or vertical roller mills, depending on the plant setup, and is another energy-intensive process, with electricity consumption ranging from 28 to 55 kWh per ton, depending on the fineness and types of additives used (Worrell 2014).

2.2.4 Energy and Fuels Consumption

Energy consumption is a critical factor in the overall environmental impact of cement production. The cement industry in Sweden has historically relied on fossil fuels such as coal, petcoke, and heavy fuel oil to meet the high thermal energy requirements of clinker production (Voldsund et al. 2018). However, in recent years, there has been a shift towards using alternative fuels, including waste-derived fuels, to reduce reliance on fossil fuels. These alternatives include solvents, waste oils, and plastic-based fuels, which are used in cement kilns as part of Sweden's efforts to increase sustainability in the sector(Heidelberg Materials 2024b). The use of high-efficiency technologies such as preheaters, precalciners, and waste heat recovery systems has further improved energy efficiency. Typically, around 3.0-3.5 GJ of thermal energy is required to produce one ton of clinker, while electricity consumption can range from 80 to 100 kWh per ton of cement. Despite these improvements, fuel combustion remains a major source of CO_2 emissions, accounting for approximately 40% of the total emissions in cement production.

2.2.5 Carbon Capture and Storage (CCS) Technologies

Carbon Capture and Storage (CCS) technologies are increasingly seen as a viable solution for mitigating the CO_2 emissions associated with cement production. It involves capturing CO_2 emissions before they are released into the atmosphere, compressing the captured CO_2, and transporting it to storage sites, where it is injected into deep geological formations for long-term sequestration. In cement production, CO_2 is emitted both from the calcination of limestone and from the combustion of fuels in the kiln. CCS can capture up to 90-95% of these emissions, significantly reducing the carbon footprint of cement plants. Although CCS is still in the early stages of deployment in the cement industry, several pilot projects in Europe, including in Sweden, are investigating its feasibility. The main challenges associated with CCS are the high energy demands for CO_2 capture and compression, as well as the costs of installing and operating the technology (Einbu et al. 2022). In Slite case, the CCS technology that will be implemented by 2030 is the monoethanolamine (MEA)-based carbon capture, one of the most widely proposed methods for post-combustion CO_2 capture in industries such as cement production. MEA is an amine-based solvent that absorbs CO_2 from flue gases after combustion. The CO_2-rich solvent is then heated to release the captured CO_2, which is subsequently compressed and prepared for transport to storage facilities (Einbu et al. 2022). However, the process is energy-intensive, particularly during solvent regeneration, where significant heat is required. Once captured, the CO_2 is typically compressed into a liquid state and transported, often by ship, to long-term storage sites in geological formations.

Cement Production Process at Slite, Gotland.

3.1 Cement Process at Slite

The following description of the cement production process is based on information from (Heidelberg Materials Cement Sverige AB 2023), with an overview of how the process will look like with the CCS implementation, shown in Figure 3.1. The cement production process at Cementa's Slite plant is a highly structured operation that begins with limestone extraction from nearby quarries. The limestone mined is first crushed to approximately 80 mm in size at the quarry itself before being transported via conveyor belts to the plant's stone storage facility, located at the Eastern Quarry. This storage area serves as a buffer to ensure continuous operation, as well as a mixing point to help achieve uniform raw material quality before it enters the production process.

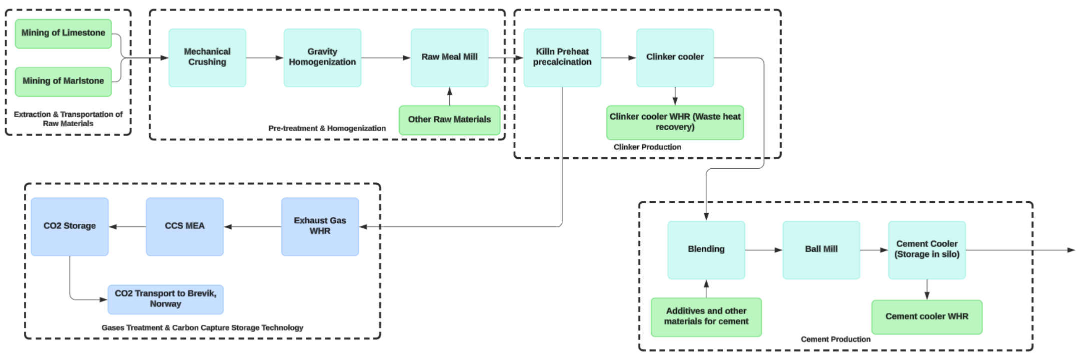

Figure 3.1: Cement Production Process at Slite

Once transported to the factory, the crushed limestone is combined with other essential raw materials, including those rich in silicon, aluminum, and iron, in a raw mill. These materials are finely ground into a homogeneous powder known as "raw meal," that is temporarily stored in silos before being transferred to the cyclone tower and kiln, the central components of the clinker production process. The production of clinker, which is the key intermediate product in cement manufacturing, takes place in a rotary kiln—a long, rotating furnace that heats the raw meal to temperatures as high as 1,450°C (Gäbel et al. 2004). This process is critical, as it causes the calcium from the limestone to react with silicon, aluminum, and iron to form clinker minerals. Before reaching the kiln, the raw meal passes through the cyclone tower, where it is preheated to about 900°C, and undergoes calcination, a process in which carbon dioxide (CO_2) is released from the limestone. This preheating and calcination process allows for more efficient energy use within the kiln, as the partially treated raw meal meets the hot gases flowing in the opposite direction (Heidelberg Materials Cement Sverige AB 2023).

Therefore, inside the kiln, the raw meal undergoes further heating and is transformed into clinker—small particles. These clinkers are then cooled rapidly in an air-based cooling system before being stored in silos or transported to the cement mills for further processing. The final step involves grinding the clinker with a small amount of gypsum, producing the fine powder known as Portland cement. Additional materials, such as fly ash or blast furnace slag, may also be interground to produce blended cement varieties, depending on the desired cement composition(Gäbel 2001). Throughout this process, significant attention is given to minimizing environmental impact. Emissions, especially carbon dioxide, sulfur dioxide, nitrogen oxides, and dust, are key concerns due to the fuel combustion and calcination involved in clinker production. To mitigate these emissions, the Slite plant employs a variety of pollution control measures, including electrostatic precipitators, selective non-catalytic reduction (SNCR) systems for nitrogen oxides, and a flue gas desulfurization system to reduce sulfur dioxide. Additionally, a scrubber system is in place to capture SO_2 emissions, using a slurry of limestone and water, which is subsequently used as gypsum in the cement grinding process (Heidelberg Materials Cement Sverige AB 2023).

Energy efficiency is another focus area for the plant. Waste heat from the kiln and cooler systems is recovered and used to dry raw meal and coal, as well as to generate steam for both current operations and the planned carbon capture and storage (CCS) facility. The Slite plant's infrastructure includes not only production facilities but also significant logistics capabilities, with conveyor belts, silos, and storage areas dedicated to raw materials and finished products. The proximity to the company's harbor facilitates the transport of raw materials and fuels to the plant and allows bulk cement shipments to be distributed efficiently by sea.

3.2 Carbon Capture Technology MEA-based

The CCS technology is aimed at capturing CO_2 produced during the calcination of limestone and fuel combustion—processes central to cement production. The selected technology relies on the use of an amine-based absorption system, which is recognized for its effectiveness in capturing CO_2. Amines are chemical compounds that can bind with CO_2, making them well-suited for the capture process in this context (Heidelberg Materials Cement Sverige AB 2023). As seen in Figure 3.2, the capture process begins with the flue gases, which are first cooled to enhance the absorption efficiency of the amine solution. This cooling takes place in a direct contact cooler, where the gases are brought to a temperature optimal for CO_2 capture. During this step, water vapor present in the gases condenses into water, which can be reused within the production cycle after purification (Heidelberg Materials Cement Sverige AB 2023).

Once cooled, the flue gases are directed to an absorber column, where an amine-based absorbent solution is introduced. As the gases move upwards, they interact with the absorbent solution, which captures the CO_2 CO_2-laden amines then separate from the rest of the flue gases, which, now cleaned of most of their CO_2, are released into the atmosphere (Heidelberg Materials Cement Sverige AB 2023). The captured CO_2, bound to the amines, is then sent to the next stage of the process.

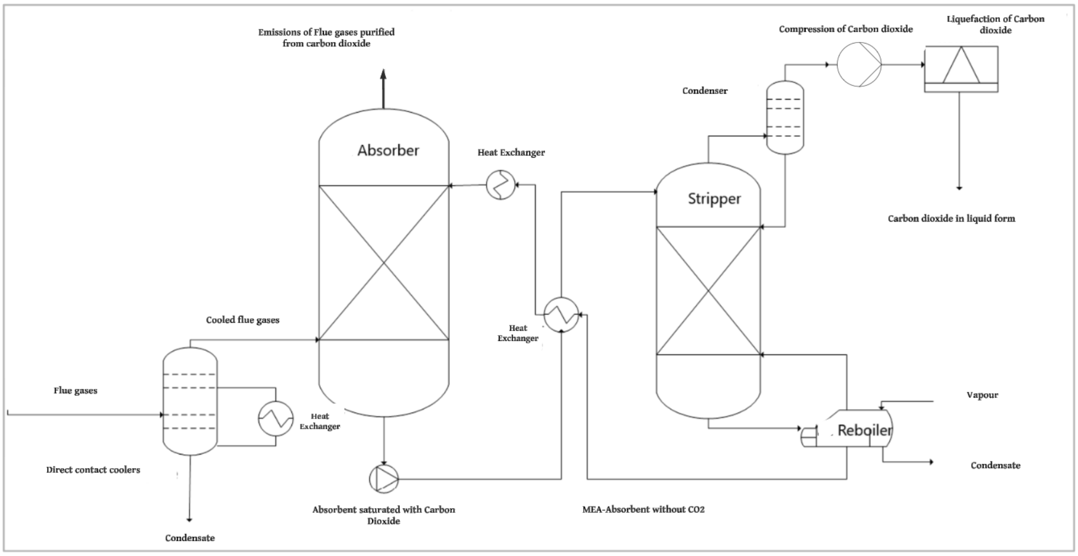

Figure 3.2: Carbon Capture MEA-based Schematic (Heidelberg Materials Cement Sverige AB 2023)

The saturated amine solution is transported to a heat exchanger, where it is heated before being transferred to a device known as a stripper. In the stripper, the solution is further heated to release the captured CO_2. The stripped amine solution, now free of CO_2, is recycled back into the process to capture more carbon dioxide. The heating required in this step is typically supplied by waste heat or heat pumps, further improving the process's energy efficiency (Heidelberg Materials Cement Sverige AB 2023).

After the CO_2 is separated from the amine solution, it is compressed and liquefied for storage and transport. This liquefied CO_2 will be stored on-site at the Slite facility before being transported to a long-term storage site beneath the seabed (Heidelberg Materials Cement Sverige AB 2023). Initially, the captured CO_2 will be transported to the Heidelberg site in Brevik, Norway, for permanent storage. The planned CCS system at Slite will aim to capture and transport around 400,000 tons of CO_2 annually to the Brevik site as part of a larger effort to reduce the environmental impact of cement production (Heidelberg Materials 2024a).

Life Cycle Assessment - Slite

In this chapter the LCA of cement production process at Slite is described in order to understand the environmental impact of this process, the research focus on CO_2 emissions from cradle-to-gate in the context of Sweden's covering all stages of cement production, from raw materials extraction to the storage of the cement used in construction, and compare it with a LCA considering the MEA-based CCS technology on the cement production process.

4.1 Goal and Scope of the LCA

In this master's thesis, the LCA methodology is applied to accurately assess carbon dioxide (CO_2) emissions at each stage of the traditional cement production process in Slite, Sweden. This study not only identifies the most environmentally impactful stages but also evaluates the potential reduction of CO_2 emissions through the integration of carbon capture and storage (CCS) technology. This MEA-based CCS technology aim to capture up to 1.8 million tons of CO_2 per year by 2030 at Slite, but it is essential to consider that this process is not without emissions, CCS technology is subject to efficiency losses, and there are emissions associated with energy use, electricity consumption, and the transportation of CO_2 in liquid form to storage locations, such as seabeds or dedicated facilities (Burger et al. 2024).

Given the substantial impact of cement industry, accurately representing the current emissions and exploring viable solutions to mitigate its environmental footprint is crucial. In Sweden, this is particularly relevant as the country aims to establish the world's first climate-neutral cement factory in Slite by 2030 (Heidelberg Materials 2024a). This initiative is part of Sweden's broader ambition to create a fossil-free competitive industry. The goal of this LCA is to analyze and compare both: the conventional cement production and the scenario with CCS implementation, this analysis is expected to provide valuable insights for decision-making on decarbonization strategies in the cement industry.

The Life Cycle Impact Assessment in this study is executed through the integration of all inventory data into the OpenLCA software, complemented by the Ecoinvent Database version 3.1 cut-off along with reasonable assumptions and substitutions to reflect real-world scenario accurately. As noted by (Guinée 2002), LCA serves as a critical tool for guiding environmental policy and industrial strategies by providing detailed assessments of the life cycle impacts of various products and technologies.

The scope of this Life Cycle Assessment (LCA) is comprehensive, covering the entire product life cycle from cradle-to-gate i.e., this analysis encompasses the environmental impact of all raw materials, including their extraction, transportation (for imported materials), processing, till the production, and final storage of cement. The transportation of liquefied CO_2 to Heidelberg Materials facility in Brevik, Norway, is considered when assessing the implementation of CCS technology in the LCA. Therefore, the emissions associated with transportation are also evaluated.

4.1.1 Functional Unit

In this Life Cycle Assessment (LCA), the functional unit for both approaches is defined as 1 tonne of cement. For the first approach, which assesses the traditional cement production process, the functional unit encompasses the entire production process from raw material extraction to the final cement product. In the second approach, where the system boundaries extend only to clinker production—the stage with the highest CO_2 emissions—the functional unit remains 1 tonne of cement. However, this approach considers the implementation of carbon capture and storage (CCS) technology starting from the clinker production stage, which captures CO_2 before the cement production is completed. This allows for a consistent comparison of environmental impacts across both systems while accounting for the effect of CCS on emissions reduction.

4.1.2 System Boundaries

The Life Cycle Assessment (LCA) of the traditional cement production process includes the following stages: the extraction of the primary raw materials (limestone and marlstone), the preparation of the raw meal with necessary additives, the clinker production process, and cement grinding up to its storage in silos. Whilst, the LCA with the implementation of the Carbon Capture and Storage (CCS) technology considers the extraction of raw materials, the preparation of the raw meal, and in the clinker production there is an exhaust gas stream that is treated before going to the process of carbon capture described on section 3.2. At this point, the flue gases containing CO_2 are captured and processed for storage. In this scenario, the system boundary is cradle-to-gate, where the "gate" extends to the storage of the captured CO_2 at Brevik, Norway, since the initial plan involves transporting the captured CO_2 to facilities there.

For simplicity, the LCA analysis is divided into three main processes: the first stage covers the extraction, transportation, and pre-homogenization of raw materials to produce the raw meal. The second stage is the clinker production process, and the third stage encompasses cement grinding and storage.

This LCA is based on 2023 material flow data of the whole process provided by the Swedish Environmental Institute (IVL).

4.1.3 Impact Categories

In this Life Cycle Assessment (LCA) of cement production, the ReCiPe 2016 methodology was selected, focusing on midpoint indicators. This approach enables a detailed assessment by examining specific environmental impacts, which are particularly relevant for evaluating the processes involved in cement production, including raw material extraction, clinker production, and carbon capture and storage (CCS) implementation.

For the LCA of the traditional cement production process, several impact categories are analyzed. These include global warming potential (GWP), which accounts for the emissions of CO_2 and other greenhouse gases. Cement production, especially during the clinker production stage, is a significant contributor to CO_2 emissions, as it involves both fuel combustion and the calcination of limestone. Other key impact categories include acidification and eutrophication, which result from the release of nitrogen oxides (NO_x) and sulfur oxides (SO_2) during the high-temperature combustion processes in the kiln. These emissions can contribute to environmental issues such as acid rain and nutrient pollution in aquatic ecosystems.

The ReCiPe method also assesses photochemical ozone formation, terrestrial ecotoxicity, and freshwater ecotoxicity, which are influenced by the release of volatile organic compounds (VOCs) and other pollutants from the cement manufacturing process. Additionally, categories like abiotic depletion highlight the consumption of fuels used in kiln operations and raw material extraction.

Impact Category	Definition	Unit
Abiotic Depletion	referred to the consumption of non-biological resources such as fossil fuels and minerals	kg Cu eq and kg oil eq
Terrestrial Acidification	Increase in soil and water acidity due to acidifying emissions	kg SO_2 eq
Marine Eutrophication	Nutrient enrichment in marine environments, causing algal blooms and water quality issues	kg N eq
Global Warming Potential	Contribution of emissions to the greenhouse effect and climate change	kg CO_2 eq
Photochemical Oxidation	Type of smog created from the effect of sunlight, heat and NMVOC and NO_x	Kg NO_x eq

Table 4.1: Impact Categories in Cement Production LCA

4.1.4 Data Collection and Analysis

The majority of the data used in this study was sourced from IVL and official reports available on the company's website. This data was cross-verified with several LCAs conducted for cement industries across European plants. Electricity consumption for each stage of the process was derived from a literature review, taking into account the total electricity usage of the factory. In cases where data was limited or unavailable, estimations and assumptions were made based on literature, and consultations were held with experts at IVL. As the CCS technology is not yet implemented, all data related to it was sourced entirely from relevant literature.

4.1.5 Assumptions and Constraints

- All quantities of raw materials, fuel consumption, and energy use are calculated based on the requirements to produce one ton of cement.
- Electricity consumption for each stage is assumed based on a literature review of various processes and compared to the plant's current electricity usage of 45 MW.
- Most data in the LCA is sourced from Europe or Switzerland, as these regions provide the most comprehensive datasets.
- The initial analysis does not account for the flow of captured CO_2.
- An average fuel transport distance is assumed, based on maritime data showing that heavy fuel oil is delivered to Slite from Cyprus several times.
- Material transport, such as gypsum, is assumed to originate from ports between France and the Netherlands, based on records of cargo ships arriving at Slite from these countries.
- The environmental impact of the carbon capture technology is assessed using theoretical values from the literature, assuming a 95% CO_2 capture efficiency for the CCS technology.
- The factory operates year-round, with the exception of a 28-day shutdown for maintenance, totaling 8,088 operational hours annually.
- Raw materials, fuels, and cement additives are traced upstream to their extraction as natural resources. Alternative materials, fuels, and additives are considered by-products or waste from other systems, but their production is not included in the LCA. However, transport for use in cement production is included.

The production and maintenance of equipment for manufacturing and transport, the extraction and production of alternative raw materials, fuels, and cement additives, and the working materials like explosives, grinding media, and refractory bricks, are not consider under the scope of this study.

4.1.6 Sensitivity Analysis

Based on the LCA results incorporating CCS, a sensitivity analysis will be conducted to evaluate the potential decrease in carbon capture efficiency. While literature suggests that the process can achieve up to 95% efficiency, this figure may be lower at an industrial scale. The analysis will help inform decision-making and develop strategies to optimize the CCS process and reduce emissions associated with it.

4.2 Life Cycle Inventory

The following sections present detailed explanations of the development of the Life Cycle Inventory (LCI) and the Life Cycle Assessment (LCA) model for each system. The assessment considers the impact of extracting raw minerals (limestone and marlstone), making clinker, and producing cement, but it does not consider its end use, the study only focuses on it until it is stored. In the case for the carbon capture technology, it is included in its analysis.

4.2.1 Data Collection Methodology

For the data collection, the flowchart in Figure 4.1 illustrates the system boundaries for the first LCA iteration, detailing the various processes involved in cement production at Slite. The second flowchart, shown in Figure 4.2, represents the system with the inclusion of the CCS process and its transportation to Brevik, Norway. Both cases focus on the production of clinker and cement at Slite – Gotland during 2023, considering the quantity of additives used and imported, as well as the fuels specifically employed in the clinker production stage. At this stage, several types of fuels are used for the calcination process. As part of Slite's efforts to reduce emissions from this energy-intensive process, the use of waste, used tires, and converted fuel oil has increased, as these alternatives generate fewer emissions compared to traditional fossil fuels (Heidelberg Materials 2024b). The flow-material rates for these processes were provided by IVL and were compared with official reports on Slite's production and emissions data from previous years.

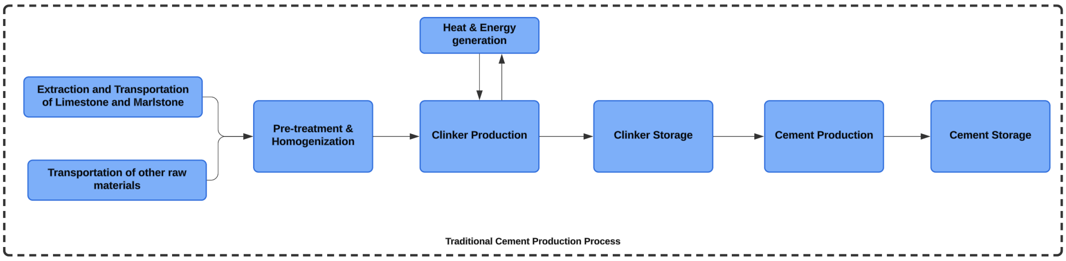

Figure 4.1: System Boundaries - LCA Cradle-to-Gate of Traditional Cement Production Process

The fuel and electricity data for other stages of the process were gathered from multiple LCAs conducted at cement production plants across Europe. Additionally, previous assessments carried out in 2001 on the Slite plant were reviewed. This information was cross-checked with the historical production data from the Slite plant to ensure accuracy (Gäbel et al. 2004).

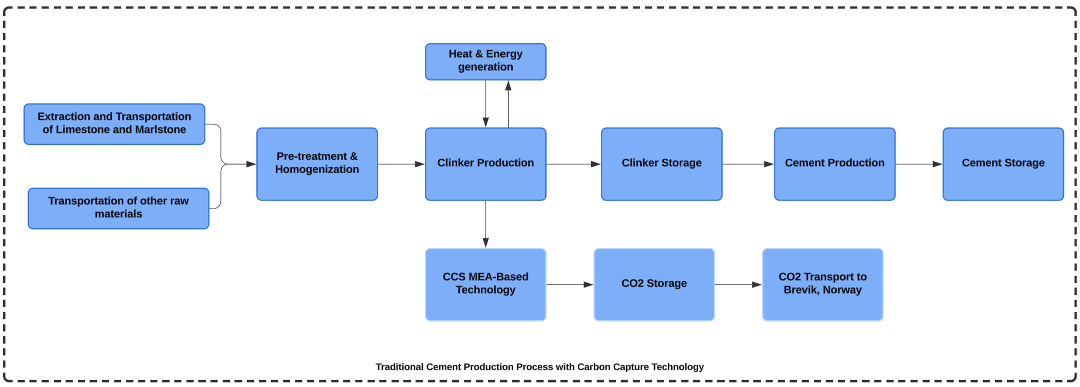

Figure 4.2: Boundaries System - Cradel-to-gate of Traditional Cement Production Process with CCS

Following these procedures, the model was set up in OpenLCA, divided into three main stages for the traditional process: 1) Extraction, transportation, crushing, and pre-homogenization; 2) Clinker production; and 3) Cement production. The selection of input and output flows is presented in section A.1. For the second iteration, the same stages were included, with the addition of the carbon capture storage technology. The inputs and output flows for this iteration are shown in section A.2.

After cross-checking the data with previous studies and official reports from Slite, all quantities were standardized based on the amount required to produce one ton of cement. By dividing the amount of each additive used in 2023 by the total cement production during the same year, standardized values were obtained. For example, the clinker-to-cement ratio was calculated using the standard equation:

$$\text{Clinker-to-cement ratio} = \frac{\text{Total clinker produced (2023)}}{\text{Total cement produced (2023)}}$$

Since the functional unit was defined as one tonne of cement for both cases. Accordingly, the electricity and energy consumption for each stage was recalculated based on specific references, which will be detailed in the inventory.

4.2.2 Inventory for the LCA - Cement Production at Slite with Carbon Capture Storage

The following is the detailed inventory of inputs concerning the cement production process at Slite, the "input" column represents the raw materials as they were described in the previous section section 3.1, while the “inputs" in the model setup were the ones used in Open LCA section A.1 based on the available items on the ecoinvent database. The source of each value is also shown in the inventory table.

Extraction and Transportation of raw materials				
Input	**Quantity**	**Quantity (per 1 ton of cement)**	**Unit**	**Source**
Limestone mined	1 072 916	0,576	t/yr	Data provided from IVL
Marlstone mined	321 235	0,1801	t/yr	Data provided from IVL
Total Raw Material	1 394 151	0,781	t/yr	Data provided from IVL
Fuel for quarry and crushing	16,4	0,3814	MJ/yr	(Region Gotland 2024)
Electricity for raw material grinding	34 853 775	18,54	kWh/ton of raw material	(Valderrama et al. 2012)
Average distance from port (Chemical/Oil tanker)	2 400	-	km	(VesselFinder 2024)
Transportation of fuel	-	0.915	ton-km	(VesselFinder 2024)
Pre-treatment, Crushing and Homogenisation				
Input	**Quantity**	**Quantity (per 1 ton of cement)**	**Unit**	**Source**
Limestone	1 619 351 916	0,861	t/yr	Data provided from IVL
Marlstone	1 010 120	0,537	t/yr	Data provided from IVL
Iron ore/Iron oxide	39 814	0,021	t/yr	Data provided from IVL
Slagg	162 906	0,087	t/yr	Data provided from IVL
Bauxite	3 187	0,002	t/yr	Data provided from IVL
Sand	114 606	0,061	t/yr	Data provided from IVL
Total Raw Material	2 949 984	1,569	t/yr	Calculated value based on sum of raw material quantities
Raw meal (mass balance from raw material used)	2 920 484	-	t/yr	Assuming 1% loss
Electricity for raw material preparation	35	54,91	kWh/ton of raw material	(Worrell 2004)

Table 4.2: Inventory Standardized for the stage of Extraction and pre-treatment of raw material

Clinker Production				
Input	**Quantity**	**Quantity (per 1 ton of cement)**	**Unit**	**Source**
Raw Meal	2 920 484	1,569	t/yr	Value calculated
Fossil fuel from plastic waste	73 113 000	38,88	kg/yr	Data provided from IVL
Biogenic	80 021 000	42,56	kg/yr	Data provided from IVL
Converted Fuel Oil	1 602 000	0,85	kg/yr	Data provided from IVL
A/C Fuel	2 460 000	1,31	kg/yr	Data provided from IVL
Tyres	13 464 000	7,16	kg/yr	Data provided from IVL
Petcoke	2 900 000	1,54	kg/yr	Data provided from IVL
Coal	108 473 000	57,69	kg/yr	Data provided from IVL
Average distance from different ports in Europe	1 766,67	-	km	(VesselFinder 2024)
Transportation fuel consumption	-	154,84	ton-km	(VesselFinder 2024)
Average electricity	17 - 23	36,08	kWh/ton clinker	(Worrell 2004)
Output	**Quantity**	**Quantity (per 1 ton of cement)**	**Unit**	**Source**
Clinker	1 785 540	0,95	t/yr	Value calculated
Carbon dioxide	1 511 971 000	804,7	kg/yr	Data provided from IVL
Nitrogen Oxides	1 023 689	0,544	kg/yr	Data provided from IVL
Sulphur Oxides	143 320	0,076	kg/yr	Data provided from IVL
Carbon Monoxides	4 910 299	2,611	kg/yr	Data provided from IVL
Electricity generated	14,8	-	kWh/yr	Data provided from IVL
District heating generated	14,3	-	kWh/yr	Data provided from IVL

Table 4.3: Inventory Standardize for the stage of Clinker Production

Cement Production				
Input	**Quantity**	**Quantity (per 1 ton of cement)**	**Unit**	**Source**
Clinker	1 785 540	0,95	t/yr	Value calculated
Gypsum	86 631	0,046	t/yr	Data provided from IVL
Iron sulfate	9 891	0,0053	t/yr	Data provided from IVL
Fly ash	65 849	0,0350	t/yr	Data provided from IVL
Average distance from different ports in Europe	1 700	-	km	(VesselFinder 2024)
Transportation of additives fuel consumption	-	78,32	ton-km	Value calculated
Average electricity (ball mill, finish grinding, conveyor belts and packing cement	32-37; 28-41; 10	85	kWh	(Worrell 2004) (Valderrama et al. 2012)
Output	**Quantity**	**Quantity (per 1 ton of cement)**	**Unit**	**Source**
Cement	1 880 350 540	1	t/yr	Value calculated

Table 4.4: Inventory Standardized for the stage of Cement Production

4.2.3 Inventory for the LCA - Carbon Capture Storage Technology

Based on the feasibility study by Gassnova, it is assumed that the ship used for transporting the captured CO_2 from Slite to Brevik is a low-pressure vessel with a capacity of 6,000-7,700 m^3, operating at 6-8 bar and -50°C, with the CO_2 density estimated at 1,100 kg/m^3 (Gassnova 2016). Given the annual transport requirement of 400,000 tons of CO_2, as indicated on the Slite website, the number of trips per year is calculated based on the ship's capacity and the CO_2 density. Additionally, according to the same source, a distance of 1,034.64 km is assumed for the route from Slite to Brevik, allowing for the calculation of the ton-kilometer (ton-km) demand factor, which is critical for assessing the energy and emissions associated with the transport phase (Einbu et al. 2022; Al Baroudi et al. 2021). This estimation helps inform the overall energy requirements and environmental impact of the CO_2 transportation process as part of the CCS chain

Carbon Capture Technology			
Input	**Quantity**	**Unit**	**Source**
Carbon Dioxide from exhaust gas	1 511 971	t/yr	Data provided from IVL
CO_2 per ton of cement	804,09	kg/yr	Value calculated
CO_2 captured per ton of cement	0,7639	t/yr	Value calculated
Efficiency	95 %	-	(**AlBaroudi2021**)
Density of CO_2	1 100	kg/m^3	(Al Baroudi et al. 2021)
Fuel Consumption (Amine use)	4,0 %	MJ/kg CO_2	(**AlBaroudi2021**)
Distance from Slite to Brevik port in Norway	1 150	km	(MyShipTracking 2024)
CO_2 captured	1 436 372,45	t/yr	Calculated with the efficiency of the CCS process
CO_2 to be transported to Brevik	400 000	t/yr	(Slite CCS 2024)
Electricity consumption for compression of CO_2	110	kWh/ton liquid CO_2	(**AlBaroudi2021**)
Capacity of Ships to transport CO_2 (Low pressure - [6 000 - 7 700 m^3 and 6 - 8 bar @-50°C]	7 535	ton liquid CO_2 /ship	(Gassnova 2016)
CO_2 captured transported per km	7 795 999,74	ton-km/trip	Calculated with the efficiency of the CCS process
Number of trips per year to transport the 400 000 tons	54	trips	Calculated based on the capacity of the low pressure ship (Gassnova 2016)
Transported demand of CO_2 Slite to Brevik	420 983 986,02	ton-km/yr	Calculated with the ton-km/trip x of trips
Electricity consumption of CO_2 captured/ton of cement	0,881	MWh	(Al Baroudi et al. 2021)
Output	**Quantity**	**Unit**	**Source**
CO_2 emissions (not captured) per ton of cement	0,0420	t/yr	Value calculated

Table 4.5: Inventory Standardized for the stage of Carbon Capture Storage Technology

Life Cycle Impact Assessment Results

5.1 Results of Traditional Cement Production Process at Slite

The results for the indicators mentioned in Table 5.1 are presented below, all based on producing 1 tonne of cement. The results correspond to the base case of traditional cement production at Slite, where energy demands are met using a mix of fuels as mentioned in previous sections. The contributions of each process to the different impact categories and indicators are illustrated in Figure 5.1.

Impact Category	**Total Ammount**	**Unit**
Abiotic Depletion	2,20 and 94,74	kg Cu eq and kg oil eq
Terrestrial Acidification	0,354	kg SO_2 eq
Marine Eutrophication	0,00354	kg N eq
Global Warming Potential	911,156	kg CO_2 eq
Photochemical Oxidation (Human health)	0,341	Kg NO_x eq
Photochemical Oxidation (Terrestrial ecosystems)	0,352	Kg NO_x eq

Table 5.1: Impact Categories results in traditional Cement Production LCA

In the context of Life Cycle Assessment (LCA), impact categories like global warming potential, eutrophication, acidification, and photochemical oxidation play a critical role in assessing the environmental footprint of industrial processes like cement production. Photochemical oxidation, measured in kg NO_x eq, is particularly relevant due to the significant NO_x emissions generated during the production process. For this specific cement production process, the highest contributions to photochemical oxidation originate from the clinker production stage. This is primarily due to the high-temperature requirements for the calcination of limestone, which leads to substantial NO_x emissions as a byproduct (International Energy Agency 2018; WBC for Sustainable Development 2018). Following this, the extraction, transportation, and pre-homogenisation stages also contribute significantly to photochemical oxidation, largely because of the fuel consumption and machinery emissions during raw material handling (United Nations Environment 2020). The transportation of additives from various ports of Europe to the Slite site further adds to the impact, as does the market for heavy fuel oil and petroleum products, which are used as energy sources throughout the process (Gartner 2019).

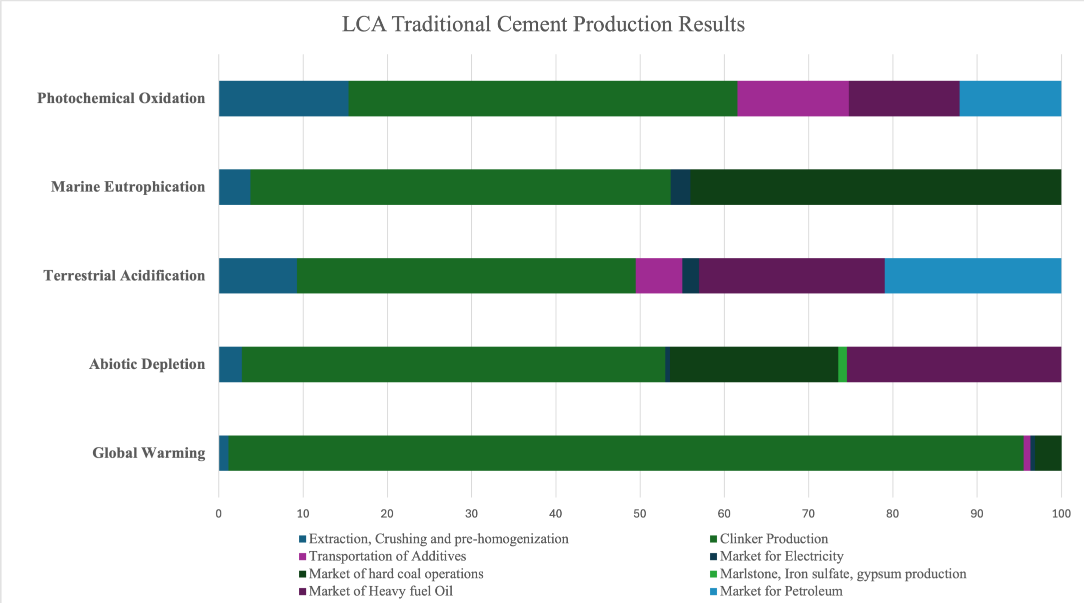

Figure 5.1: Results - LCA Cradle-to-Gate of Traditional Cement Production Process

Marine eutrophication, measures the potential contribution of nutrient-rich emissions—primarily nitrogen and phosphorus compounds—to the over-enrichment of water bodies, which can lead to harmful algal blooms and subsequent depletion of oxygen levels in marine ecosystems (Guinée 2002; Hauschild et al. 2018). According to the graph Figure 5.1, the highest contribution to marine eutrophication comes from the clinker production stage. This is due to nitrogen oxide (NO_x) emissions released during the high-temperature combustion required for calcination, which can convert into nitrate compounds and contribute to nutrient enrichment when they enter waterways (International Energy Agency 2018). Additionally, operations involved in the extraction and processing of hard coal significantly contribute to this impact category. Runoff from coal mining sites often contains nitrogen compounds, further adding to the eutrophication potential (Gartner 2019). The extraction, crushing, and pre-homogenization stages of raw materials also contribute, mainly due to dust and emissions from equipment and transport (WBC for Sustainable Development 2018). The market for electricity in Sweden, which is predominantly renewable, has a relatively lower direct impact on eutrophication compared to fossil fuel-dominated energy sources. However, indirect emissions associated with energy production and transmission still play a role (United Nations Environment 2020).

As a consequence of the cement production process, soil acidification and harm to terrestrial ecosystems can occur. Terrestrial acidification is the category impact that measures the potential release of acidifying substances like sulfur oxides (SO_x) into the environment. (Hauschild et al. 2018; Guinée 2002). In the context of traditional cement production at Slite, the highest contribution to terrestrial acidification originates from the clinker production process, accounting for 40% of the total impact. This is primarily due to the SO_x emissions released during the high-temperature combustion required for limestone calcination (International Energy Agency 2018). The market operations involved in obtaining and transporting heavy fuel oil contribute to 22% of the acidification potential, as the refining and transportation stages release significant amounts of SO_x (United Nations Environment 2020). Petroleum coke, used as a supplementary fuel in the clinker stage, accounts for 20% of the acidification impact, further emphasizing the impact of fossil fuel consumption in this category (Gartner 2019). The transportation of additives to the Slite site, often carried by freighters powered by marine gas oil (MGO), contributes additional emissions, especially sulfur compounds that contribute to acid rain (WBC for Sustainable Development 2018). Lastly, the market for electricity in Sweden, although primarily based on renewable energy sources, still contributes a small percentage to terrestrial acidification through indirect emissions from energy generation and grid losses (Swedish Energy Agency 2020). These results highlight the need for alternative fuels and emissions control technologies to mitigate the acidification potential of cement production.

Abiotic depletion is a crucial impact category in Life Cycle Assessment (LCA) that measures the consumption of non-renewable resources, such as minerals and fossil fuels, which can lead to the depletion of natural reserves (Guinée 2002; Hauschild et al. 2018). For traditional cement production at Slite, the highest contribution to abiotic depletion comes from the clinker production process, due to its high demand for energy and raw materials (International Energy Agency 2018). This is followed by the operations associated with heavy fuel oil usage, which play a significant role in the overall energy input for cement production, contributing to the depletion of fossil fuel reserves (United Nations Environment 2020). The operations involved in the hard coal market also add to the abiotic depletion impact, as coal mining and refining consume significant amounts of non-renewable resources (Gartner 2019). Additionally, the extraction, crushing, and pre-homogenization of raw materials contribute to the depletion of mineral resources, as these processes are energy-intensive operations (WBC for Sustainable Development 2018). The production and processing of minerals such as marlstone, iron sulfate, and gypsum—essential additives in the cement-making process—further contribute to this impact category, reflecting the resource-intensive nature of cement production (Swedish Energy Agency 2020). These findings underscore the need for adopting more resource-efficient practices and exploring alternative materials to mitigate the depletion of non-renewable resources in the cement industry.

Finally, the Global Warming Potential (GWP) is a central impact category in this Life Cycle Assessment (LCA) as it measures the potential of greenhouse gas emissions to contribute to climate change, expressed in terms of kg CO_2 equivalent (Hauschild et al. 2018; Intergovernmental Panel on Climate Change 2013). For the traditional cement production process at Slite, the highest contributions to GWP come from the clinker production process, due to the significant CO_2 emissions generated during the calcination of limestone at high temperatures (International Energy Agency 2018). The hard coal used as a fuel source further adds to the GWP through its associated mining, transport, and combustion-related emissions (WBC for Sustainable Development 2018). Additionally, the extraction, crushing, and pre-homogenization of raw materials contribute to the overall carbon footprint due to the use of machinery and fossil fuel-based energy during these stages (Gartner 2019). A smaller portion of the GWP impact is attributed to the transportation of raw materials and additives, as well as electricity consumption, which, although predominantly sourced from renewable energy in Sweden, still involves indirect emissions during energy production and transmission (Swedish Energy Agency 2020). These results emphasize the critical need for reducing CO_2 emissions at each stage of cement production to decarbonize this industry.

5.2 Results of Traditional Cement Production Process at Slite with Implementation of CCS

The results for the indicators mentioned in Table 5.2 are presented below, all based on the production of 1 tonne of cement. The contributions of each process to the different impact categories and indicators are illustrated in Figure 5.2. In the case of the LCA of traditional cement production with CCS, the impact category that showed the most significant change was Global Warming Potential, primarily due to the implementation of the CCS technology.

Impact Category	Total Ammount	Unit
Abiotic Depletion	2,20 and 94,74	kg Cu eq and kg oil eq
Terrestrial Acidification	0,354	kg SO_2 eq
Marine Eutrophication	0,0035	kg N eq
Global Warming Potential	107,16	kg CO_2 eq
Photochemical Oxidation (Human health)	0,341	Kg NO_x eq
Photochemical Oxidation (Terrestrial ecosystems)	0,352	Kg NO_x eq

Table 5.2: Impact Categories results in Cement Production LCA with CCS

With the implementation of carbon capture storage (CCS) technology, the Global Warming Potential (GWP) for the cement production process at Slite significantly decreases, with CO_2 equivalent emissions reduced from 911 kg CO_2 eq to 107 kg CO_2 eq per tonne of cement, assuming a 95% capture efficiency, as shown in Table 4.5 (Rubin et al. 2015) (Zero Emissions Platform 2013). The clinker production process in general continues to contribute the most to GWP in this scenario, due mainly to the use of hard coal, heavy fuel oil, and petroleum coke. This outcome aligns with the increased energy demand for amine regeneration in the CCS process, which is energy-intensive and typically relies on fossil fuels (IEA Greenhouse Gas RD Programme 2011). Additionally, there is a notable increase in the contribution from the use of waste tires and transportation, attributed to the additional transport required to move the captured and liquefied CO_2 to the storage facilities in Brevik, Norway (Intergovernmental Panel on Climate Change 2005).

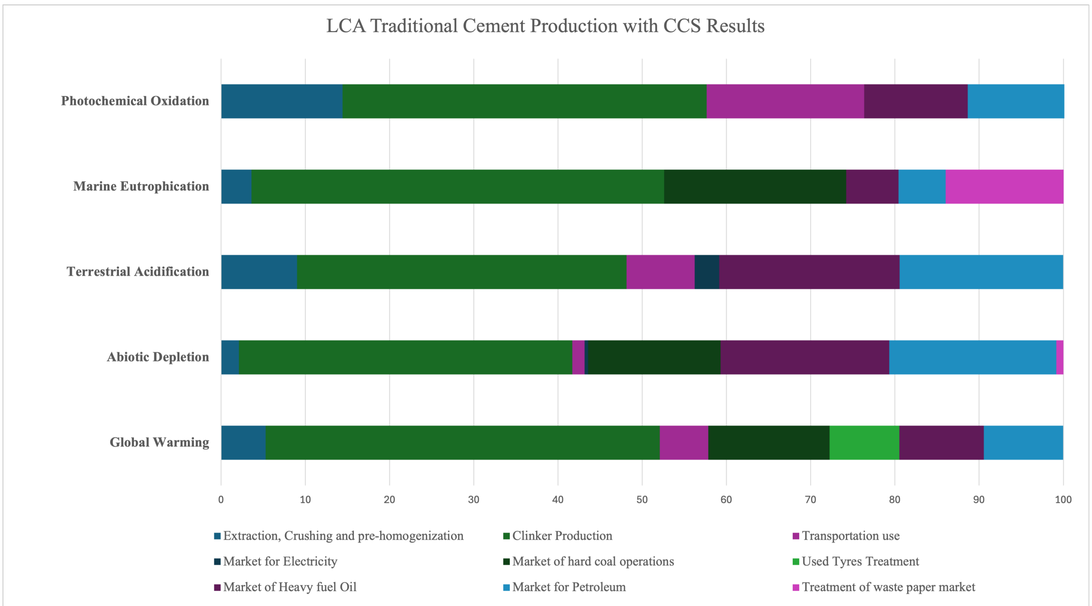

Figure 5.2: Results - LCA Cradle-to-Gate of Traditional Cement Production Process with CCS

For the Abiotic Depletion impact category, the CCS implementation results in a reduction in the contribution from the clinker production process, reflecting the lowered demand for raw materials due to reduced emissions. However, the impact from transportation increases, as the CCS process requires additional logistics for CO_2 transport (Gibbins and Chalmers 2007). Although the process also involves a higher electricity consumption for CO_2 compression, this does not significantly alter the contribution to this category due to the relatively low-carbon electricity mix in Sweden (Swedish Energy Agency 2020). A minor shift is observed in the contribution from waste paper treatment, which is typically used in clinker production, indicating some changes in waste management practices.

In the case of Terrestrial Acidification, the most significant change in the contribution pattern arises from the increased transportation needs for moving CO_2 from Slite to Brevik. This additional transportation generates higher NO_x and SO_x emissions, which contribute to acidification potential (Bui et al. 2018).

For Marine Eutrophication, the CCS scenario results in a reduction in the contribution from hard coal operations, reflecting the decreased reliance on this fuel due to lower clinker production emissions. However, there is a noticeable impact from heavy fuel oil use and the energy demands of amine regeneration, which involves the heating and treatment of the solvent used for CO_2 capture (Metz et al. 2005).

Finally, the photochemical oxidation impact category shows minimal changes in the overall contribution pattern. The main contributors remain the clinker production process and raw material extraction, with a slight increase in the impact associated with transportation due to the new logistics required for CO_2 transport (United Nations Environment 2020). Despite the significant reductions in GWP, the energy and transport needs of the CCS process introduce trade-offs in other impact categories, highlighting the need for careful consideration of the entire lifecycle when implementing CCS in industrial processes.

5.3 Sensitivity Analysis

Since the efficiency of the CCS process at an industrial scale might be lower than the assumed 95%, a sensitivity analysis was conducted using various efficiency levels to assess their impact on the Global Warming Potential (GWP) category.

Carbon Capture Technology Sensitivity Analysis			
CCS Efficiency	**CO_2 captured/ton of Cement**	**Ammount of GWP**	**Unit**
95%	0,7639	107,16	kg CO_2 eq
90%	0,7237	147,36	kg CO_2 eq
85%	0,6835	187,57	kg CO_2 eq
80%	0,6433	227,78	kg CO_2 eq
75%	0,6031	267,96	kg CO_2 eq

Table 5.3: Variations on Carbon Capture Efficiency

When the efficiency of Carbon Capture and Storage (CCS) technology decreases, the amount of CO_2 emissions captured inevitably declines, leading to an increase in the Global Warming Potential (GWP). In this analysis, a reduction in CCS efficiency from 95% to 90% as shown in table Table 5.3 results in an increase in GWP from 107.15 kg CO_2 eq to approximately 147 kg CO_2 eq per tonne of cement produced. This shift highlights a critical challenge in CCS deployment: even small decreases in efficiency can significantly impact the overall effectiveness of emissions reduction efforts. According to Rubin et al. (2015), the performance of CCS systems is highly dependent on maintaining optimal operational conditions, and variations in efficiency can affect not only CO_2 capture rates but also the energy requirements and costs associated with the process (Rubin et al. 2015). Therefore, ensuring a consistent capture rate is crucial for achieving meaningful reductions in carbon emissions from cement production.

To mitigate the potential negative impact of lower CCS efficiency, it is essential to plan ahead by exploring ways to enhance the performance of existing CCS systems or by integrating complementary strategies to decarbonize the cement industry. These strategies could include optimizing the energy use of the CO_2 capture process, using advanced solvents with lower regeneration energy demands, or developing more efficient heat integration methods, as suggested by Gibbins and Chalmers (2007) (Gibbins and Chalmers 2007). Additionally, the cement industry could diversify its decarbonization approach by incorporating alternative technologies such as renewable energy integration, the use of low-carbon cement materials, and increasing the use of alternative fuels like biomass (IEA Greenhouse Gas RD Programme 2011). Such multi-faceted approaches would not only reduce the reliance on CCS but also enhance the resilience of decarbonization efforts in the face of fluctuating CCS efficiencies.

Conclusions and Future Work

The implementation of Carbon Capture and Storage (CCS) in the cement production process at the Slite plant presents a significant opportunity for reducing CO_2 emissions, with the potential to decrease the Global Warming Potential (GWP) by capturing up to 95% of the emissions generated during clinker production. However, as the sensitivity analysis highlights, any reduction in the efficiency of the CCS process can substantially impact the effectiveness of this technology, leading to an increase in CO_2 emissions. This underscores the need for continuous optimization of CCS operations to ensure that capture rates remain high and energy consumption is minimized. According to Gassnova's feasibility studies, maintaining optimal operational conditions and minimizing energy use during CO_2 compression and transport is crucial for the long-term success of CCS in the cement industry (Gassnova 2016).

Decarbonizing the cement industry requires more than just carbon capture and storage. To further reduce emissions, the industry must explore alternative fuels and energy sources to replace fossil fuels in the clinker production process. This could include the increased use of biomass and waste-derived fuels for energy-intensive processes such as CO_2 compression. As noted by Rubin et al. (2015), transitioning to lower-carbon fuels can reduce both direct and indirect emissions from cement plants, offering a complementary pathway to CCS for reducing the overall carbon footprint of cement production (Rubin et al. 2015). Additionally, integrating energy efficiency measures and waste heat recovery systems, such as those proposed by Gibbins and Chalmers (2007), can further lower the energy demands of both the cement production and CCS processes, making the system more sustainable (Gibbins and Chalmers 2007).

To address the environmental impacts associated with the transportation of captured CO_2, optimizing transport logistics is essential. For example, using low-emission shipping technologies or increasing the capacity of ships used to transport CO_2 can reduce the overall emissions associated with transportation (Al Baroudi et al. 2021). Localizing storage sites closer to cement production facilities could also minimize transportation distances and associated emissions, making the overall process more efficient and less environmentally intensive.

In the broader context of decarbonizing the cement industry, it is also crucial to explore alternative cement types and production methods that reduce the reliance on traditional clinker. Producing blended cements that incorporate supplementary materials, such as fly ash and blast furnace slag, can reduce the demand for clinker, which is the most energy-intensive component of cement. These materials not only lower the CO_2 emissions of the cement production process but also contribute to the circular economy by utilizing industrial by-products (United Nations Environment 2020). Additionally, a key area for future work is managing stored CO_2 over the long term, especially as storage sites, such as seabed reservoirs, approach their capacity limits. Exploring Carbon Capture and Utilization (CCU) pathways—converting CO_2 into useful products like synthetic fuels, chemicals, or construction materials—aligns with circular economy principles and offers a potential solution to the storage challenge (MacDowell et al. 2017). Such approaches can reduce the burden on storage sites while creating new market opportunities for the cement industry.

Ultimately, while CCS offers a viable route for reducing emissions from the cement industry, it should be viewed as part of a holistic decarbonization strategy that includes efficiency improvements, alternative fuels, optimized logistics, and innovation in cement composition. This comprehensive approach will be crucial for achieving Sweden's goal of climate-neutral cement production by 2030 and ensuring the industry's sustainability in the face of evolving environmental challenges.

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Appendix A

A.1 Model Setup for LCA - Traditional Cement Production at Slite

Input Flows	Category	Description
Transport, freight, inland waterways, barge tanker - RER (Europe)	H:Transportation and storage	To represent the emissions due to transportation of imported raw materials
Slagg - GLO (Global)	C:Manufacturing / 23:Manufacture of other non-metallic mineral products	Used in the preparation of the raw meal for clinker production
Sand - CH (Switzerland)	B:Mining and quarrying / 0810:Quarrying of stone, sand and clay	Used in the preparation of the raw meal for clinker production
Marlstone (calcerous marl) - CH (Switzerland)	B:Mining and quarrying / 0810:Quarrying of stone, sand and clay	Extracted in the quarrying nearby Slite, pretreated and used to prepare the raw meal
Limestone, crushed, for mill - CH (Switzerland)	B:Mining and quarrying / 0810:Quarrying of stone, sand and clay	Extracted in the quarrying nearby Slite, pretreated and used to prepare the raw meal
Iron Ore - RER (Europe)	B:Mining and quarrying / 0710:Mining of Iron ores	Used to prepare the raw meal
Bauxite, without water - GLO(Global)	B:Mining and quarrying/0710:Mining of Iron ores	Used to prepare the raw meal
Electricity, medium voltage - SE (Sweden)	D: Electricity / 3510: Electric power generation, transmission and distribution	Used in the raw Material grinding (Conveyor belts and raw mill) and for the raw meal preparation
Heavy fuel oil - Europe without Switzerland	C: Manufacturing / 1920: Manufacture of refined petroleum products	Fuel consumption of equipment during this stage, is mainly imported from Cyprus

Table A.1: Input Flows in OpenLCA - Extraction, Transportation, Crushing and Pre-homogenization

Output Flows	Category	Description
Raw Meal	Clinker production	The product from the pre-homogenization of raw materials is used as the input for clinker production

Table A.2: Output Flows in OpenLCA - Extraction, Transportation, Crushing and Pre-homogenization

Input Flows	Category	Description
A/C Fuel (Waste paint, hazardous waste incineration) - CH (Switzerland)	E: Waste Management / 3822: Treatment and disposal of hazardous waste	Corresponds to non-recyclable production waste and chemicals that are processed by specialized companies to produce fuel for the cement industry
Converted Fuel Oil (Waste mineral oil, hazardous waste incineration) - CH (Switzerland)	E: Waste Management / 3822: Treatment and disposal of hazardous waste	Corresponds to waste oil collected from various sources that is processed into Recovered Fuel Oil (RFO) at specialized plants, and is used as an alternative fuel, particularly by the cement industry
Biogenic fuel (Waste paper unsorted, non-hazardous waste) - Europe without Switzerland	E: Waste Management / 3811: Treatment and disposal of non-hazardous waste	Corresponds to plastic and paper waste collected from various sources that is processed to be incinerated and use it to light the kilns
Hard coal - WEU (Western Europe)	B:Mining and quarrying / 051:Mining of hard coal	Used as a fuel for clinker production
Petroleum coke - Europe without Switzerland	C:Manufacturing / 1920: Manufacture of refined petroleum products	Used as a fuel for clinker production
Used tyre - GLO (Global)	C:Manufacturing of other non-metallic mineral products / 2394:Manufacture of cement, lime and plaster	Tyres that cannot be reused or recycled, they are utilized as alternative fuel in the cement process
Raw Meal	Cement production	The product from the pre-homogenization of raw materials is used as the input for clinker production
Heavy fuel oil - Europe without Switzerland	C: Manufacturing / 1920: Manufacture of refined petroleum products	Fuel consumption of equipment during this stage, is mainly imported from Cyprus
Transport, freight, inland waterways, barge tanker - RER (Europe)	H:Transportation and storage	To represent the emissions due to transportation of imported raw materials
Electricity, medium voltage - SE (Sweden)	D: Electricity / 3510: Electric power generation, transmission and distribution	Used in the raw Material grinding (Conveyor belts and raw mill) and for the raw meal preparation

Table A.3: Input Flows in OpenLCA - Clinker Production

Output Flows	Category	Description
Clinker - Europe without Switzerland	C:Manufacturing of other non-metallic mineral products / 2394:Manufacture of cement, lime and plaster	Corresponds to the clinker for producing Portland cement II A
Carbon dioxide	Elementary flows/Emissions to air/high population density long-term	Corresponds to emissions to air reported
Nitrogen oxides, SE	Elementary flows/Emissions to air/high population density long-term	Corresponds to emissions to air reported
Sulfur oxides, SE	Elementary flows/Emissions to air/high population density long-term	Corresponds to emissions to air reported
Heat, district or industrial, other than natural gas - SE (Sweden)	D: Electricity / 353: Steam and air conditioning supply	To represent the heat produced during clinker production that is used for district heating
Electricity, medium voltage - SE (Sweden)	D: Electricity / 3510: Electric power generation, transmission and distribution	Used in the raw Material grinding (Conveyor belts and raw mill) and for the raw meal preparation

Table A.4: Output Flows in OpenLCA - Clinker Production

Input Flows	Category	Description
Clinker - Europe without Switzerland	C:Manufacturing of other non-metallic mineral products / 2394:Manufacture of cement, lime and plaster	Corresponds to the clinker for producing Portland cement II A
Gypsum, mineral - CH (Switzerland)	B: Mining and quarrying / 0810:Quarrying of stone, sand and clay	Refers to gypsum imported from quarries near Sweden in Europe and used as an additive in cement production.
Iron sulfate - RER (Europe)	C:Manufacturing / 2011:Manufacture of basic chemicals	Used as an additive in cement production
Iron coal ash - Europe without Switzerland	C:Manufacturing / 2394:Manufacture of cement, lime and plaster	used as an additive in cement production
Transport, freight, inland waterways, barge tanker - RER (Europe)	H:Transportation and storage	To represent the emissions due to transportation of imported raw materials
Electricity, medium voltage - SE (Sweden)	D: Electricity / 3510: Electric power generation, transmission and distribution	Used in the raw Material grinding (Conveyor belts and raw mill) and for the raw meal preparation

Table A.5: Input Flows in OpenLCA - Cement Production

Output Flows	Category	Description
Cement, Portland - Europe without Switzerland	C:Manufacturing / 2394: Manufacture of cement, lime and plaster	the final product of Portland cement II A

Table A.6: Output Flows in OpenLCA - Cement Production

A.2 Model Setup for LCA - Cement Production at Slite with Carbon Capture Storage - Reference year: 2023

Input Flows	Category	Description
Carbon Dioxide	Is a mass flow created to represent the carbon dioxide from the stream of the exhaust gas pre-treated	Corresponds to the carbon dioxide fraction produced per ton of cement during 2023
Heavy fuel oil - Europe without Switzerland	C: Manufacturing / 1920: Manufacture of refined petroleum products	Fuel consumption due tu amine use on the CCS process
Transport, freight, inland waterways, barge tanker - RER (Europe)	H:Transportation and storage	To represent the emissions due to transportation of CO_2 liquefied
Electricity, medium voltage - SE (Sweden)	D: Electricity / 3510: Electric power generation, transmission and distribution	Used in the raw Material grinding (Conveyor belts and raw mill) and for the raw meal preparation

Table A.7: Input Flows in OpenLCA - CCS Process

Output Flows	Category	Description
Carbon Dioxide, liquid - RER (Europ)	C:Manufacturing/2011: Manufacture of basic chemicals	Corresponds to the carbon dioxide captured per ton of cement during 2023
Carbon dioxide	Elementary flows/Emissions to air/high population density long-term	Corresponds to emissions to air that are not captured due to the technology's efficiency.

Table A.8: Output Flows in OpenLCA - CCS Process